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Francesca Principato

ABSTRACT

In developed countries, the level of urbanization is increasing and should reach 83% in 2030 (United Nations, 2002; Antrop, 2004). Increasing urbanization generates a series of issues, that could reduce the quality of life in cities for their inhabitants and lead to an exploitation of natural resources. The transformation of vegetated areas into impervious surfaces, such as roads, parking lots, and buildings, results in fragmentation of the landscape, which negatively impacts the flora and fauna and the roles that they play in the ecosystem. The combined effect of urbanization and climate change resulted in increased vulnerability of urban areas and a disruption of the natural water cycle (Piro et al., 2012). The increasing imperviousness of urban areas reduces the infiltration and evapotranspiration capacity of urban catchments and results in increased runoff and reduced groundwater recharge (Piro et al., 2012).

Increases in the incidence of flooding and combined sewer overflows (CSOs) in urban areas demonstrate that the traditional approach is inadequate for managing stormwater. Conversely, the *Low Impact Development* (LID) approach aims to preserve and restore natural features, minimize the imperviousness of urban catchments, and increase their infiltration and evapotranspiration capacities. LID techniques include bio-retention cells, grass swales, porous pavements, green roofs, and many other measures.

Among these recent Low Impact Development (LID) strategies for urban stormwater management, vegetated roofs appear to be particularly relevant especially given the huge amount of unused roof in urban area. Several Research have been conducted on run-off mitigation by green roofs (Beattie & Berghage, 2004; Carter & Jackson, 2007). Several studies have shown that green roofs may have significant effects on retaining rainfall volumes (DeNardo et al., 2003; VanWoert et al., 2005; Getter et al., 2007; Simmons et al., 2008; Gregoire & Clausen, 2011; Gromaire et al., 2013), delaying the peak flow rate (Bengtsson et al., 2005; Carter & Rasmussen, 2006; Spolek 2008) and reducing the runoff volume discharged into the combined sewer systems (CSSs) (Liptaň, 2003; Berndtsson, 2010; Voyde et al., 2010; Stovin et al., 2012). The roof's hydrological response to precipitation events is highly variable and related to a particular set of climate conditions and changes with vegetated roof design.

The above considerations suggest that if vegetated roofs have to be widely deployed as part of stormwater management strategies, it is basic understand how specific roof systems will respond to specific rainfall events; this requires reliable modeling tools that enable to

optimize the performance of the vegetated roof systems over a wide range of design types and different operating conditions.

From this premises derive this research work, with the title: *“Vegetated roofs as a Low Impact Development (LID) approach: hydrologic and hydraulic modeling for stormwater runoff mitigation in urban environment”*, which concerns the performance of green roof, as a LID system, focusing on the hydrologic and hydraulic modelling. Since hydrological-hydraulic performance of a green roof is influenced by various factors, such as the weather-climatic and structural characteristics of the vegetated cover, the main objective of the research will be to define, improve and implement a methodology for the design of green roofs by using data from two different geographical areas and climate conditions (Cosenza in Italy and Lyon in France, respectively in Mediterranean and Temperate area), in order to identify some key factors for the characterization of the response of green roof system.

More specifically, after a general introduction and an overview of the benefits that the adoption of the LID provides to the stormwater management in urban areas, compared to conventional systems, in Chapter 1 the main objectives of the research project are defined. Green roofs represent one of the most widespread *Low Impact Development* techniques, and in Chapter 2 are described its stratigraphy components and are discusses the major benefits achieved by the installation of vegetated roofs, with particular attention to their contribution in stormwater control.

In Chapter 3, the literature review is organized in relation to the research objectives: (1) the first part provides an overview of the models for the analysis of the hydraulic behavior of green roofs, as a support tool for quantitative stormwater management; (2) in a second phase was carried out a survey of the scientific studies carried out to analyze the influence of different parameters on the hydraulic and hydrological performance of extensive vegetated roof. These considerations suggest that if the green roof must be part of the stormwater management strategies, it is fundamental to understand how specific green roof system responding to specific rainfall events; this requires reliable modeling tools that allow to optimize the performance of green roof systems on a wide range of design types and in different operating conditions. As a result of these considerations, the Chapters 4 and 5 are relate to the experimentations conducted using two different models.

The Chapter 4 investigates the reliability of a conceptual model of green roof, developed jointly by *Le Prieuré* and INSA Lyon, to simulate the behavior of a specific pre-fabricated green roof technology (Hydropack® & Stock & Flow®). The model idealizes the green roof as a system consisting of four consecutive reservoirs in series, each characterized by a specific hydrological and/or hydraulic process represented by conceptual or semi-detailed equations: *Interception reservoir, substrate reservoir, alveolus reservoir and last additional storage reservoir*. The model has been applied to two different experimental sites: 1) a 1 m^2 experimental Pilot Scale green roof at Le Prieuré, Moisy, France and 2) a 282.5 m^2 Full Size green roof at the Congress Center in Lyon, France.

The model is calibrated with a non-linear least square algorithm for the substrate water depth and the total outflow for the Pilot Scale and the Congress Center green roof respectively. The Nash-Sutcliffe (NS) criterion and the Root Mean Squared Error (RMSE) are used as model performance indicators. Simulation results show that the model has a high ability to replicate the behavior observed for the substrate water depth during rainfall events, either with one peak or even in complex events with several peaks, as confirmed by high NS values (above 0.6 for 78 % of the cases, and above 0.97 for 46 %) and low RMSE values. The first results of the sensitivity analysis indicate that the response of the model is strongly determined by the initial substrate water content, which requires to be considered as one of the key parameter in the model when used at the event scale. Simulation results for the full size roof globally show the model ability to reproduce the dynamic behavior of the roof total outflow in case of continuous long term simulations which are much more challenging than event scale simulations as in Moisy. The model provides good results during months with significant rainfall events and outflows (NS = 0.74 for November 2012) while it performs less accurately during drier months with low rainfall amounts and very low outflows close to the limits of detection of the used flowmeters (NS = 0.25 in February 2013). Nevertheless, NS = 0.59 for the entire period of nine months calibrated globally.

In the Chapter 5, the *SIGMA DRAIN* Model, developed during the project PON01_02543 to simulate the hydraulic behavior of the extensive vegetated roof installed at the Unical experimental site, is propose. The SIGMA DRAIN (SD) model uses the calculation engine of EPA-SWMM (Storm Water Management Model) software for the simulation of the hydrological and hydraulic phenomena, while being completely independent of the user interface. The SD model idealizes the green roof as a system consisting of three components in series, each of them corresponding to the main technological modules of the roof: the top layer covered by vegetation is conceptualized as sub-catchment, while the soil and drainage layers are schematized through two storage tanks, describing respectively the percolation through the growing medium and the transport through the drainage layer. A mass balance equation is applied to each block, taking into account the specific physical phenomena that occur in each module; the flow is instead regulated by the Richard's equation.

In order to estimate the reliability of the model, it was first calibrated and then validated with the software HYDRUS-1D. Since the hydraulic/hydrologic behavior of a green roof is most influenced by soil layer characteristics (especially at event scale), the surface layer has not been considered in the modelling. Looking at the results in terms of outflow of the individual rainfall events, it has been possible to note that the SD model approximates well the model HYDRUS-1D for precipitation above 20 mm, while for events with lower rainfall depth, the performance of the model are not satisfactory; such behavior is attributable to the fact that in the model *Sigma Drain*, differently from HYDRUS-1D, not taken into account the initial water content of the substrate. To confirm this, the simulations carried out by combining more consecutive events (at multi-event scale), showed an average NS index value of 0.8, demonstrating that the inter-event conditions are considered to be relevant in the assessment of response model.

After validation procedure, the model was loaded with datasets collected in two different sites (Unical, in Italy and Lyon, in France), in order to analyze the influence of the hydrologic parameters on the green roof efficiency. A similar behavior for both scenarios (Unical and Lyon) is evident by comparing the results provided by SIGMA DRAIN in terms of runoff: the two sites area follow the same trend and it has been estimated a threshold rainfall depth of 13 mm, below which the green roof retains almost the totality of the event. For event higher than 13 mm, it is possible to notice a strong proportionality between rainfall and runoff depths (to small events with redoubt rainfall depth correspond law runoff depth values) and a mean value of SRC equal to 46% and 38% for Unical and Lyon dataset, respectively.

Furthermore, to statistically determine the significance of the hydrological parameters on the hydraulic efficiency of the experimental green roof, a multiple linear regression analysis, using the rainfall data collected from the experimental site at University of Calabria, was evaluated. The multi-regression relationships, are then validated by using the rainfall data recorded at Congress Center in Lyon. These equations can be used to preliminarily predict the runoff depth and the retention capacity, for a given rainfall events, when more advanced model are not available.

From these results it clearly emerges that a the green roof package, developed at University of Calabria, under Mediterranean climate conditions, has a good hydraulic performance also in a different climate, as the Temperate one, in which the Lyon data were recorded.

Finally, in Chapter 6 are exhibited general conclusions on the research project and possible future developments.

In conclusion, this research aims to promote the green roof, not only as a tool for environmental mitigation, but specifically as a sustainable urban drainage solution to restore the fundamental natural water cycle processes in the urban environment.

SOMMARIO

Nei paesi sviluppati, il livello di urbanizzazione è in continuo aumento e dovrebbe raggiungere l'83% nel 2030 (United Nations, 2002; Antrop, 2004). Il notevole incremento della popolazione comporta una continua espansione areale delle città che si traduce nella progressiva cementificazione di aree vegetate sempre più grandi. L'effetto combinato di urbanizzazione (che riduce la disponibilità di spazi naturali e allo stesso tempo modifica la rete di scorrimento superficiale) e cambiamenti climatici (che incrementano la frequenza e l'intensità delle precipitazioni) (Piro et al., 2012) ha comportato una maggiore vulnerabilità delle aree urbane ed uno sconvolgimento del ciclo idrologico naturale. Durante gli eventi di pioggia intensi, i tassi di infiltrazione ed evapotraspirazione si sono notevolmente ridotti, e di conseguenza si è verificato un incremento del volume di deflusso delle acque meteoriche che sovraccarica il sistema di drenaggio urbano (Piro et al., 2012).

In un'ottica di sviluppo ambientale sostenibile, nasce quindi l'esigenza di potenziare la rete di deflusso superficiale mediante l'introduzione di soluzioni sostenibili che consentano di rispristinare, per quanto possibile, le condizioni idrologiche che caratterizzavano il bacino prima dello sviluppo urbano (Cannata, 1994). L'insieme di queste tipologie di interventi a basso impatto che, seguendo un approccio ecologicamente basato, consente una gestione delle acque piovane direttamente alla fonte così da prevenire molti problemi che possono accorrere lungo il percorso di trasporto, viene identificato in letteratura con l'acronimo LID (*Low Impact Development*).

Tra queste, la tecnica del verde pensile che protegge, ripristina o imita il ciclo idrologico di pre-sviluppo e, sfruttando gli spazi disponibili sulle coperture a tetto (altrimenti inutilizzate), può essere applicata anche in ambienti urbani densamente edificati, è di particolare interesse ambientale per l'insieme dei benefici che comporta su scala del singolo edificio e del comprensorio urbano circostante (Tillinger, et al., 2006). Diversi studi hanno evidenziato come le coperture vegetate possano avere effetti sulla ritenzione degli eventi di pioggia (DeNardo et al., 2005; VanWoert et al., 2005; Getter et al., 2007; Gregoire and Clausen, 2011), riducendo il volume di deflusso e la portata al colmo (Berntsson, 2010; Palla et al., 2010; Voyde et al., 2010; Stovin et al., 2012) e ritardando il picco di piena (Carter e Rasmussen, 2006; Spolek, 2008).

Da queste premesse nasce il seguente lavoro di tesi, che ha riguardato lo studio del Verde pensile come sistema a basso impatto ambientale, per la mitigazione dei deflussi nell'idraulica urbana, focalizzando l'attenzione sulla Modellazione Idrologico-Idraulica: *"Vegetated roofs as a Low Impact Development (LID) approach: hydrologic and*

hydraulic modeling for stormwater runoff mitigation in urban environment". Il principale obiettivo della ricerca è stato quello di definire, migliorare ed implementare una metodologia per la progettazione dei tetti verdi utilizzando i dati provenienti da diverse aree geografiche (nel caso specifico sono stati analizzati i dati provenienti da due diverse realtà geografiche: Cosenza in Italia e Lione in Francia), al fine di individuare alcuni fattori chiave per la caratterizzazione della risposta di un sistema a verde pensile.

Più nello specifico, dopo un'introduzione generale ed una panoramica sui benefici che l'adozione delle LID offre alla gestione delle acque meteoriche in ambiente urbano rispetto ai sistemi convenzionali, nel Capitolo 1 sono stati definiti i principali obiettivi del progetto di ricerca. Tra le soluzioni naturalistiche che operano il controllo della formazione dei deflussi superficiali mediante i processi di ritenzione e detenzione, quella del Verde Pensile viene particolarmente trattata nel Capitolo 2; vengono descritte le componenti stratigrafiche ed illustrati i più importanti effetti benefici conseguibili dall'installazione di coperture vegetate, con particolare attenzione al contributo nella regimazione delle acque meteoriche.

Dal momento che la risposta idrologico-idraulica di una copertura vegetata è influenzata da diversi fattori quali le condizioni meteo-climatiche e le caratteristiche costruttive della copertura vegetata, la revisione della letteratura (Capitolo 3) è organizzata in relazione agli obiettivi della ricerca: (1) la prima parte fornisce una panoramica dei modelli per l'analisi del comportamento idraulico dei tetti verdi, visti come strumento di supporto alla gestione quantitativa delle acque di pioggia; (2) nella seconda parte è stata eseguita una ricognizione degli studi scientifici effettuati per analizzare l'influenza dei suddetti parametri sulle prestazioni idrologiche ed idrauliche di una copertura vegetata di tipo estensivo. Tali considerazioni suggeriscono che se il verde pensile deve essere parte delle strategie di gestione delle acque piovane, è fondamentale capire come specifici sistemi di copertura rispondano ad eventi pluviometrici specifici; questo richiede strumenti di modellazione affidabili che consentano di ottimizzare le prestazioni dei sistemi a verde pensile su una vasta gamma di tipi di costruzione e in diverse condizione operative. Come risultato di tali considerazioni, i capitoli 4 e 5 riguardano le sperimentazioni condotte utilizzando due diversi modelli.

In particolare il Capitolo 4 indaga l'affidabilità di un modello concettuale di tetto verde, sviluppato congiuntamente dalla *Le Prieuré* e l'INSA di Lione, per simulare il comportamento di una specifica tecnologia di tetto verde pre-fabbricato (Hydropack® & Stock&Flow®). Il modello si basa sul percorso dell'acqua attraverso quattro serbatoi disposti in serie, ciascuno caratterizzato da uno specifico processo idrologico e/o idraulico rappresentato da equazioni concettuali o semi-dettagliate: *Serbatoio di Intercettazione*, *Substrato*, *Serbatoio Alveolare* ed un *Serbatoio di Raccolta*. Il modello, adattabile a qualsiasi tipo di copertura attraverso l'attivazione/disattivazione di serbatoi e funzioni opzionali, intende simulare il comportamento dinamico del tetto verde a diversi intervalli di tempo, indagarne l'affidabilità ed ottimizzarne le prestazioni.

Il modello è stato testato e calibrato utilizzando un database raccolto su due siti sperimentali, rispettivamente per un anno e nove mesi, misurati al passo temporale di 1 minuto:

1) per l'unità prefabbricata di 1 m^2 (Hydropack®) prodotta ed installato a Moisy (Francia) da Le Prieuré, la calibrazione è stata condotta a scala d'evento per valutare il contenuto idrico nel substrato;
2) per il tetto verde a grandezza naturale di 282 m^2 presso il Centro Congressi di Lione (Francia),la calibrazione è stata condotta a scala mensile per valutare il deflusso totale in uscita dal tetto verde.

Tutte le simulazioni del modello sono state effettuate utilizzando il linguaggio di programmazione MatLab. Come indicatori delle performance del modello sono stati utilizzati il criterio di Nash-Sutcliffe (NS) e il Root Mean Squared Error (RMSE). I risultati delle simulazioni effettuate sull'unità Hydropack hanno mostrano che il modello ha una elevata capacità di replicare il comportamento osservato per il contenuto idrico nel substrato durante eventi piovosi, come confermato dagli alti valori di NS (sopra 0,6 per il 78% dei casi, e sopra 0,97 per il 46%) e valori RMSE bassi. I primi risultati hanno inoltre indicato che la risposta del modello è fortemente determinata dal contenuto iniziale di acqua nel substrato (Hs0) che andrà considerato come uno dei parametri chiave del modello quando è usato a scala di evento. Per quanto riguarda le simulazioni mensile effettuate sul tetto verde a scala reale, i primi risultati hanno mostrato una buona capacità del modello di replicare il comportamento osservato per la portata in uscita dal tetto, solo per alcuni eventi; prestazioni inferiori si osservano per alcuni eventi a causa di dubbia affidabilità dei dati o nel caso di eventi con precipitazioni molto piccole.

Nel Capitolo 5 viene proposto un modello concettuale (*SIGMA DRAIN)*, sviluppato nel corso del progetto PON01_02543 per simulare il comportamento idraulico della copertura vegetata di tipo estensivo installata nel sito sperimentale dell'Unical. *SIGMA DRAIN* utilizza, per la simulazione dei fenomeni idrologici e idraulici, il motore di calcolo del software EPA SWMM (Storm Water Management Model), pur essendo completamente svincolato dall'interfaccia utente del software. Il nuovo modello idealizza il tetto verde come un sistema costituito da tre componenti disposte in serie, ognuna caratterizzata da uno specifico processo idrologico-idraulico, corrispondenti ai tre moduli tecnologici principali della copertura: lo strato superficiale è concettualizzato come un sottobacino mentre i successivi strati di terreno e di accumulo sono schematizzati attraverso due serbatoi lineari che descrivono rispettivamente la percolazione attraverso il substrato colturale e il trasporto attraverso lo strato drenante. Un'equazione di bilancio di massa viene applicata a ciascun blocco, tenendo conto dei fenomeni fisici specifici che si verificano in ciascun modulo; il flusso è invece regolato dall'equazione di Richards.

Al fine di stimarne l'affidabilità, il modello è stato prima calibrato e poi validato con il software HYDRUS-1D, che modella l'infiltrazione dell'acqua nel sottosuolo; visti i parametri idraulici richiesti dal software, tale operazione ha riguardato essenzialmente lo strato di terreno piuttosto che quello di vegetazione ed accumulo. Osservando i risultati in termini di deflusso dei singoli eventi di pioggia, è possibile constatare che il modello *Sigma Drain* approssima bene il modello HYDRUS-1D per precipitazioni al di sopra dei 20 mm, mentre per eventi con altezza di pioggia inferiore le performance del modello non risultano soddisfacenti; tale comportamento è attribuibile al fatto che nel modello *Sigma Drain*, differentemente da HYDRUS-1D, non si tiene conto del contenuto idrico iniziale del substrato. A conferma di ciò, le simulazioni effettuate in continuo, hanno mostrato in media un valore dell'indice di NS pari a 0.8, a dimostrazione che le condizioni idrologico-idrauliche antecedenti l'evento considerato sono rilevanti nella valutazione della risposta del modello.

Particolare attenzione è stata riposta all'analisi del coefficiente di deflusso e ai fattori idrologici che sono determinanti nelle performances del tetto quali: la precipitazione, l'intensità e la durata di pioggia, nonché il periodo intra-evento che intercorre tra due eventi indipendenti. A seguito delle simulazioni effettuate con *SIGMA DRAIN*, dal confronto dei risultati ottenuti in termini di deflusso tra gli eventi di pioggia registrati con passo temporale di 1 minuto sul sito sperimentale dell'Unical e presso Lione, si è evidenziato per entrambi gli scenari un comportamento analogo, stimando un valore soglia delle precipitazioni di 13mm, al di sotto del quale il tetto verde trattiene la quasi totalità dell'evento. Per eventi con altezza di pioggia superiore a 13 mm, è stata rilevata, invece, un coefficiente di deflusso che si attesta in media attorno al 46% e 38% rispettivamente per il set di dati regisrati all'Unical e a Lione; è possibile osservare, inoltre, l'esistenza di una proporzionalità diretta tra precipitazione e deflusso.

Per analizzare al meglio l'influenza dei singoli parametri idrologici sull'efficienza idraulica del tetto verde, è stata poi ricavata, con i dati di pioggia dell'Unical, un'equazione statistica sulla base di analisi di regressione lineare multipla, successivamente validata con i dati di Lione, che consenta di avere una prima stima della capacità di ritenzione del tetto verde in funzione della durata dell'evento e dell'altezza di pioggia. In definitiva è possibile osservare che ogni singolo parametro, sia esso idrologico o fisico, apporta un'influenza significativa sulle prestazioni idrauliche di una copertura vegetata. Risulta, dunque, approssimativo valutare l'efficienza di una copertura vegetata mediamente su scala annuale o stagionale, in quanto ogni singolo evento di pioggia, in funzione delle proprie caratteristiche e di quelle della copertura stessa, sarà trattenuto in maniera differente.

I risultati ottenuti dalle sperimentazioni hanno evidenziato come la copertura vegetata di tipo estensivo, progettata e realizzata all'Unical, in clima Mediterraneo, presenti un ottima efficienza idraulica anche considerando i dati di pioggia di un'altra realtà come Lione, caratterizzata da un clima Temperato.

Infine, nel Capitolo 6 vengono esposte le conclusioni generali sul progetto di ricerca e i possibili sviluppi futuri.

Con questo lavoro di tesi, che fornisce indicazioni utili alla realizzazione di una pianificazione urbanistica sostenibile che consenta di attuare una gestione integrata della risorsa idrica, si intende promuovere il verde pensile non solo quale strumento di mitigazione e compensazione ambientale in generale, ma nello specifico quale soluzione di drenaggio urbano sostenibile per il ripristino dei processi fondamentali del ciclo idrologico naturale nell'ambiente urbano.

TABLE OF CONTENTS

Chapter 1 – BACKGROUND AND THESIS OBJECTIVES

1.1 Introduction

At the turn of the millennium, a historic milestone was reached when the global population passed the six billion mark, doubling since the late 1950s (Sustainability Reporting Program., 2007).

During the last sixty years the urban areas of the world are growing at an alarming rate and an extreme and rapid increase in the urban population has occurred. The process in which the total urban population increases with 70 million people annually, while the rural area population is about static, is called urbanization (UN 2008). In 2001, the total world's urban population was 48% and UN (2008) predicts that in 2030, more than 60% of the total world population will live in urban areas. It is predicted that the world population will be concentrated in urban areas, reaching by 2050 70% and 86% in more developed countries (Dept. of International Economic and Social Affairs, 2007). As a matter of fact, ongoing changes to the natural physiographic characteristics are a result of urbanization. Consequently, the effects of urbanization are of critical concern due to the unprecedented rate of growth and scope of urban centres.

Urban infrastructure often cannot keep up with the demands of population influxes. While population increase can be a positive driving force of change, there are also numerous negative effects. Among the numerous economic, social, and political consequences of urbanization, environmental impacts have been increasingly significant, demonstrated by the evident signals of change. Increasing urbanization generates a series of issues, that could reduce the quality of life in cities for their inhabitants and lead to an exploitation of natural resources. The transformation of vegetated areas into vast tracts of impervious surfaces such as roads, parking lots, and built structures results in fragmentation of the landscape, which negatively impacts the flora and fauna and the roles that they play in the ecosystem. Noticeable changes has been seen in terms of climate, significant natural resources have been depleted, and increased forms and amount of pollutions are constantly being released into the air, water, and land. Consequently, issues related to urban environmental sustainability are finding their way into top level discussions within many governments worldwide. One such issue is the role of water in urban areas (Marsalek et al., 2006).

Several researches identify that ongoing urbanization have changed several characteristics of water systems in urban areas. Deforestation, streets, pavements and traditional roofs have increased the rate of total impervious area. Since an impervious area does not allow water to penetrate into the soil, the increase of impervious regions from urban sprawl leads directly to considerable increase of storm water volume reaching municipal storm sewers, and ultimately local waterways.

An important hydrological effect that results from these changed characteristics are changes in the rainfall-runoff relation. First, the combined effect of increased input from precipitation and an increase in total impervious area, reduce the overland flow times and drain flow times cause an increase in urban runoff volumes (Marsalek et al., 2006). As more land is cleared, natural vegetation and depressions that intercept rainfall and temporarily store water are lost, and as a result alter the local hydrologic cycle (Bradford & Gharabaghi, 2004). This effect results in higher runoff peaks during a precipitation event and lower base flows during dry spells.

In the past decade, a rising number of severe catastrophic weather events have struck urban areas in a detrimental manner. This brought new attention to the current urban environment, its drainage infrastructure and its inability to survive these hydrologic events and perform its functions. Recently, due to the degeneration of urban water resources, a paradigm shift is occurring where the principles of sustainability are the driving force for developments, both new and old. The new philosophy is that urban centers will be built in a holistic manner where characteristics such as drainage and transportation infrastructure will be integrated with the natural landscape and habitats. This evolving paradigm shift focuses on the taking an integrated approach to urban water management.

1.2 The Hydrological Cycle

Hydrology is the study of the movement and storage of water over and under the surface of the earth. The movement of water over the terrestrial part of the earth’s surface is a continous process known as the hydrological cycle. Dunne and Leopold (1978) extend the definition of the hydrologic cycle to include the movement of both water and its constituents.

Any discussion on stormwater related issues must begin with a discussion of the hydrologic cycle. Understanding the hydrologic cycle concept is essential if there is to be any understanding of cause and effect as it relates to stormwater management. For the purpose of this study, the principle of the hydrological cycle and the introduced terminology, can be of great value though. It gives a theoretical foundation for later green roof research steps and understanding. Figure 1.1 illustrates, in a very simplistic form, the essential elements of the hydrologic cycle.

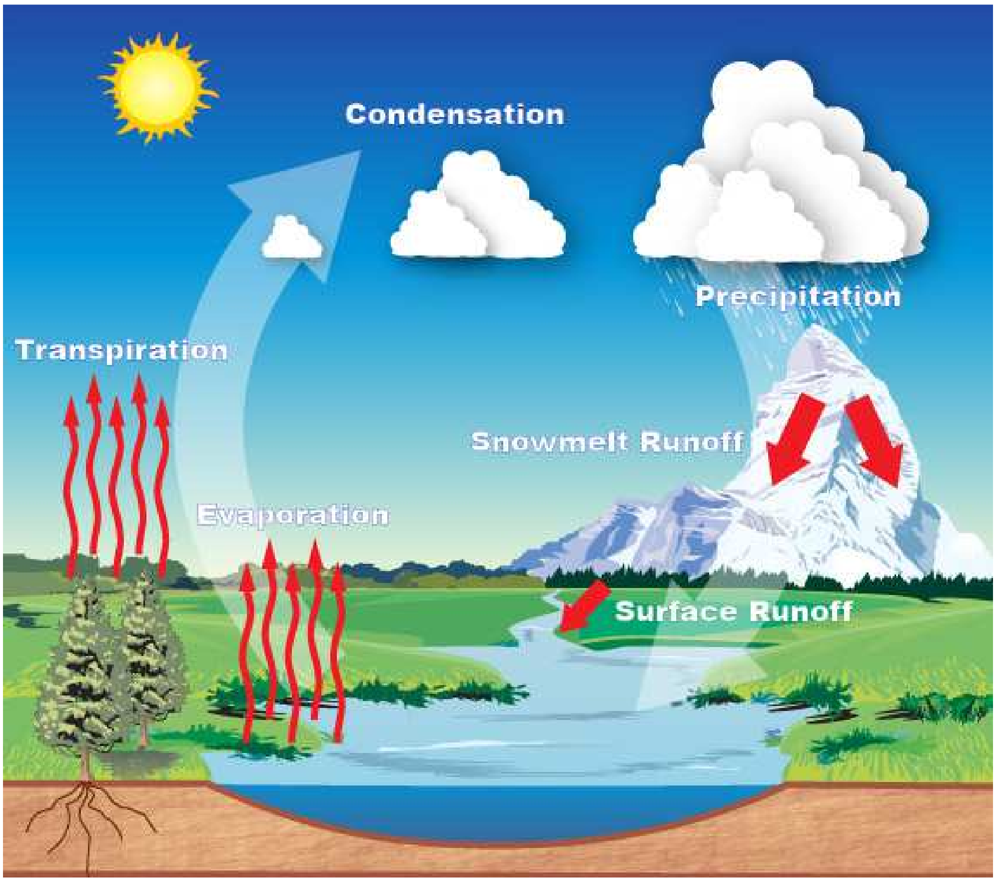

Figure 1.1. - The Natural Hydrological Cycle

The water cycle arrows make the point of continuous movement and transformation. Of all aspects of the water cycle, its dynamic quality - the never ending cycling from atmosphere to the land and then to surface and groundwater and back again to the atmosphere, must be emphasized. The concept of continuous movement is essential in order to understand the hydrologic cycle system.

Solar energy is one of the main force behind the hydrological cycle (van der Akker & Savenije, 2006). It drives the cycle by evaporating water from the surface of the earth storing it as vapour in the atmosphere. As atmospheric conditions change, water vapour can condense and fall back to the ground as precipitation.

Precipitation, that reaches the first separation point on the earth's surface as snow, rainfall or hail, will first be temporarily stored on the ground, vegetation, buildings and paved area. A portion of the water that lands on vegetation will be intercepted, returning to the atmosphere through evaporation without ever having reached the ground. Direct evaporation from this temporary surface storage is called interception. Xiao et al. (2000) report interception losses of approximately 20% of the total annual precipitation that falls in forested areas, while Dunne and Leopold (1978) found that the median reported interception loss from forests in

North America is 27%. The remaining precipitation drips off leaves and slowly moving through the layers of vegetation until it reaches the ground and may replenish the soil water as infiltration.

As long as the rate of water delivery to the surface is smaller than the infiltration capacity, the process is supply controlled (Hillel, 1982). This means that water infiltrates as fast as it arrives. When the rate of water delivery starts exceeding the infiltration capacity of the soil, the process is surface controlled or profile controlled (Hillel, 1982). Excess water that is beyond the actual rate of infiltration will flow away as overland flow. A hydrological expression named evapotranspiration is often used as a collection term for the sum of all fluxes from plant transpiration and evaporation from the soil and the open water.

Another portion of water that enters the soil can move either vertically or laterally through the soil. Significant lateral movement of water through soil is called through flow or interflow. Downward movement of water through the soil is called percolation. Percolating water eventually makes its way to a saturated zone, where all spaces between rock and soil are filled with water. The water filling the spaces between soil particles and rock in the saturated zone is called groundwate. The zone below the groundwater table is called the saturated zone. In the saturated zone, the pore spaces are almost completely filled with water and the pressure is equal or greater than atmospheric pressure (Ward & Robinson 1990). The water pressure in the unsaturated zone is smaller than atmospheric pressure (Ward & Robinson 1990). Water can leave the saturated zone via capillary rise to the unsaturated zone or via groundwater seepage into water bodies such as seas and oceans.

It is important to appreciate that the system itself is a closed loop. What goes in must come out. Impacts on one part of the cycle create comparable impacts elsewhere in the cycle. Precipitation that infiltrates and percolates deeper into the ground can take weeks or months to reach streams, as opposed to minutes and hours as it does through overland runoff. This subsurface flow helps to even out the inconsistent flow originating from precipitation events.

To summarize, the route taken by precipitation that falls over land can follow one of three principal paths: it can return to the atmosphere through evapotranspiration; infiltrate the ground; or, travel across the surface as runoff. The mixture of each path taken is known as the water balance. Arnold and Gibbons (1996) generalize that in a forested area 40% of precipitation returns to the atmosphere through evapotranspiration, 50% infiltrates the ground and only 10% runs off continuing its path back to the ocean. A more dramatic shift can be seen when examining the water balance of a particular watershed.

1.3 Combined effects of urbanization and climate changes

The increase in urban areas has important implications for flood risk because compared to all other land use changes affecting an area's hydrology, urbanization is by far the most forceful (Leopold, 1968). Urbanization is the process where natural areas are largely cleared of vegetation and replaced with buildings and pavements (Horner & May, 1998). While the broader term urbanization is often used to describe the source of these changes, the vast majority of the hydrologic impacts are caused by just one feature of the urban landscape: impervious surfaces (Booth & Jackson, 1997). The impervious surfaces are some of the most impactful features of land development on the environment (Dunne & Leopold, 1978; Ferguson, 1994; Arnold & Gibbons, 1996). Ferguson (1994) defines an impervious surface as one that alters the hydrologic cycle, preventing water from following natural paths and processes, degrading pre-development storage and flow regimes. Evapotranspiration from a forested area accounts for the path taken by approximately 40% of the annual precipitation. Extensive urban development resulting in high levels of imperviousness reduces this value to 30% of the annual precipitation. The reduction of vegetation in urban areas reduces the amount of water returned to the atmosphere through evapotranspiration by up to 25% as compared to a forested area. Arnold and Gibbons (1996) indicate that as a stream catchment changes from a natural forested condition to low levels of impervious cover (10-20%) runoff volumes can double. Increasing imperviousness to higher levels (75-100%) can increase runoff by a factor of five compared to the forest condition.

In nature, as indicated previously, when rainwater falls on a natural surface, some water returns to the atmosphere through evaporation, or transpiration by plants; some infiltrates the surface and becomes groundwater; and some runs off the surface. The relative proportions depend on the nature of the surface, and vary with time during the storm (Surface runoff tends to increase as the ground becomes saturated).

Development of an urban area, involving covering the ground with artificial surfaces - such as roads, sidewalks, parking lots, driveways, and rooftops (Schueler, 1994) - has a significant effect on these processes. Figure 1.2 illustrates the dramatic changes in the proportion of precipitation entering different flow pathways when land use changes from native vegetation to an urban landscape. In particular, the rainfall which was previously captured by the land now falls on artificial surfaces which increase the amount of surface runoff (Roesner et al.,

2001) in relation to infiltration, and therefore increase the total volume of water reaching the river during or soon after the rain.

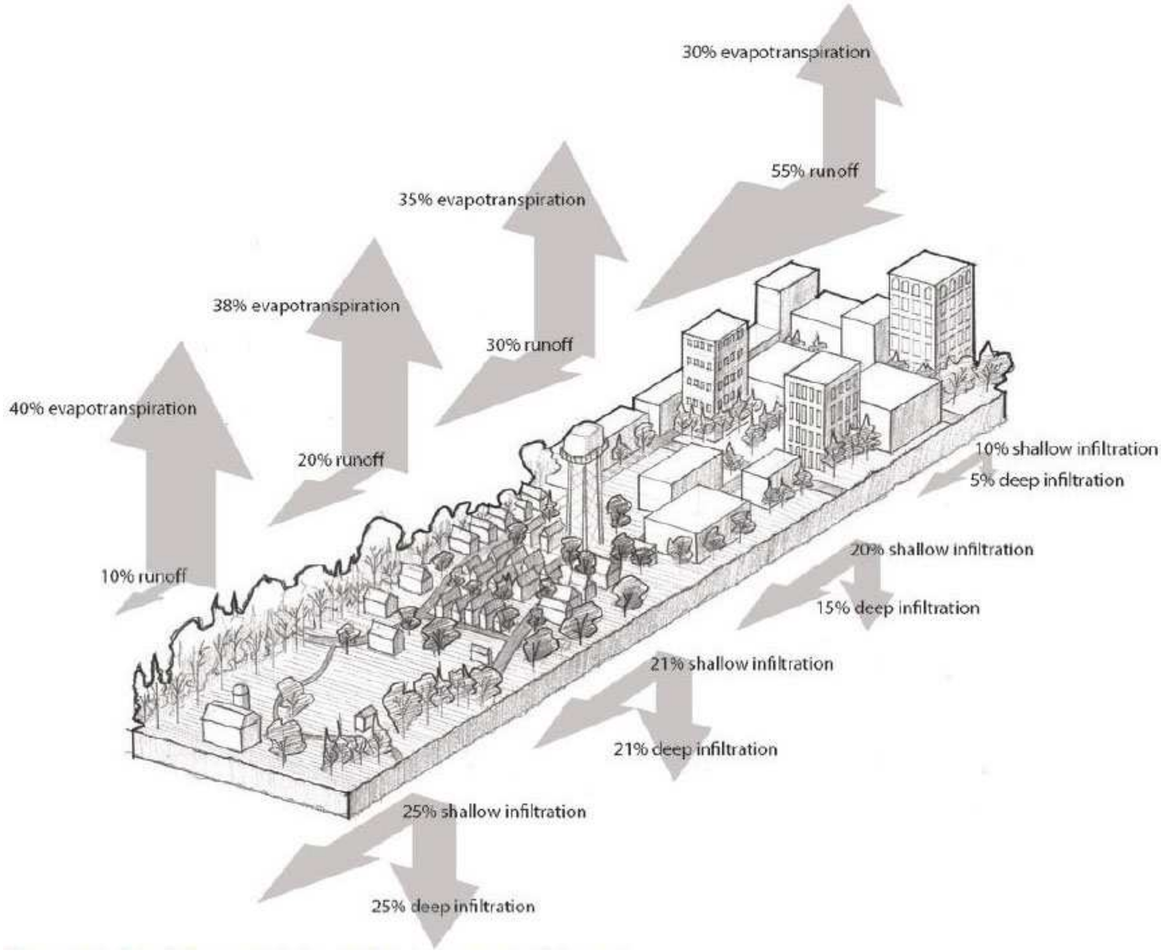

Figure 1.2. - Changes to the Water Balance as a result of different levels of imperviousness

Perhaps the most significant effect of urbanization is a change in the rainfall-runoff relation (Carter & Rasmussen, 2006; Leopold, 1968). Not only is there a change in the total volume of stormwater runoff from urban areas, but the characteristics of the runoff change as shown in the Figure 1.3. Surface runoff travels quicker over hard surfaces and through sewers than it does over natural surfaces and along natural streams. This means that, for a given event, both the peak discharge (the peak rate of runoff) and the duration (the amount of time) that this higher peak flow occurs is increased in urban versus rural or forested watersheds. Combined, these result in larger, more frequent peak flows with more total volume (Jones et al., 2005; Roesner et al., 2001).

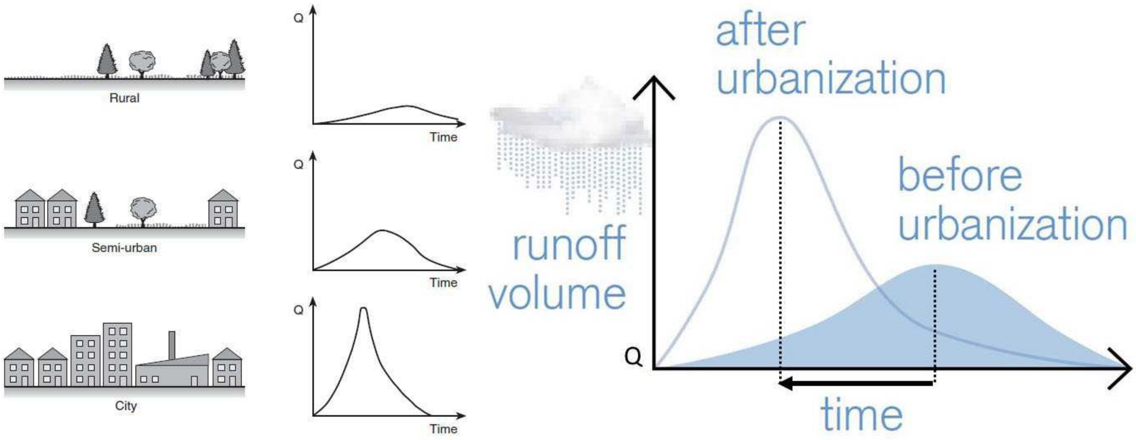

Figure 1.3. - Effect of urbanization on peak rate of runoff; Q is the rate of runoff

These hydrological changes are often addressed as a public safety issue, resulting in the construction of storm drainage system. The typical storm drainage system is designed to convey runoff quickly and efficiently away from developed areas to the receiving stream or water body. Such systems, however, have the concomitant effect of further increasing peak flows farther downstream unless stormwater detention methods are used (Hollis, 1975; Arnold & Gibbons, 1996).

This obviously increases the danger of sudden flooding. It also has strong implications for water quality. The rapid runoff of stormwater is likely to cause pollutants and sediments to be washed off the surface or scoured by the river. In an artificial environment, there are likely to be more pollutants on the catchment surface and in the air than there would be in a natural environment (Butler & Davis, 2004).

An emerging challenge in the field of urban drainage is global warming, potentially leading to climate change. The Intergovernmental Panel on Climate Change (IPCC), a scientific body responsible for providing assessments on the current state of the climate, supports the view that the warming of the earth’s temperature is indisputable. During the past 100 years the earth’s temperature has risen by an estimated 0.56 to 0.92°C, and it is expected to increase at a rate of 0.2°C per decade for at least the next two decades (IPCC, 2007a). It is anticipated that climate change, as it is commonly referred to, will have many adverse affects across the planet (IPCC, 2008).

There is broad consensus in the scientific community that atmospheric emissions from human activities such as deforestation, the combustion of fossil fuels, and intensive agricultural production, are the main clue to the cause of earth's climate changes (IPCC, 2007b). The increase in concentrations of these greenhouse gases in the atmosphere has corresponded with the rise of the earth’s average temperature. According to a study conducted by Giannakopoulos et al. (2009) in the Mediterranean region, between 2030 and 2060, may occur an increase in average annual temperatures from one to three degrees centigrade.

Modifying the global energy cycle directly affects the world's water resources. Global warming increases the amount of land evapotranspiration and ocean evaporation, which in turn causes longer and more frequent droughts in some parts of the world and higher intensity precipitation in other parts through the increase in moisture availability and cloud cover (Hengeveld, 2005).

Average precipitation is predicted to increase between 5-20% in certain regions of the world and will cause greater extremes in weather than we have now, with stronger and more intense rainfall with more ever short duration (Houghton et al., 2001 Groisman et al., 2005; Madsen & Willcox, 2012).

The rate of heavy precipitation, or rainfall intensity, is expected to increase at a greater rate than that of average precipitation. This will cause extreme rainfall events to occur more often. These events that for its heavy impact are called ‘extreme rainfall events’ are frequently followed by flash floods and sometimes accompanied by severe weather such as lightning, hail, strong surface winds, and intense vertical wind shear (Jones et al. 2004). Escalating flood hazard may be a widespread global issue because the intensity of extreme storm events is very likely going to increase over most areas during the 21st century (IPCC, 2008). Their danger is due not only to their strong impact on cities, rural areas and, generally, to the entire humankind, but also to the fact they are very uneven and hardly predictable (Jones et al., 2004). Many studies (Berz, 2001; Frich et al., 2002; Milly et al., 2002; Kostopoulou & Jones, 2005; Casas et al., 2007) in fact, testify how these events are extremely dangerous and how they can have extreme consequences especially in urban areas where, very often, existing drainage systems are unable to handle high peak flows due to these ones, causing occurrence of surface water flooding. The stormwater infrastructure of urban areas will fail to control a greater runoff volume and flooding will become more persistent (Semadeni-Davies et al., 2008).

Given the negative repercussions that cities are currently experiencing or are expected to experience, governments have already begun or are in the process of implementing measures to deal with climate change. While mitigation aims to reduce greenhouse gas emissions, adaptation focuses on the implementation of measures and strategies that will help reduce the earth's vulnerabilities to the climate. The fight against climate change requires coordinated actions between mitigation and adaptation: in addition to the mitigation policies, each country must add policies for adaptation to climate change, in light of their specific conditions. Understanding how climate change affects different regions of the world is imperative for the implementation of appropriate adaptation strategies in order to try to reduce their negative effects.

Although several European governments and communities are using Green Infrastructure (GI) to achieve a variety of environmental and economic goals, including resilience to climate change, application of GI solutions are not yet widespread as adaptation best practices. Many communities, as Italian one, either are unaware of the benefits of GI to begin with or believe it's more expensive or difficult to implement than traditional grey approaches.

The IPCC (2001) defines adaptation to climate change as an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities". An adaptation measure that has been identified as a promising method for providing relief against the effects of climate change is the green roof. Promoting the use of green roof in the plan for adaptation means taking actions based on the use of natural solutions, bioengineering techniques, designs based on the sustainable use of natural resources which, whenever possible, are preferred with respect to traditional cement-based systems.

1.4 Low Impact Development (LID) for Stormwater Management

Stormwater management is a definition that is used to describe all endeavours to control runoff in areas affected by urban development (Gribbin, 2013). Stormwater management policy tendencies can be subdivided into two main trends:

1. Traditional stormwater management solutions;
2. Low Impact Development.

In the past, the philosophy of stormwater management was to dispose precipitation runoff away from buildings and into local waterways as quickly as possible (Gilroy & McCuen, 2009). These methods typically included end-of-pipe solutions where water was removed from a site and stored in an off-site, downstream facility (Gilroy & McCuen, 2009). While these end-of-pipe solutions achieved the objective of controlling downstream peak discharge rates, they did not address other important issues such as increased runoff volume, and preservation of aquatic life (Gilroy & McCuen, 2009).

During the past three decades, the practice of stormwater management has changed significantly. By the 1990s, it was recognized that the traditional designs and systems of stormwater management was out of touch with the environmental values of society. Therefore, new development approaches have been studied and identified, aiming to abandon the traditional *"end-of-pipe"* approach, introducing more *"natural"* and *sustainable* drainage techniques, based on practices such as infiltration and stormwater storage; these allow peak flow reduction in the network, time of concentration increment and, last but not least, abatement of stormwater pollutant loads.

Sustainable stormwater management should strive to naturalize the built environment with the goal of reaching predevelopment flow conditions through the conservation of green space, the use of green infrastructure, and innovatively engineered systems. From this perspective, use of Sustainable Urban Drainage Systems (SUDS) improves not only stormwater management, but even the generic water management such as supply, drainage and treatment. In addition, these techniques are applicable in new development areas but can be still applied in already urbanized catchments.

The movement towards making better use of natural drainage mechanisms has been given different names in different countries; the development and use of terminology has come about in a more informal manner, driven by local and regional perspectives, understandings and context (Fletcher et al., 2014). These measures are currently identified in Anglo-Saxon literature with the term SUDS (Sustainable Urban Drainage System or Sustainable Drainage Systems), in American literature with BMPs (Best Management Practices) and LID (Low Impact Development) while in Australian bibliography as WSUD (Water Sensitive Urban Design). While each of these terms has their own definitions and unique nuances, in general, they are not mutually exclusive and at times are interchanged with each other to suit context and audience.

The term LID (low impact development) has been most commonly used in North America and New Zealand (Fletcher et al., 2014). The approach attempts to minimize the cost of stormwater management, by taking a "design with nature approach" (Barlow et al., 1977). The original intent of LID was to maintaining or replicating the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape (USEPA, 2000). LID practices are based on the premise that stormwater management should not be seen as merely stormwater disposal; as shown in the figure below (Fig. 1.4), LID is designed to emulate the predevelopment hydrologic regime through both volume and peak runoff rate controls.

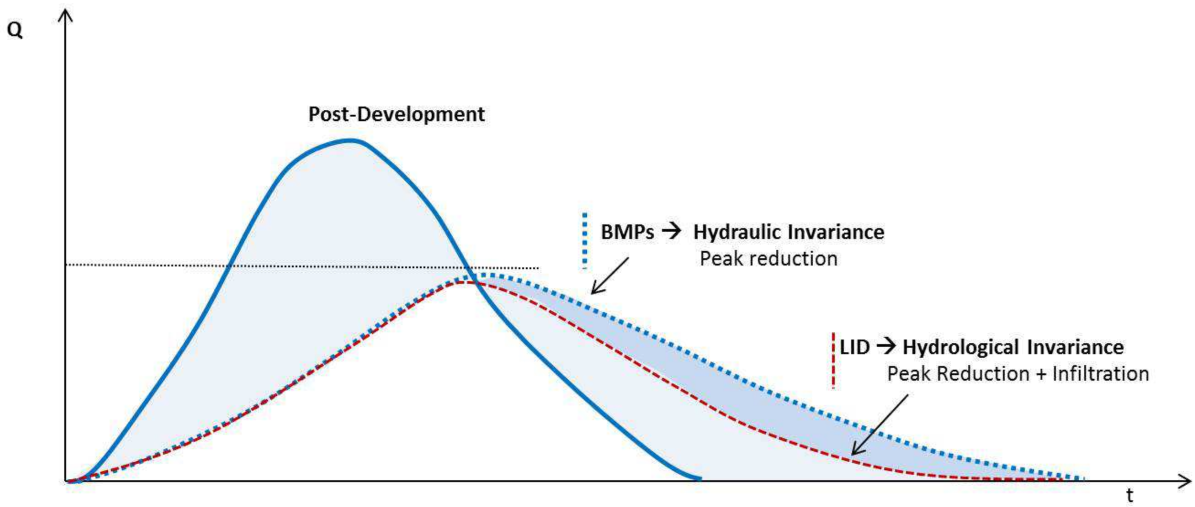

Figure 1.4. - Comparison of the hydrologic response of conventional BMPs and LID

First implemented in Prince George’s County, Maryland (PGCo, 1999a), the LID approach moves beyond the typical stormwater design and encourages more careful site design in the planning phases.

The fundamental approach of LID is the antithesis of conventional stormwater management. Instead of concentrating surface runoff and quickly conveying it to a centralized location in the watershed, LID is characterised by smaller scale stormwater treatment devices - such as bio-retention systems, green roofs and swales, permeable pavement, located at or near the source of runoff - and uses decentralized designs that seek to control rainwater runoff at the source (Gilroy & McCuen, 2009; PGCo, 1999a).

LID relies on runoff management measures that reduce imperviousness and retain, infiltrate and reuse rainwater. According to the Environmental Protection Agency’s (EPA, 2000) Low Impact Development Center, LID is a “*site design strategy with a goal of maintaining or replicating the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape. Hydrologic functions of storage, infiltration, and ground water recharge, as well as the volume and frequency of discharges are maintained through the use of integrated and distributed micro-scale stormwater retention and detention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time.*”

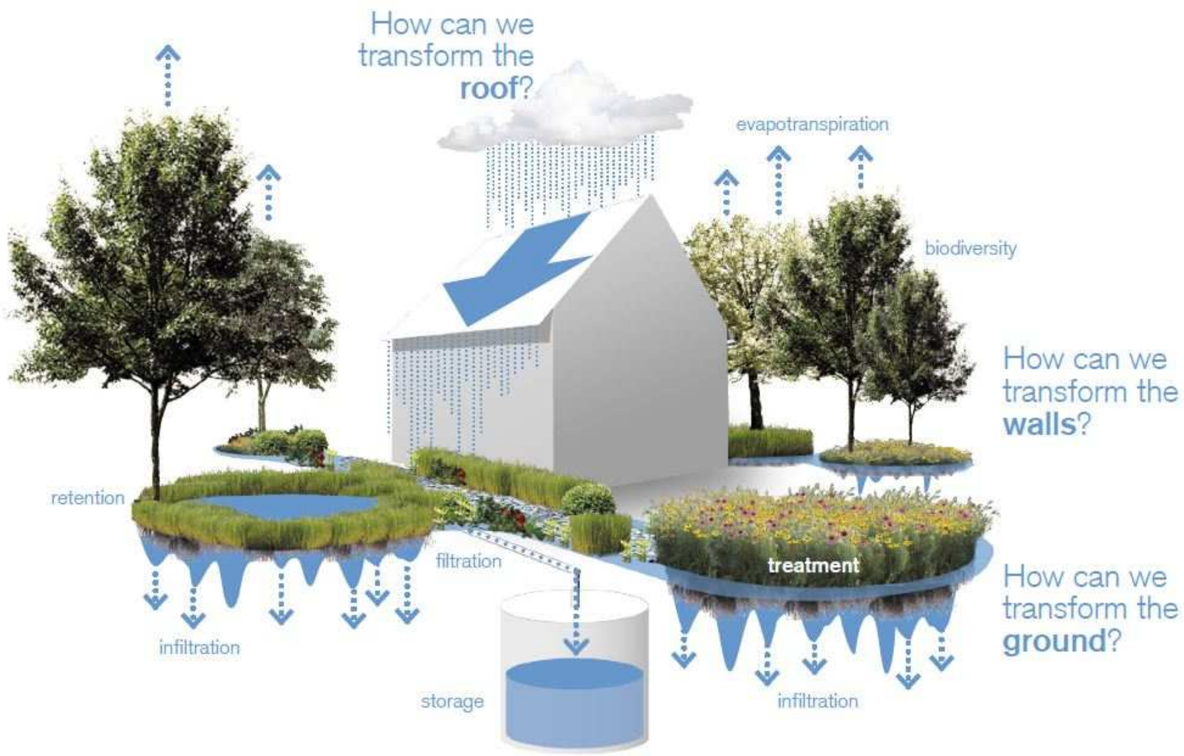

Figure 1.5. - LID concepts are scalable to various sized project and land-use types.

Principles of LID

LID is a green approach for stormwater management that seeks to mimic the natural hydrology of a site using decentralized micro-scale control measures (Coffman 2002; HUD2003) by achieving water balance (Davis 2005). LID adheres to the following principles among others (PGCo 1999b; DoD 2004):

- Integrate stormwater management strategies in the early stage of site planning and design;
- Manage stormwater as close to the source as possible with distributed micro-scale practices;
- Promote environmentally sensitive design;
- Promote natural water features and natural hydrologic functions to create a hydrologic multifunctional landscape;
- Focus on prevention rather than mitigation and remediation;
- Reduce costs for the construction and maintenance of stormwater infrastructure;
- Empower communities for environmental protection through public education and participation.

Goals of LID

LID's approach to urban planning and design aims to minimize the hydrological impacts of urban development on the surrounding environment. Both stormwater management and LID are directed at providing flood control, flow management, and water quality improvements. LID recognizes that opportunities for urban design, landscape architecture and stormwater management infrastructure are intrinsically linked.

The main goals of LID principles and practices include runoff reduction (peak and volume), infiltration increase, groundwater recharge, stream protection, and water quality enhancement through pollutant removal mechanics such as filtration, chemical sorption, and biological processes (Leopold, 1968; Gribbin, 2013, Hunt et al. 2010). This is accomplished first with appropriate site planning and then by directing stormwater towards small-scale systems that are dispersed throughout the site with the purpose of managing water in an evenly distributed manner.

LID is a versatile approach that can be applied to new development, urban retrofits, redevelopment, and revitalization projects. Because LID embraces a variety of useful techniques for controlling runoff, designs can be customized according to local management requirements and site constraints. The suitability of LID techniques must be evaluated by designers and developers based on site's topographic and climatic conditions that are appropriate to meet stormwater control requirements and specific project constraints and opportunities (De Greeff & Murdock, 2011).

Three primary objectives of LID can be summarized as follows:

- Reduction of the total volume of stormwater runoff through the restoration of deep baseflow and evapotranspiration by providing higher levels of detention and storage.
- Reduction of peak flow as a result of increased infiltration and slower surface flow from urban surfaces.
- Improved water quality due to the retention and assimilation of pollutants on the landscape.

Benefits of LID

LID drainage systems have a broad and interconnected range of benefits and advantages over the conventional approach. In short, LID is a more environmentally sound technology. By addressing runoff close to the source through intelligent site design, LID can enhance the local environment and protect public health. LID protects environmental assets, protects water quality, and builds community livability. Other benefits include:

- Protects surface and ground water resources
- Reduces non-point source pollution
- Reduces habitat degradation
- Applicable to greenfield, brownfields, and urban developments
- Multiple benefits beyond stormwater (aesthetics, quality-of-life, air quality, water onservation, property values)

LID projects have additional indirect benefits, such as improving property values in poverty-stricken neighborhoods, increasing community involvement in riparian area management, and raising community awareness and education regarding the stream and watershed ecology, while still achieving the goals of the traditional drainage systems (Dunn 2010).

In conclusion, to summarize, if properly implemented, these green infrastructure practices can provide stormwater management benefits that include the restoration of a more natural balance between stormwater runoff and infiltration, reduced flooding, water quality and aquatic ecosystem improvement, wetland creation and enhancement, control peak of runoff rates, reduced stream bank erosion, and the restoration and enhancement natural ecosystems (CNT and American Rivers, 2010).

1.5 Aim of the Research

Despite the use of LID (Low Impact Development) as storm water management techniques has assumed increased importance in recent years (Sitzenfrei et al., 2013), and their benefits are well known, the transition to sustainable urban drainage systems is very slow (Piro et al., 2012). Due to the lack of adequate modeling and analysis tools, LID systems do not yet have the strong scientific foundation that conventional stormwater management systems have. Design and performance prediction are dependent upon field data from LID installations and effective hydrologic models are needed.

A good understanding of the functioning of LID measures can contribute to effective large-scale implementation and design strategies with the final goal to maintain or re-establish predevelopment site hydrology. Since roofs account for 20-50% of the total land cover in urban areas (USEPA, 2008; Gromaire-Mertz et al., 1999), green roofs are an interesting LID measure with great large-scale implementation potential in existing urban areas as well as in areas with new housing development.

From this premises derive this research which concerns the performance of green roof, as a LID system, focusing on the hydrologic and hydraulic modelling for stormwater runoff mitigation in urban environment.

Since hydrological-hydraulic performance of a green roof is influenced by various factors such as the weather-climatic and structural characteristics of the vegetated cover, the main objective of the research will be to define, improve and implement a methodology for the design of green roofs by using data from two different geographical areas and climate conditions (Cosenza in Italy and Lyon in France, respectively in Mediterranean and Temperate area), in order to identify some key factors for the characterization of the response of green roof system.

More in detail, the primary goal is to formulate, calibrate and test a green roof model to simulate green roof rainfall-runoff. From a practical point of view, the model is intended to provide a tool for practitioners, regulators and policymakers requiring objective quantitative performance data, to inform on the development of stormwater management strategies, and to improve decision-making and design of sustainable stormwater drainage systems in a Mediterranean climate conditions.

In addition to this primary goal, specific objectives of this study are:

- To develop and calibrate a green roof conceptual model, which mimics the physical structure of an innovative green roof system;
- To determine the quantitative hydrological performance of the experimental green roof installed at Univeristy of Calabria, in Mediterranean area;
- To verify that the green roof performance are better than those of a conventional roof, impervious type;
- To establish the influencing hydrological factors on the hydraulic efficiency of the Unical green roof;
- To determine multi-regression equations, specific for the site of interest, which can be useful for preliminary design consideration, in the case a detailed model of a green roof is not available

In conclusion, this research aims to promote the green roof, not only as a tool for environmental mitigation, but specifically as a sustainable urban drainage solution to restore the fundamental natural water cycle processes in the urban environment.

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Chapter 2 – VEGETATED ROOFS OVERVIEW

2.1 Vegetated Roof as a Sustainable Solution

This introduction aims to provide a general background about green roof history and its evolution as Sustainable Solution. Green Roofs have been in use for thousands of years, primarily as insulation and for aesthetic reasons and, only in the recent years, scientific and technical research has been focused on the others benefits they could bring and on the runoff control. Green roofs could be a very efficient method to minimize different problems of modern and future cities, as several studies have stated that the level of urbanization will increase in the future, challenging the quality of urban life (UN, 2002).

The origin of roof gardens traces back thousands of years to Mesopotamian civilizations. For example, the Hanging Gardens of Babylon constitute an example of gardens constructed on rooftops (Snodgrass & Snodgrass, 2006; Dunnett & Kingsbury, 2004). Europe has recognized and accepted the role of green roofs for centuries. Norway and Ireland utilized sod and thatch roofs on their homes as insulators from cold winter weather (Osmundson, 1999). In Italy the practice of greening roofs was known and used also during the Roman age and the middle age up to present years, assuming through the time different values and functions (Osmudson, 1999; Abram, 2006). It is only on the 20th century, when few vanguard architects - as Gropius, Frank Lloyd Wright and particularly Le Corbusier - have promoted this technology in the modern architecture, that green roofs started to assume their current role in architecture up to arrive to the modern-engineered green roof systems (Osmudson, 1999; Appl, 2009). From the 90s the widely known advantages of green roofs have encouraged the expansion of the roof greening strategy in several countries such as Austria, Switzerland and, in particular, Germany where, green roofs reached 13% of the flat roofs in 2003 (Herman, 2003). From the first roof landscaping guidelines (FLL), created by the German Landscape Research & Construction Society by the end of the 19th century, some countries have also released guidelines for implementation of green roofs like the UK, USA, New Zealand, Australia, etc. (Locatelli et al., 2014). Despite the growing interest and research on green roofs, this greening technique in Italy is relatively new and the scientific findings about their effectiveness in the Mediterranean areas are deficient (Fioretti et al., 2010). Recently two important steps in green roofs policing came through the production of a national standard regulation for green roofs (UNI

11235:2007) and the inclusion of green roofs in the national legislation (D.P.R.59/09); these regulations bring greater awareness to the use of this non-traditional techniques for the stormwater management in urban areas, based on the sustainable urban drainage concept (Lanza et al., 2009).

The accelerated urban growth has affected many of the earth's natural processes; vegetation that originally provided interception and evapotranspiration is removed, and natural depressions in the landscape, which normally detain 50% of the runoff, are eliminated (Dunne & Leopold, 1978). Impervious surfaces like asphalt, concrete rooftops, roads, and parking lots are replacing natural surfaces affecting ecological balances. The volume and rate at which the runoff is delivered to the receiving water body is greatly increased (Andoh, 1997), resulting in a reduction of the hydrologic response time and greater recurrence of flood events. In order to restore balance to urban ecosystems, there must be ways to bring back depleted green surfaces.

Best Management Practices (BMPs) require green space that may not be available in cities. Green roofs are a good Low Impact option, as an alternative BMP, because they use traditionally impervious and already existing surfaces (Oberndorfer et al. 2007, Moran, 2005; Liptan & Strecker, 2003). Roof surfaces in cities range from 30% to 40% of all impervious surfaces, offering a distinct opportunity to convert impervious roofs to green space without losing functionality (Oberndorfer et al. 2007; Hutchinson et al. 2003).

In recent years, green roof as Low Impact Development (LID) system have been developed to aid in the improvement of stormwater management. Green roofs also have the potential to reduce urban stormwater pollution by adsorbing particles from wet and dry atmospheric deposition. Their effectiveness to reduce stormwater quantity and treat it for water quality has been studied primarily in cold temperate climates such as Sweden, Germany, Michigan, Ontario, Oregon, and Pennsylvania (Berndtsson et al., 2006; Van Woert et al., 2005; Liptan & Strecker, 2003). Energy savings gained by using green roofs has been explored in warmer climates such as the Mediterranean and the tropics (Theodosiou, 2003; Wong et al., 2003). However, the effective use of a green roof as a Low Impact approach for stormwater in an area depends on a number of hydrological and climatic factors in that particular location.

As specified in the following paragraphs, green roofs could minimize urbanization impacts in different ways, including the improvement of stormwater management practices.

It must be noted that more efficient results could be achieved considering an integrated approach. This means that green roofs along with other stormwater infrastructures, such as retention basins, should be associated to obtain stormwater runoff volume and peaks discharge reductions (Piro et al., 2012). There are several factors affecting green roof performances, but due to features of the different studies, it is very difficult to generalize the results. Furthermore, green roofs performance is strongly connected with the local climate, so it is very difficult to apply the same system to locations that are different in terms of temperature, rainfall events and seasons.

2.2 Vegetated Roofs Types

Green or vegetated roofs are generally categorized into two types: intensive and extensive. This splitting between the two systems relate primarily to the level of maintenance required while are not directly related to the substrate depth or to the size of the vegetation. The UNI 11235, in fact, through the following diagram in Figure 2.1, provides a differentiation of green roofs by means of: i) thickness; ii) maintenance costs and iii) the construction costs of a green roof, required to maintain in fully operational conditions the system and to define it (extensive or intensive).

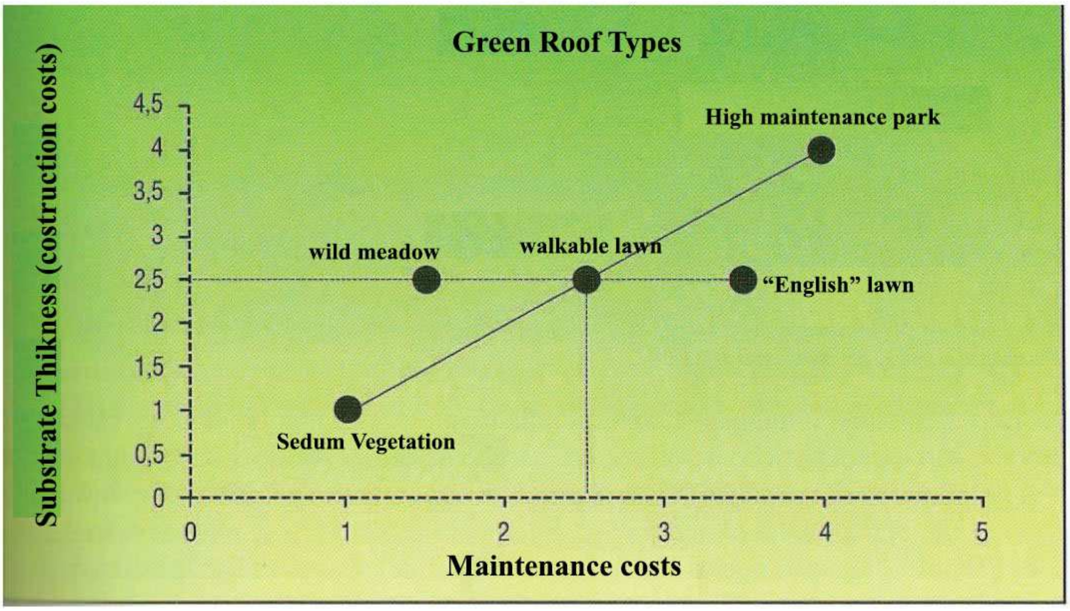

Figure 2.1 – Relationships between maintenance costs and substrate thickness/costruction costs

By analyzing the graph, proceeding to the right on the abscissa, it is perceived that the green roofs types gradually change from extensive to intensive, as a function of the maintenance costs. At the bottom left is located the "Sedum vegetation", absolutely the most extensive system, while at the top right there is a "high maintenance park", a typically intensive system (Abram, 2006).

The two types are also distinguished through a range of characteristics that include purpose, substrate depth, vegetation type and supporting structural requirements.

Intensive green roofs are so named because of their ‘‘intense’’ maintenance needs. These roofs systems have greater depth of soil or growing medium (over 15cm) which favors deeper roots and then allows for greater diversity in size and type of vegetation (ASTM 2008), from lawn and herbaceous perennials plants to shrubs and even small trees (Grant et al., 2003; Dunnett & Kingsbury, 2004).

Since intensive roofs have greater depth compared to extensive roofs, they are capable of storing water for longer periods; for this reason, the associated high-saturated weight requires significant structural support for the roof.

Many intensive roofs are designed to be at least partially accessible (Dunnett & Kingsbury 2004) thus, being more close to the concept of conventional gardens, are often referred as roof gardens (Grant et al., 2003; Dunnett & Kingsbury, 2004). This Roof gardens typically require regular irrigation because of the harsh climatic conditions that persist in the roof environment and the same maintenance as gardens on the ground.

Extensive green roofs are those that are constructed with a relatively small substrate depth - between 8 and 15 cm - and due to their shallow depths, are often limited to grasses and drought tolerant plants **(**Dunnett & Kingsbury, 2004; Snodgrass & Snodgrass, 2006).

The shallow soil depth and exposure to intense and desiccating sunlight and wind, as well as the lack of consistent supplemental watering, require vegetation with an elevated tolerance to the oscillations in water availability, capable of surviving to these harsh and dry conditions. Generally, this kind of plants are known as succulents and the *sedum* is most often used for these conditions.

To minimize weight and maintain acceptable water retention characteristics, the growing media used is often a specialized lightweight mixture of organic and inorganic materials (Martin, 2008). Because of the lighter weight of growing medium and vegetation, extensive systems may not require structural upgrades of the building where they are intended to be used and can, therefore, be less expensive and well suited for retrofit applications (Metro Vancouver, 2009).

Extensive roofs are primarily designed for function rather than form: used for their environmental benefits such as storm water management and insulating properties. Typically they do not require irrigation except during the initial growth period to establish vegetation, but otherwise is not required because plants should be able to survive solely on the natural rainfall that reaches the roof (Neufeld et al., 2009).

Compared to their intensive counterparts, they are usually not accessible by general public use as a garden or open space, other than for occasional maintenance, and may be designed for flat or sloped roofs (Dunnett & Kingsbury, 2004; FLL, 2008).

Extensive green roofs help overcome some the challenges associated with intensive green roofs; due to their minimal requirement for additional roof structural capacity and low maintenance, it is believed that the wide spread use of green roofs in an urban area would most likely be accomplished with extensive green roof systems (Martin, 2008). For this reason, extensive green roofs are the most common option for typical single-family homes and other buildings only able to retrofit rather than completely remodel. Figures 2.2, below, shows the cross sections of these two types of green roofs.

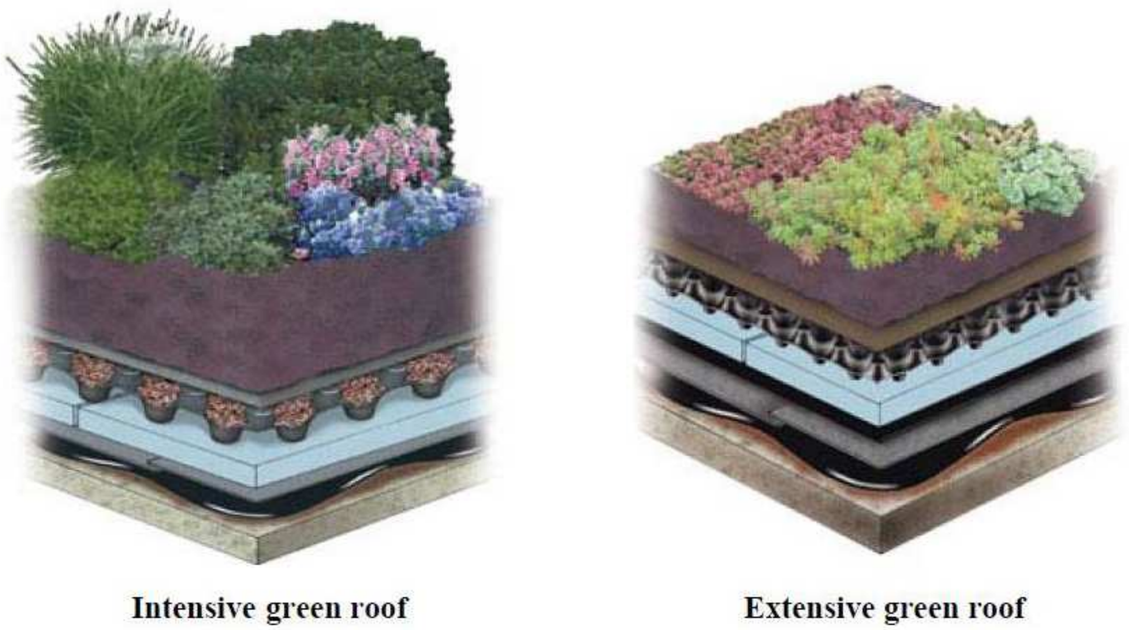

Figure 2.2 – Characteristic Cross Section of Extensive and Intensive Green Roofs

In the following Table (Tab. 2.1) are shown schematically the advantages and disadvantages associated with the two main green roof types, extensive and intensive green roofs.

Table 2.1 – Advantages of Intensive and Extensive green roof sysems.

INTENSIVE GREEN ROOF	*EXTENSIVE GREEN ROOF*
Greater diversity of vegetation	Lightweight
Greater range of design	Suitable for large surfaces
Best insultaion properties and stormwater management	Low maintenance costs and may be designed for no irrigation
Greater options for human uses	More suitable for refurbishment projects
Generally accessible	Lower capital costs
Greater biodiversity potential	Easier to replace

2.3 Components of an extensive vegetated roof

The term green roof is used to describe an engineered roofing system that allows plants to grow on top of buildings while protecting the integrity of the underlying structure. It is intended to partially replace the vegetated footprint that was destroyed when the building was constructed.

A typical green roof structure consists of multiple layers, each of which plays an important role in the overall system function. The structure may vary but usually includes six basic elements, from the bottom, green roof design starts with (1) the roof construction and continues with (2) the waterproofing-root barrier, (3) the drainage layer, (4) a geotextile filter fabric/membrane, (5) a lightweight growing media or substrate, and finally (6) plants or vegetation (Mentens et al., 2006; Cantor, 2008). It may also include additional layers such as insulation, vapor control or support panels. All these definitions express different features of a unique technology. Figure 2.3 shows the green roof structure with the basic six components described above.

Figure 2.3 – Typical components of an extensive green roof

A *waterproof barrier* is placed on top of the roof construction to prevent undesired leakage. Above the waterproof barrier, a root resistance layer is placed in order to prevent root penetration through the waterproof barrier or roof construction (Peck et al. 1999, Peck 2002, Snodgrass & Snodgrass 2006). At present, a protection layer that combines the waterproof and root barrier layer is frequently used. Subsequently, a *drainage layer* is applied on top of the root barrier. The drainage layer**,** engineered coarse media or plastic profiled elements, provides rapid drainage for precipitation in excess of system storage capacity and ventilates/aerates the substrate; this prevents the deterioration of the vegetation layer and leakage of water through the lower barriers (WTCB 2006). A *filter fabric* is placed on top of the drainage layer; this layer prevent clogging by the small particles originating from the substratum, and sometimes comes coupled with the drainage layer. The *substrate* or growing media, where the roots of the plants grow and the water is absorbed, is the layer placed on top of the drainage layer and filter fabric. It supports the plants and, providing sufficient oxygen, water and nutrients, allow to the roots to settle and develop there. The most upper layer is the *vegetation* or plant level. Depending on the green roof type, plants used range from native plants and drought tolerant plants such as Sedum, to grasses, shrubs and trees (Mentens et al. 2002).

The components of a green roof can be classified as either physical, including the deck, waterproofing membrane, insulation, root barrier, drainage layer and the permeable filter layer, or dynamic, including substrate and vegetation (Weiler & Scholz-Barth, 2009). Designers have the flexibility to choose among different materials and technologies in order to achieve the overall design intent of the project. The order of the physical layers may vary among projects, however, in general, these layers are installed in the way that provides the maximum protection to the waterproof membrane so that the life of the project is maximized.

The waterproofing-root barrier

Primary prerequisite in the realization of a green roof stratigraphy is to predict and achieve a sure waterproofing, which must satisfy precise performance characteristics, and which must guarantee the water tightness and the resistance to the roots and micro-organisms. The waterproofing layer is the bottom layer subjected to the other layers that make up the green roof system; the action of these loads can produce the perforation of the waterproofing membrane and the roots penetration into the layers and, consequently, dangerous infiltration to the building. In order to contain this risk are used inorganic material that the roof vegetation is not able to degrade or penetrate.

Among the products used to prevent root penetration are ethylene propylene diene monomer (EPDM), polyvinyl chloride (PVC) rolls and high-density polyethylene sheets, or butyl rubber (Dunnett & Kingsbury, 2004; Snodgrass & Snodgrass, 2006). In almost all cases, however, the resistance to the roots action is integrated with the sealing water element.

The drainage layer

Another layer that influences green roof's water retention is the drainage layer. This layer represents the heart of the system and its correct realization largely determines the good result and the duration of the greening. The main functions of the drainage layer in any green roof are i) to drain stormwater and excess irrigation, ii) to protect the waterproof membrane (Connelly et al., 2005), iii) to maintain the aeration in the root zone (Snodgrass & Snodgrass, 2006), and iv) to remove excess water as quickly as possible to prevent over saturation; indeed prolonged saturation of a roof can bring physiological disorders to the plants and could favor the colonization of pathogenic organisms. In some cases, the drainage layer also provides extra storage as the means of irrigating the green roof and providing additional nutrients for the plants grown. All functions are important in dependence with the draining effectiveness but, that of airing of the radical zone, is one that is usually neglected, although could limit the development of the vegetation if it is not well calibrated.

According to Dunnet & Kingsbury (2004), three main categories of materials can be used for drainage i.e., granular materials, porous mats and lightweight plastic or polystyrene modules. All these layers vary in their form and water retention characteristics, all factors that further influence the water retention capacity of a green roof and the amount of water available to plants. More in detail, coarse *granular materials* include: gravel, stone chips, broken clay tiles, clinker, scoria (lava rock), pumice, expanded shale and expanded clay granules (Dunnet & Kingsbury, 2004) with large amounts of air or pores between them. A layer of granular materials can be incorporated underneath the substrate profile increasing the root space for plants (Dunnet & Kingsbury, 2004).

Porous mats, made of a range of materials such as recycled clothing and car seats, act like sponges that absorbs the excessive water. Some materials can negatively affect plants since they tend to extract the available water necessary for plant growth (Dunnet & Kingsbury, 2004). Finally, *lightweight plastic or polystyrene modules* exhibit great flexibility in design and appearance; these solutions introduce the advantage of the lightness, ease of installation and a good resistance to compression, allowing to be used as a sub-foundation for heavy building elements, contemporarily maintaining continuity and effectiveness of drain. Any given thickness, the drainage capacity is significantly higher than those of the granular materials, with lower weights.

Usually in these systems the water is accumulated in special hollows, obtained opportunely modeling the elements. Drainage outlets must be kept free of substrate particles at all times in order to maintain their functionality (Dunnet & Kingsbury, 2004).

The filter fabric

The aim of the filtering layer, installed between the growing media and the drainage layer, is to prevent the descent of substrate's fine particles in the draining layer, and to provide anchorage to the radical apparatuses. Therefore, this layer is responsible for keeping the substrate in place, and preventing blockage or damage of drainage outlets. To ensure an efficient operation both of the substrate layer, without erosion of its particles thinnest which may have a negative impact on runoff water quality, and that of the drainage layer, the filter fabric should have a permeability at least 10 times great than that of the growing medium.

Materials with appropriate characteristics of resistance to the traction, to the cut and puncturing, and with suitable water permeability are employed. Without use of this kind of materials there would be the clogging of the filter layer that would reduce or interrupt the vertical flow of the drainage water and the gas exchanges between the substratum and draining layer. It is highly recommended to use a filter cloth or mat, such as semi-permeable polypropylene fabric, to prevent the movement of fine particles from the substrate into the drainage layer (Snodgrass & Snodgrass, 2006).

The growing media

As a substrate for vegetated roof cannot be used the normal substrata for gardening or, even worse, ground. The green roof substrates must have particular characteristics.

The substrate used on an extensive green roof (also known as growing media) is usually a unique blend of mineral materials, stabilized organic matter and stabilized lightweight aggregates (Weiler & Scholz-Barth, 2009), designed to retain water and be lightweight. In percentage, typical extensive green roof substrate, is comprised of 80-90% (by volume) light-weight aggregate (LWA) and 10-20% (by volume) organic matter (Fassman et al., 2013). LWA, usually mixed with sand and/or organic materials in order to provide an adequate proportion of fine particulate matter to support the plants, provides pore space for air, water, and gas exchange, and ensures rapid drainage.

Organic material must be present in the substrate mix in order to support plant life by storing and providing nutrients (especially nitrogen) and moisture (Fassman et al., 2013). It also provides some cushioning and physical resistance to compaction. Although the organic fraction of an extensive green roof is small, the generally fine particle size and high moisture retention typical of organic matter contributes significantly to saturated weight and reduces permeability.

Studies have shown that increased organic content can aid plant growth, but a predominantly organic medium is not recommended for extensive green roofs because introduces a set of potential problems (Hoffman, 2005). One of the most important aspects of medium is that the depth should be relatively constant over a long period of time, and a highly organic medium makes this impossible: its decomposition over time will increase nutrient leaching from the media, reduces moisture, nutrient storage, and substrate depth. A high proportion of fines increases moisture storage and may benefit plant growth but decreases permeability and increases weight. Maintaining high permeability of the substrate media is important to prevent ponding and excess weight. For all these reasons, it is recommended that the organic material is at most 15% by volume (Rowe et al. 2006).

Light-weight aggregates that have typically been used for extensive green roofs include expanded clay and expanded slate (Fassman & Simcock, 2012). Whatever the media is, thought should be given on the weight of components used and their composite drainage characteristics. Ideally, the growing medium or substrate is recommended to have the characteristic of being highly efficient in absorbing and retaining water while at the same time having free-draining properties. This is generally accomplished by granular mineral materials that absorb water and fine particles to which water will cling.

The granular products can be roughly classified as natural minerals, artificial minerals and recycled or waste materials (Dunnet & Kingsbury, 2004); the most ecologically sound materials are those that are derived from waste or recycled products (Mentens et. al, 2006). Recycled clay bricks and crushed concrete are used as aggregate components in Europe and especially in the UK. They are not lightweight, but do have high permeability where particle size is coarse. Better porosity and chemical characteristics for plant growth render bricks a more favourable growing media than crushed concrete.

Though a wide media variety is available, the selection however normally depends on the requirement of that particular location based on a number of tradeoff factors.

By following these guidelines the resulting substrate should contain a well-balanced amount of small and large pores between the inorganic particles, which in conjunction with the organic matter, determines the dynamics for water retention. Indeed, composition is an important consideration for water retention, plant growth and water quality of runoff.

The substrate water-holding capacity, defined as the amount of water that a substrate can retain after saturation and drainage, plays an important role in extensive green roofs (Handreck & Black, 2002). This property is responsible for retaining stormwater, and for continuously providing the air and water required for plant development.

The vegetation

In addition to growing media, plants are also an integral component of green roofs. Plants are important in a green roof system because of aesthetics, cooling via transpiration, shading and creating a monolithic layer by holding the substrate in place with its root system (Cantor, 2008).

In terms of green roofs as a stormwater management practice the main function of plants is their ability to reduce media moisture content via transpiration and increase interstitial pore space available for water storage. This is important because the amount of storage available for the next storm event depends on how much water was released via transpiration rate of the plants after drainage stops. After a storm, the available storage volume in the growing media depends on the percent of available volume of void pores.

When selecting plant material, certain aspects must be considered, for instance: the design intent, aesthetic appeal, local environmental conditions, plant characteristics, disease and pest resistance, and substrate composition and depth (Getter & Rowe, 2006). Some of the desirable characteristics for extensive green roof plants include: easy propagation, rapid establishment, and high ground cover density (White & Snodgrass, 2003). It is also important, for sustaining a full coverage, that the plants possess the mechanisms to perpetuate their propagation in the long term, as long as the environmental conditions are favorable (Getter & Rowe, 2006).

An ideal extensive green roof is self-sustaining and requires minimal maintenance, including irrigation (Snodgrass & McIntyre, 2010). As a consequence, green roof plants must be able to survive frequent harsh conditions. Often the largest stressor is the summer water deficit, which is exacerbated by extreme heat and high wind (Butler and Orians, 2009). High winds and intense solar radiation that comes with the exposed positioning also decrease the survival of plants. Therefore plants that naturally survive in similar conditions are sought after.

The most adaptable green roof plant species have low growing habits, shallow and perennial root systems, and exhibit a high tolerance to extreme environmental and biological conditions (Snodgrass & Snodgrass, 2006). Succulent plants adapt well in these conditions (Getter & Rowe, 2006); for this reason, they are widely-used in extensive green roof projects. Succulent plants can retain significant amounts of water in their tissues, contributing to the overall storage of water on the roof and to the reduction in annual runoff. Succulents like *Sedum*s and *Delosperma* contribute to about 40% of the reduction in runoff attributed to the green roofs they grow in, with the remaining 60% due to evaporation from the growth medium (Berghage et al., 2007). Sedum, in particular, has shown the greatest survival in a wide range of conditions (Snodgrass & Snodgrass, 2006). Sedums close their stomata to maintain adequate water within the plant during drought conditions. Through *Crassulacean Acid Metabolism* (CAM) photosynthesis (whereby transpiration is reduced during the day to maintain the minimum water loss) the plants open their stomata to receive CO_2 during the night to prevent excessive losses from leaves and store the CO_2 as an acid to use for photosynthesis the next day when they close their stomata again to protect against the hotter day climate (Harper G.E., 2013).

Though different sedum plants are available, selection of a variety in a specific project normally follows a practice of using the previously tried and tested plants (Emilsson & Rolf, 2005). It is not appropriate to use the same vegetation mixes everywhere. With this reason, trialing of different species for their suitability in a particular location should be done (Dunnet & Kingsbury, 2004) before installing a green roof.

Recently there has been interest in the use of native species in green roof plantings as they have been shown to provide benefits over traditional Sedum monocultures such as enhanced biodiversity of native insect (Monterusso et al., 2005). Furthermore, introducing non-native species, while beneficial for stormwater retention, may be invasive in a specific area and have detrimental effects to the ecosystem as a whole (Dvorak & Volder 2010). Native plants, instead, having evolved to grow and survive in their local microclimatic conditions, and to resist local pests and diseases (MacIvor & Lundholm, 2011), are generally preferred because they are adapted to local conditions and preserve the natural biodiversity (Oberndorfer et al. 2007).

In conclusion, the individual conditions of a specific region and green roof may determine whether native species or imported succulents will be better suited for the environment of the green roof.

2.4 Advantages of Vegetated Roofs

Green spaces in urban areas are often scarcely represented and this lead cities to have to deal with many environmental, economic and sociological issues. Since green roofs mimic some of the natural systems that are lost due to development, thereby reducing some of the negative effects of development, there are numerous reasons for building green roofs in place of conventional roofs.

Furthermore, compared to traditional grey infrastructures, Green Roofs (GRs), which incorporate both the natural environment and engineered systems, offer a wide range of benefits to people and wildlife and preserve ecosystem values and functions (Dvorak & Volder, 2010)

Vegetated roofs achieve multiple benefits which operate at different scales. Some are evident only when relatively large numbers of roofs are greened in an area, while other benefits are realized at a single building scale. Although the entity of individual benefits varies from roof to roof (according to design of the system), several authors have categorized their benefits according to three main areas of benefits: aesthetic, economic and environmental (Dunnet & Kingsbury, 2004).

This section will give an insight into the broad spectrum of green roof effects, taken from the literature reviewed. In particular, with regard to the scope of this research, the main focus is on the influence that green roofs have on the artificially changed rainfall-runoff relationship in urban areas.

Amenity and Aesthetic Benefits

The living comfort or well-being of urban population is influenced by green roofs in many ways: green roofs improve the quality of life for urban dwellers, decrease stress and create space for relaxation and recreatio. More in detail, the main aesthetic benefits of a green roof are the following:

- *Increased living comfort.* Both intensive and extensive green roofs can create an attractive space increasing possibilities for recreational activities for building occupants, and views for those in neighboring buildings. Intensive roofs in particular can offer a place of refuge and relaxation for people who work in a building, thus reducing stress and boosting worker productivity.

- *Improvement in quality of life*. A natural environment has positive influence on human's state of mind and physical well-being (Menten et al., 2002). Kaplan et al., (1988) reported that employees who had a view of natural landscapes were less stressed, experienced greater job satisfaction, and reported fewer headaches and other illnesses than those who had no natural view.

- *Air quality improvements.* The air quality in urban areas is improved by green roofs because small airborne particles are absorbed and the humidity level of the air is kept more constantly by green roofs (WTCB, 2006). Vegetation behaves as a sink of pollutants resulting in the removal of certain pollutants from the air through dry deposition process and microclimate effects (Emilsson et al., 2006; Yang et al., 2008).

- *Noise reduction benefits*. Green roofs are better in absorbing sound than conventional and concrete roofs. When used on buildings without ceiling insulation, they can reduce the amount of noise transmitted inside the top floors of a building, particularly in areas with heavy air or automotive traffic. Studies on the acoustic effects have proofed that green roofs reduce external noise levels up to 35-60 dB, while normal roofs reduce noise levels up to 30-50 dB depending on the roof weight and construction type (WTCB 2006).

Economic Benefits

The following are the major economic benefits of extensive green roofs:

- *Increased roof life.* Green roofs increase the useful roof life expectancy up to two times the lifetime of an ordinary flat roof (Mentens et al., 2002).

The various components of the green roof, absorbing infrared and UV-radiation which normally deteriorate and break roof materials by photochemical reactions, protect the roof waterproofing membrane (Getter & Rowe, 2006; Murphy, 2007). The insulating effect played by green roofs, by reducing the extreme temperature fluctuations on the roof surface, prevents the roof membrane from experiencing frequent freeze thaw cycles that also degrade a roof. By avoiding drastic temperature variations, the roof membrane does not expand and contract as it occurs in non-vegetated roofs (Getter & Rowe, 2006).

Therefore, properly designed and installed green roofs can extend the roof membrane life span (Köehler, 2003; Liu & Baskaran, 2003; Banting et al., 2005, Abram, 2006) and, in general, the life of a roof by 2 to 3 times its normal life.

- *Energy Savings and thermal benefits.* Green roofs have been shown to impact positively on a building's energy consumption by improving its thermal performance, decreasing the desire for air conditioners in summer and radiator heating in winter periods (Cantor, 2008, Mentens et al., 2002). In winter, their insulating effect help to reduce the heat loss from inside the building through the roof, consequently reducing heating needs as compared with black roofs. The soil insulating value is soil specific and determined by the soil characteristics and moisture content (Oberndorfer et al., 2007, Dunnett & Kingsbury, 2004). In summertime, green roofs can also act as an insulating layer, reducing heat flux, or the transfer of heat from a building's exterior to its interior through the roof by up to 72% (Spolek, 2008). Green roof evaporation and transpiration provide a natural cooling mechanism to the building (Oberndorfer et al., 2007, VanWoert et al., 2005). Summer cooling from green roofs is the result of the soil mass absorbing solar radiation that is released slowly overnight and reduces roof surface temperatures and ambient air temperatures, thus lowering cooling energy demand (Niachou et al., 2001; Liu & Minor, 2005).

After these considerations, by reducing buildings' energy consumption, green roof can represent a tool helping the climate change mitigation on a global scale. Temperature is one of the main problems connected to the climate change, and in warm climates, such as the Mediterranean mitigating temperature, may helps to improve quality of life and reduce energy consumption to cool down indoor environments.

- *Cost Optimization.* A green roof might have higher initial costs than most conventional roofs, however a full performance analysis can identify how the roof benefits at the same time both the building owner and the community. In many cases, these advantages justify the cost of green roofs, particularly in densely populated areas (Kosareo & Ries, 2007). As illustrated by Banting et al., 2005, in Toronto city green roofs through their positive benefits can generate a cost reduction by up to 38% for the stormwater management, 25% for the urban heat island effect and 22% for the building energy consumption. In addition, they have a number of other economic benefits including growth in real estate values (Peck et al., 1999, and Siegler, 2006).

Green roofs, which are considered green infrastructure, can also create employment opportunities in production, installation, and maintenance of the roof.

Environmental Benefits

The following aspects constitute the major environmental benefits of extensive green roofs:

- *Biodiversity and Habitat creation*. Biodiversity is a measure of the variety of plants and animals in an area; this diversity of species can make an ecosystem more resilient. In high-densely populated urban environments, where green spaces are scarce, green roofs have the potential to reintroduce nature, which can function as a home for the many species of plants and animals that disappeared during urbanization (Cantor 2008). Invertebrates and birds have been documented inhabiting green roofs, demonstrating their potential as a biodiversity tool (Brenneisen, 2003; Gedge, 2003; Kadas, 2006). Therefore, providing new habitat for plants and animals in urban areas, as well as for migrating birds, green roofs can encourage biodiversity. Increased biodiversity can help ecosystems continue to operate even when they are disturbed by development or in other ways.

Dunnett et al. (2010) stated that from both an ecological and an aesthetic viewpoint, there are considerable benefits in promoting plant species-diversity in green roof vegetation; however, in creating habitat the use of native species of local provenance is advised (Grant et al., 2003). The use of local resources should provide higher guarantees of suitability and adaptation to the local climate and its potential must not be underestimated.

-*Reduction of urban heat island effect.* In cities, a high portion of the incoming solar energy is absorbed by the hard, heat-absorbent surfaces (Fig.1.1). As a consequence, the local climate in the city is altered, causing a significant rise of the urban temperature and other alterations, known as the heat island effect (Alexandri and Jones, 2008; U.S. EPA, 2005). The urban heat island effect is a phenomenon that explains warmer environmental temperatures in built-up areas compared to those in surrounding rural or suburban areas due to the absorption of solar radiation by buildings and other man-made surfaces, and the lack of natural cooling from vegetation. Higher environmental temperatures have negative impacts on the society because of the increase in energy consumption, air pollution levels and greater rates of heat related illness (U.S. EPA, 2005).

There are two ways to mitigate urban heat island: i) increasing vegetation, or ii) increasing surface reflectivity. The Environmental Protection Agency's Office of Atmospheric Programs and also the Urban heat island group suggest that reintroducing vegetation to urban areas through green roofs is one of the most promising solutions to mitigate the problem of heat islands.

Green roofs absorb less sunlight than dark roofs, through the process of evapotranspiration and by providing a shading effect to buildings. In the summer, green roofs cool buildings and the air around them through evapotranspiration, or the movement of water from the soil both by evaporation and by transpiration, the process by which water exits through pores in the leaves of plants. This creates a cooling effect on and around buildings.

Concluding, green roofs accomplish and consequently reduce both a building's energy use (Fang, 2008; and Bass, 2007) and, on an urban-scale, when combined with other measures - like street tree planting and other large-scale greening efforts - reduce the urban heat island because increased evaporation helps to cool the entire city (Cantor 2008).

As can be noted, vegetated roofs provide a range of environmental benefits addressing many aspects of sustainable development. Since the focus of this research is stormwater management, the next section will focuses only the green roof's capacity to mitigate urban stormwater runoff. Detailed discussion of the benefits provided by vegetated roofs in stormwater management, is presented in the next paragraph and in the Chapter 3.

2.5 Role of Vegetated Roofs in Stormwater Management

The environmental contribution of a green roof can be examined by testing how the urban hydrologic cycle is altered by the difference between conventional roof runoff and green roof runoff. According to paragraph 1.3, urbanization increases the total imperviousness and decreases infiltration rates, resulting in both increased rainfall-runoff volumes and peak discharges; these can cause downstream flooding and can deteriorate groundwater and surface waters bodies via infiltration of polluted substances from the surface area. During small storm events in an urbanized catchment, larger amounts of runoff are delivered to the stream system than would occur in an undeveloped or natural catchment. Green roofs have the ability to retain some precipitation, in turn reducing the amount of runoff.

Precipitation falling over a green roof can follow a number of different paths ending in evaporation, transpiration or runoff. As precipitation falls over a green roof a portion of the water is intercepted on the surface of the vegetation where some evaporates back to the atmosphere, while the remainder runs down and infiltrates the growing media. By design, the hydraulic conductivity of a green roof is high enough that the infiltration rate exceeds the precipitation rate of the most intense storm likely to be experienced by the site (Miller, 2003; Beattie & Berghage, 2004; Villarreal & Bengtsson, 2005). Achieving this prevents overland flow - which is not desirable as it reduces the retention and detention capacity of the green roof - ensuring that all moisture passes into the growing media. Precipitation infiltrates the substrate until the available storage capacity is consumed; water percolates through the growing media and filter fabric exiting through the drainage layer to centralized roof drains.

Water that drains through a green roof is referred to as runoff; the runoff depth plus the retained depth of water equals the total depth of precipitation. The amount of runoff is a common variable used to assess the stormwater response of a green roof. The portion of water that does not runoff the green roof is the quantity retained.

It has been given evidence by several studies that green roofs can significantly reduce the amount of stormwater runoff compared to that of conventional roof designs, with volume retention scores in the order of 40–80% of the total rainfall volume. From literature’s data it is also evident that green roofs alter the runoff hydrograph, delaying runoff starting time, reducing the runoff peak rates (decrease of 60–80%) and distributing the runoff over a longer period beyond the end of precipitation events (Köhler et al., 2001; VanWoert et al., 2005; Berghage et al., 2009; Villarreal & Bengtsson, 2005; Teemusk & Mander, 2007; Tillinger et al., 2006; DeNardo et al., 2005; Mentens et al., 2006; Carter & Rasmussen, 2006).

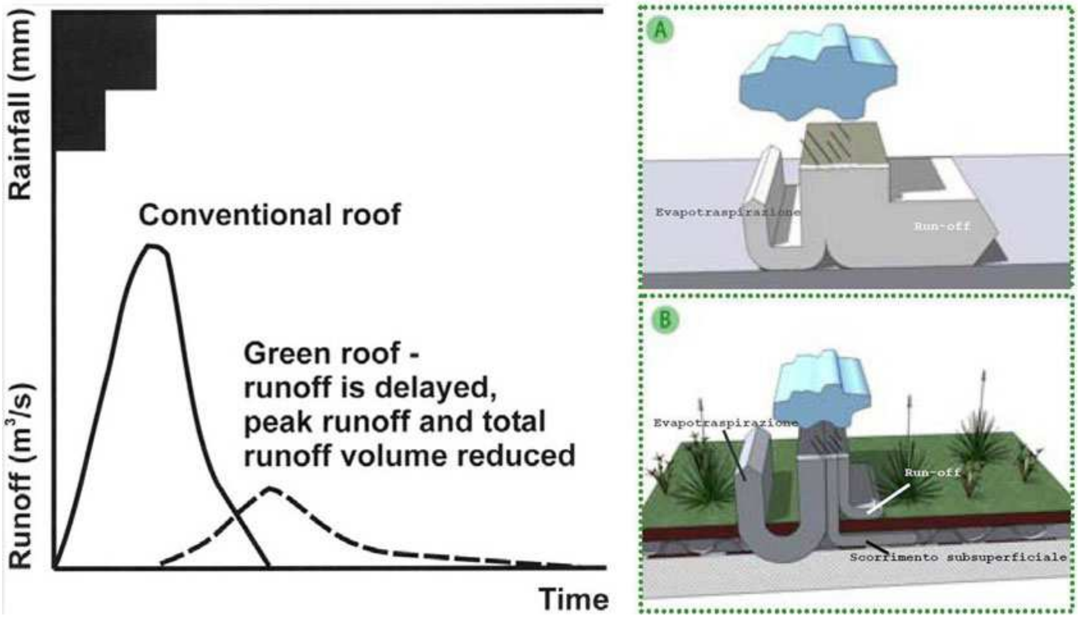

Figure 2.4 – Comparison between Conventional and Green Roof Hydrographs

The reduction of stormwater runoff quantity is possibly the most important benefit of extensive green roof (Getter & Rowe, 2006). During a rainfall event the main hydrological phenomena operating within a green roof are (Figure 2.5):

- *Interception of precipitation by the vegetation layer*. Water is used by plants, which require it for physiological processes, including transpiration (this is one of the ways water is rapidly removed from the green roof substrate and returned to the atmosphere (Getter & Rowe, 2006).

- *Infiltration and Retention in the substrate*. Water can be stored and retained in the pore spaces of the substrate or taken up by absorbent materials in the mix (Dunnet & Kingsbury, 2004).

- *Storage and Detention in the drainage layer*. Rainfall detention is defined as water temporarily detained after a rainfall event to be later released it at a later time; resulting in both a delay and reduction in the peak flow of runoff from a green roof (Bengtsson, 2005; Bengtsson et al., 2005; Villarreal & Bengtsson, 2005; VanWoert et al., 2005), as well as an extension of the runoff period at the end of the rain event (VanWoert et al., 2005).

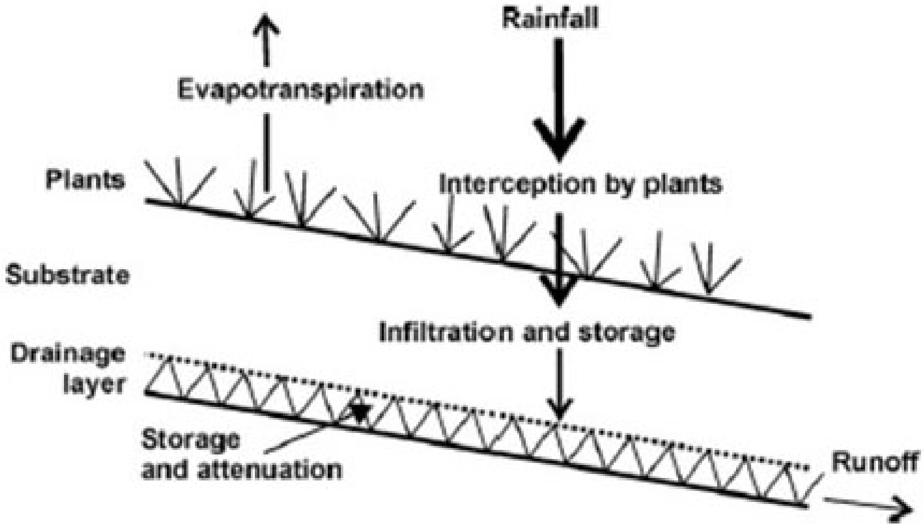

Figure 2.5 – Main hydrological phenomena operating within a green roof

Rainfall retention, instead, is defined as the fraction of rainfall that is retained on the roof that eventually is evaporated from the growing medium or transpired by the plants. Several studies have reported varying water retention capacities of green roofs. However it's hard to synthesize the results of these researches into a general understanding of the quantitative hydrological effects of green roofs because the performances appear to be dependent upon several different factors as climatology (e.g., rainfall events, length and intensity of the event, antecedent dry weather period), construction types (e.g. composition of the layers; roof slope, growing media, drainage layer size) and green roof age (Berndtsson, 2010; Carter and Rasmussen 2006; Getter et al., 2007; Carpenter and Kaluvakolanu 2010; Hilten and others 2008). Additionally, apart from these parameters that can influence the green roof performance, also the Retention and Detention Performance Indicators values cannot be directly compared because of the use of different designs, different measurement strategies and measurement locations, with corresponding meteorological conditions.

Roofs represent a large area of impermeable surfaces in town and their beneficial effect on stormwater management for a city can reach 38% in savings (Banting et al., 2005); this explains so much research interest on this field. These systems can form a key part of a site-level stormwater management plan, reducing peak flow rates and increasing the amount of time water takes to flow from a site into the sewer, depending on the size of the roof and the distance the water has to travel.

Considering the various factors affecting runoff discharge, it is important to understand the response of specific vegetated systems to specific rainfall events; this requires reliable modeling tools that allow to optimize the performance of GRs system on a wide range of design types and in different operating conditions. Based on these objectives, the next chapter will provide, at first, an overview of the existing models for the analysis of the hydraulic behavior of green roofs, and in the second part, a survey of the scientific studies carried out to investigate the influence of these parameters on the hydraulic and hydrologic performance of extensive green roofs.

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Chapter 3 – VEGETATED ROOF MODELING AND LITERATURE REVIEW

3.1 Introduction

In spite an increasing awareness and well-known benefits of green roofs and other LID (Low Impact Development) techniques, the transition to more sustainable urban drainage systems is very slow (Elliot & Trowsdale, 2007; Piro et al., 2012). One of the key limiting factors in the widespread adoption of such systems is the lack of adequate analytical and modelling tools; Elliot and Trowsdale (2007) argue that the availability of effective LID modelling software that operates effectively at the necessary range of scales, could act to encourage wider uptake of LID measures.

Several Research have been conducted on run-off mitigation by green roofs (Beattie & Berghage, 2004; Carter & Jackson, 2007). Several studies have shown that green roofs may have significant effects on retaining rainfall volumes (DeNardo et al., 2003; VanWoert et al., 2005; Getter et al., 2007; Simmons et al., 2008; Gregoire & Clausen, 2011; Gromaire et al., 2013), delaying the peak flow rate (Bengtsson et al., 2005; Carter & Rasmussen, 2006; Spolek 2008) and reducing the runoff volume discharged into the combined sewer systems (CSSs) (Liptaň, 2003; Berndtsson, 2010; Voyde et al., 2010; Stovin et al., 2012). In terms of percentages, for example, Li and Babcock (2014) have shown that green roofs have a retention efficiency ranging from 30 to 86 % and the capacity to significantly reduce the hydrograph peaks from 22 to 93 % for most frequent rainfall events, as well as slowing the contribution to the urban drainage network. These retention and detention hydrological characteristics of green roofs are well known and have been re-visited recently by Stovin et al. (2013). In addition, Li and Babcock (2014) indicate that over the last two decades, 13 % of the research papers published on green roofs are dealing with their hydrological behavior.

The hydraulic and hydrologic performance of green roofs is highly variable and strongly depends on weather conditions (length of antecedent dry weather period; season/climate; characteristics of rain event like intensity and duration) and physical features of the green roof (number of layers; soil type and thickness; technological characteristics of each single component; slope; vegetation species and percentage of roof covered; etc.) (Czemiel Berndtsson, 2010; Locatelli et al., 2014). This suggests that it is difficult to predict how specific roof systems will respond to specific rainfall events.

Because of their morphological complexity, the analysis of green roofs behavior requires specific modelling techniques accounting for the complex physical phenomena involved and enabling optimizing the green roof performance over a wide range of design types and different operating conditions. Due to such many factors affecting runoff amounts, models to account for each of these variables have been proposed.

Literature review suggests that these modeling methods, which are so far successful in predicting the hydraulic properties of green roofs, mainly fall into four categories.

1) Empirical models though able to make reliable runoff estimation, need analogies between the green roof system and climatic conditions with intended design.
2) A reservoir model is the simplest model and treats a green roof system like combination of linear storage reservoirs elements. This model considering each soil layer as a separate storage element assumes that the flow from each soil layer is proportional to the amount of water stored in that layer. It is based on the principle that no runoff will take place until the water storage capacity of the green roof is exceeded. When the storage capacity is reached, green roof runoff will take place and will mimic the rainfall flow.
3) Physical models, developed for groundwater applications that solve the field equations for unsaturated flow, are capable to predict pattern of two-dimensional seepage flow through the green roof. The main problem with this model is its complexity.
4) Hardin (2006) indicates most of the mass balance models are represented by complex equations and they need a large number of variables for a solution. As they are data intensive, these models may not be equally and efficiently applicable in most of the simple green roof situations for different locations.

Therefore, in the following chapter it will be carried out, at first an overview of the existing models for the analysis of the hydraulic behavior of green roofs, seen as a support tool for quantitative management of rainwater, and then will be performed a survey of the scientific studies made to analyze the influence of these parameters on the hydrological and hydraulic performance of an extensive vegetated roof.

3.2 Literature review on vegetated roofs models

Various models describing the infiltration process have been developed and presented in the literature, with empirical relationships: the rational method, cascades of linear reservoirs, and the US Soil Conservation Service Curve Number method are used most frequently. Physically-based models are not widely used, even though they are well-suited for green roof planning and design (Palla et al., 2012) and may be more accurate than the conceptual and empirical models. The physically-based models are typically based on numerical solutions of the Richards equation (Richards, 1931) for the description of the unsaturated flow in the porous matrix of the green roof. However, a complete model to easily predict any green roof's function at various locations has yet to come to fruition; most models are site-specific and are not exportable to other locations.

Initially most of the existing models were mainly empirical, elaborated on experimental data trying to identify significant correlation between the variables involved and calibrating their parameters on extended series of data. More specifically, Mentens et al. (2006) collected experimental data of green roof hydrological performance on seasonal and annual bases in Germany. Moran et al. (2005) derived the rational coefficient based on green roof data from North Carolina. Carter and Jackson (2007) used the Curve Number (CN) method of the Soil Conservation Service (SCS) to test green roof performances at different spatial scales in Georgia, while Getter et al. (2007) derived CN varying from 85 to 90 for green roofs at several slopes in Detroit. Miller (2002; 2004) indicates that CN and the rational runoff method are based upon the dynamics of surface runoff a process much different than the through-flow drainage runoff of a green roof. To predict the response of a green roof to precipitation, it is necessary to base the method on physical processes unique to a green roof (Miller, 2002; 2004). Empirical methods are generally limited in predictive power, since their development requires site specific data and, consequently, may not be applicable for roofs of different size, construction type, areal coverage, and/or climate.

Conceptual models including linear reservoir models were also developed to test green roof impacts at multiple spatial scales and as a function of the contextual factors as well as the green roof design variables (Palla et al., 2012; Berthier et al., 2010; Carbone et al., 2014a, 2014b). The response of multi-layer green roofs systems is generally shown schematically with a combination of linear reservoirs in series, each of which interpreting the behavior of a specific layer (Zimmer & Geiger, 1997). To evaluate the hydrological impact of a green roof within an urban watershed, Sherrard (2010) built a simple bucket model for a single green roof to test its stormwater runoff reduction effects. In this study the single green roof model was extrapolated to an urban scale by simply combining the volume reduction of stormwater from a single green roof and the available roof area of the urban watershed. Sherrard found that the city of Portsmouth, NH, could expect approximately 15,000 m^3 of stormwater volume reduction per year if all flat rooftops were covered with vegetated roofs. Similarly, a bucket model was developed by Lamera et al. (2014) to simulate a rainfall-runoff relationship for a single green roof with different types of drainage layer and different climate area. Following a stage of validation and calibration, the model teste d presents rather good performance both in terms of total volume and peak hydrograph. Carbone et al. (2014b), as an evolution of a previous study (Carbone et al., 2014a), propose a conceptual model, implemented on software SWMM (EPA, 2002), to predict the hydraulic behavior of a experimental green roof installed at University of Calabria (Unical). A mass balance equation is applied to each block, taking into account the specific physical phenomena occurring in each module. The results show a good ability of the model to fit the measured data observed from the monitoring campaign.

While these models might be useful in estimating the upper bound retention behaviour of green roofs, it has been shown that observed rainfall capture is influenced by antecedent moisture conditions (Stovin et al 2012, Voyde et al 2010). Other variations of the reservoir method introduce additional parameterizations to resolve inter-event reservoir conditions by accounting for temporal evapotranspiration rates (Berghage et al., 2007, Berthier et al., 2011). Other recent research studies have focused on the measurement and modelling tools of evapotranspiration (ET) from green roof systems, to better understanding the behavior of the substrate moisture content due to ET. Stovin et al. (2013), arguing that the substrate moisture content directly affects the ET rates, have demonstrated that proper representation of ET processes is critical to the development of robust models for green roof retention. Locatelli et al. (2014) implemented a detention model based on nonlinear reservoir routing, to explore how roof configuration affected runoff volume and peak time delay. Vesuviano et al. (2014) produced and tested a detention model which models the processes in the substrate and drainage layer separately so as not to be limited to a single configuration. These more complex reservoir models have shown varying degrees of success, but are limited when reservoir moisture and evapotranspiration phenomena are assumed to be linear and/or invariant with season.

More sophisticated and far less diffused approaches in the literature are mechanistic models such as HYDRUS-1D (Hilten et al., 2008; Palla et al., 2012) and SWMS-2D (Palla et al., 2009), based on Richards' law and the Van Genuchten-Mualem functions, that mimic the hydrological and hydraulic processes occurring on and inside a green roof by using a set of equations based on fundamental physics. More in detail, Hilten et al. (2008), assessed the hydrologic performance of a modular block green roof, located in Georgia (USA), using a packaged soil moisture simulation, HYDRUS-1D, and stormwater data collected at the study site to validate results in terms of the model outflow. Palla et al. (2009) applied the SWMS_2D model to simulate the variably saturated flow within the green roof system; the model was calibrated and validated using rainfall-runoff events observed at the green roof experimental site of the University of Genoa (Italy). These models, commonly used to predict the soil moisture transport in the green roofs, revealed that rainfall depth strongly influences the performance of green roofs for stormwater mitigation, providing a complete retention for small events and detention for greater ones.

Physical models, despite being theoretically complex, are independent from the specific boundary conditions of the experimental site allowing to achieve general conclusions based on physical phenomena. For example She and Pang (2010), contrary to conventional infiltration modeling approaches, constructed a physics-based model, in FORTRAN, to simulate rain water movement within the medium of green roof. The study suggests that a portion of rain water will directly drain through the substrate to the under-drain after the field capacity is exceeded but before the substrate is completely saturated. The model was calibrated using data from the green roof located in Portland, Oregon. More recently, Carbone et al. (2015a) proposed a physically-based model, employing the explicit Finite Volume Method (FVM), for modelling infiltration into growing media. The model, verified against the HYDRUS-1D software, solves a modified version of the Richards equation using a formulation, which takes into account the main characteristics of green infrastructure substrates; the comparison of results confirmed the suitability of the proposed model for correctly describing the hydraulic behavior of soil substrates.

3.3 Hydrologic factors influencing the vegetated roof efficiency

Storm water performance can be documented in terms of runoff or retention. Retention is taken as the difference between the measured precipitation depth and the runoff depth once the precipitation event has stopped (DeNardo et al., 2005). The stormwater performance of a green roof is often reported as a percent of total precipitation or the amount of rain retained, which is eventually lost by evapotranspiration. Stormwater response can also be expressed as the total depth of retention. Numerous studies have been performed to examine the retention capabilities of green roofs and there is a wide range of depth of retention performance, while percent retention remains more constant across the studies.

Table 3.1 - Retention Response of extensive Green Roofs

Study Period [months]	Total Rainfall [mm]	Retention [mm (%)]	Substrate depth [mm]	Location	Study
12	450	207 (46)	30	*Malmö, Sweden*	Bengtsson et al.,
12	658	314 (48)	100 - 115	*Portland, Pregon*	Hutchinson et al.,
24	1099	550 (50)	100	*Germany*	Köhler et al., 2001
6	450	245 (54)	150	*Ottawa, Ontario*	Lui, 2003
3	314	173 (55)	100	*Releigh, North Carolina*	Moran, 2004
18	1514	961 (63)	51 - 102	*Goldsboro, North*	Moran, 2004
14	556	378 (68)	25 - 60	*Michigan State University*	VanWoert et al.,

As mentioned above, studies have demonstrated that GRs have a strong impact on stormwater runoff retention, but their performances are influenced by different factors such as soil substrate thickness, water content, size of rainfall event and precipitation. However the most obvious factor seems to be precipitation depth, and indeed different studies found this to be the best single predictor of retention. The correlation between event size and vegetated roof retention was broadly investigated by different studies (VanWoert et al. 2005; Moran et al. 2005; Uhl & Schiedt, 2008), but it is very difficult to compare the results and summarize and quantify the exact amount of retention because of the different features of the studies.

German studies from 1987 to 2003, as summarized by Mentens et al., (2006), have shown that the annual runoff reduction from intensive green roofs is 65% - 85% of the annual precipitation, while for extensive green roofs is around 27% - 81% (Berndtsson, 2010). It is a broad spectrum and typically - as shown in Table 3.2 - the other studies show results which fall well into such broadly stated limits (Berndtsson, 2010).

Table 3.2 - Retention Response of extensive Green Roofs (Berndtsson et al., 2010)

Reference	Rainfall retained in green roofs, average during study period (%)	Rainfall retained in green roofs, average during study period (%)	Length of study period
Bengtsson et al (2005)	46	-	17 months
VanWoert et al. (2005)	60.6	-	15 months
DeNardo et al. (2005)	45	19-98	2 months
Moran et al. (2005)	63 (roof 1)	-	18 months
	55 (roof 2)	-	15 months
Carter and Rasmussen (2006)	78	39-100	13 months
Monterusso et al. (2004)	49	-	4 rainfall events
Bliss et al. (2009)	-	5-70	6 months

In Portland, Liptaň (2003) has found that a tested green roof could reach a reduction of runoff water volume reduction of 10% - 35% during the wet season and a reduction of 65% - 100% in the dry season. Van Seters et al. (2009) reported similar values for a large green roof in Toronto. Carter and Rasmussen (2006), in Georgia, have found an inverse relationship between the rainfall depth and the percentage of water retained: for small rainfall events (< 25.4 mm) was retained the 88% of the stormwater volumes, for an average rainfall (25.4 mm - 76.2 mm) more than the 54% and for the events higher than 76.2 mm the 48%. The study conducted by Hilten et al. (2008) revealed that rainfall depth per storm strongly influences the performance of green roofs for stormwater mitigation, providing complete retention of small storms (<2.54 cm) and detention for larger storms, assuming initial soil moisture content as 0.1. Similarly, Simmons et al. (2008), in Texas, have found that small rainfall events (<10 mm) were totally retained by the green roof, and events greater than 10 mm resulted in a range of responses in line with similar studies elsewhere depending on green roof type (Getter & Rowe, 2006; Seters et al., 2007); the events with a constant precipitation of 12 mm, 28 mm and 49 mm produced a retention between 26% and 88%, 8% and 43% and 13% and 44, respectively. From that study, it was also noted that substrate and drainage layer potentially placed the largest role in detaining water. It was further observed that the retention depends on not only the rain event size (duration and depth) but also probably the rain event intensity changes.

Additional considerations include storm duration and storm intensity, although differing conclusions have been published regarding these factors and no specific relationship has been established (Moran 2004; Carter and Rasmussen 2006; Voyde et al. 2010; Villarreal & Bengtsson 2005). Villareal and Bengtsson (2005), in Lund, have observed that the green roof water retention largely depended on the rainfall intensity; in fact, lower rain intensity events produced greater retention. With a slope between 2% and 14%, for rainfall intensity of 0.4mm/min was found a retention between 39-62%; instead with an intensity of 1.3 mm/min, the retention was 10-21% of the simulated precipitation.

DiGiovanni et al. (2010) was unable to discern a unique relationship between retention and precipitation depth, but did note 100% retention for storms with an antecedent dry period to precipitation depth ratio of 8 hr/mm; Moran (2004) also found consistently high retention related to antecedent dry period and precipitation depth.

Many studies agree that the green roofs influence runoff hydrographs, not only retaining a quantity of water, but especially by delaying the runoff peak. Considerable detention variation was measured in the study of Carter and Rasmussen (2006). They found that runoff from the green roof was delayed; average runoff lag times increased from 17 minutes for the reference roof to 35 minutes for the green roof, with an average increase of 18 minutes. While most precipitation events considered were delayed between 0 and 10 minutes, the longest delay measured was approximately 2 hours. These differences in detention can be attributed to large variations in precipitation intensity as well as antecedent soil moisture conditions (Carter & Rasmussen, 2006). Prowell (2006) found a 18 minute difference in time to peak between the modular green roof peak runoff and the reference roof peak runoff. VanWoert et al. (2005) found a relative delay time of 15 minutes between the green roof runoff start time and the reference roof runoff start time for light rains, 5 minutes relative delay time for medium rains and less than 5 minutes relative delay time for heavy rains. More recently Locatelli et al. (2014) have noted that the delay of the peak flow rate was up to 40 min, while Getter et al. (2007) and Villarreal and Bengtsson (2005) have found minimal delays. However, for the majority of studies the delay of the peak flow rate was found to be up to 30 min compared to conventional roofing (VanWoert et al., 2005; Carter & Rasmussen, 2006; Simmons et al., 2008). Despite delaying the stormwater peak allows for greater flexibility in designing stormwater detention facilities and for desynchronizing stormwater flows (Carter & Rasmussen, 2006), many studies do not mention detention characteristics of green roofs. Based on available detention values, it can be concluded that, on average, initial and final green roof runoff and green roof time to peak are delayed relative to a reference roof.

3.4 Hydraulic and physical parameters influencing the vegetated roof behaviour

Green roof substrate is a key component in overall living roof design for storm-water management: substrate characteristics affect the active water storage of rainfall during storm events, directly influence the ability to sustain non irrigated plant life, and drive evapotranspiration (ET). Growing media provides the majority of the water storage capacity of a green roof. The storage capacity is not equal to the maximum moisture level that can be retained by the growing media. One variable relating to the storage capacity that is regularly documented in green roof studies is the field capacity which, usually expressed as a percent of the growing media volume, is the maximum amount of water that can be held by a freely draining sample of growing media (Bengtsson et al., 2005). When the growing media moisture reaches the field capacity, therunoff will begin (Bengtsson et al., 2005). Field capacity represents the maximum moisture level the growing media can retain, while the lower limit to the moisture level is the wilting point. Vegetation cannot draw water out of the growing media below this level (Allen et al., 1998; Bengtsson et al., 2005; Jarrett et al., 2006). With field capacity representing the maximum water level and the wilting point representing the minimum water level, Bengtsson et al. (2005) state that the storage capacity of the growing media is equal to the difference between these two values.

In literature, few studies investigated how the characteristics of the soil moisture affect the water retention capacity of the green roof (DeNardo et al., 2003; Bengtsson et al., 2005; Hilten et al., 2008). The moisture content significantly influence the retention volume and, in particular, when the substrate is close to saturation at the beginning of the rain event, only a small portion of water is absorbed (Moran et al., 2005; Connelly et al., 2005). While Bengtsson et al. (2005) have defined the storage capacity as the difference between the field capacity and the wilting point, DeNardo et al. (2005) observed that the field capacity was corresponding to the water retention capacity of the roof. Hilten (2005) have found that the field capacity and the wilting point for the engineered green roof media are 0.11 e 0.08 m^3/m^3 (volume of water per volume of soil) respectively, both less than the values obtained from Bengtsson et al. (2005) and DeNardo et al. (2005).

Furthermore, seasons with different weather conditions can influence the regime of humidity in the substrate; the moisture storage in green roofs, in fact, is affected by extrinsic meteorological factors such as air temperature, humidity, wind speed, and solar radiation, which then influence the evaporation and transpiration (Mentens et al., 2006; Berndtsson, 2010). Based on literature, climate plays a role in retention performance of a green roof, with special note that areas with high precipitation in winter perform worse because ET rates are lower and therefore green roof retention recovery is slower as opposed to summer when retention recovery is quicker.

However, it is difficult to compare the results obtained by different studies because researchers have defined seasons differently. As summarized by Mentens et al. (2006), German studies have classified three different seasons - warm (from 1st May to 30th September), cold (From 16th November to 15th March), and in-between cool season (from 16th March to 30th April and from 1st October to 15th November) - while others employed a monthly basis. Despite this, most of the works agree that green roofs have higher evapotranspiration rates and that storage capacity is renewed faster during the warm periods of summer (Mentes et. al, 2006; Villareal, 2007). Researchers as Villarreal and Bengtsson (2005) have shown that weather conditions (dry or wet) affected the retention capacity of the green-roof. Contrary to other studies, Voyde et al. (2010) have not observed a significant seasonal variation in the vegetated roof performances; probably this is due to the fact that in Auckland there are small seasonal variations. The study conducted by Uhl and Schiedt (2008) clarifies the influence of meteorological and seasonal conditions on the runoff coefficient. Under warm and hot conditions, in summer, the average runoff coefficient was 24 %; instead in winter it range from 40 % to 60 % with an average of 51 %. The cool conditions in spring and autumn resulted in a runoff coefficient between 27 % and 51 % and an average of 38 %. To confirm what already seen in previous studies, in the report "*United States General Services Administration*" (2011) it is observed that green roofs retain more water in the summer months, when the plants are active and the heat increases evaporation.

Several studies have recognized that also the type and the depth of the substrate have an impact on the stormwater retention as well (DeNardo et al., 2005; Berntsson, 2010; Stovin et al., 2012). Monterusso et al. (2002), VanWoert et al. (2005), and Mentens et al. (2006) all found that increased media depth corresponded to increased retention performance. Uhl and Scheidt (2008) obtained, by the linear regression analysis, relationships between runoff coefficient [%] and total depth of layers (Substrate and Drainage) [cm]. Storage capacity is, in fact, a linear function of pore volume and depth of the substrate and the drainage layer. The correlation between runoff coefficient and total depth is strong during warm/hot periods, instead in cold seasons the retention is often influenced by the antecedent rainfall because of the low evapotranspiration. Carbone et al. (2015b) have analyzed the hydraulic/hydrologic behavior of a green roof changing the depth of the substrate (8, 12 and 15 cm) for constant rainfall events. In particular, this study has shown that the subsurface runoff coefficient is influenced, with a linear law, by the depth of the substrate, in agreement with the results found in the literature. Indeed, previously, Mentes et al. (2006), reviewed 18 German studies, have observed that the relationship between annual precipitation and runoff was greatly influenced by the substrate depth (as summarized in Table 3.3). These values agree well with those reported by Schmidt (2006) which, based on four years worth of data, found that a 50 mm green roof retained 63% and a 120 mm green roof retained 72% of the annual precipitation.

Table 3.3 - Relationship between substrate depth and annual stormwater retention (Mentens, 2006)

Media Depth	Retention
< 50 mm	62%
-150 mm	70 %
< 150 mm	80 %

Furthermore, different studies were conducted to evaluate the influence of slope on the retention capacity of a green roof. While some studies did not find a correlation between slope and runoff (Mentes et al., 2006; Bengtsson, 2005), others have observed that the retention of runoff may depend on the slope of the green roof (VanWoert et al., 2005; Getter et al., 2007). For example, Villarreal and Bengtsson (2005) demonstrated that green roof slope affects water retention: the lower the slope (and the rainfall intensity) the higher the retention. However, the effect of the slope on the retention capacity is combined with the effect of other factors such as the physical properties of the soil, the duration and intensity of the precipitation, the flow conditions (saturated or unsaturated), the design of the layers and the choice of different kinds of materials for the drainage layer (Berntsson, 2010).

Many studies agree that the depth and the type of substrate have a greater influence on the water retention capacity of the green roof than the type of vegetation (Monterusso et al., 2002; VanWoert et al., 2005). However, it was also found that vegetation plays an important role in water retention during periods with high temperatures and small rainfall events (Dunnett et al., 2008). The main function of plants is their ability to reduce media moisture content via transpiration and increase interstitial pore space available for water storage. This is important because the amount of storage available for the next storm event depends on how much water was released via transpiration rate of the plants after drainage stops. After a storm, the available storage volume in the growing media depends on the percent of available volume of void pores. Additionally, since green roofs are defined as being “living roofs”, the plants must remain viable during the lifetime of the roof. To sustain plant life on a roof, enough *plant available water* must remain in the soil between storms. *Plant available water* is defined as the difference between field capacity and wilting point (Lang S.B., 2010). Carbone et al. (2015c) evaluated the reduction of subsurface runoff coefficient on the experimental site at the University of Calabria, Italy. The results showed that for small rainfall events, the green roof was able to reduce the stormwater through the interception by the plants, while for the higher events there was an increasing runoff in the substrate, caused by the preferential flux paths generated by the root apparatus.

Finally, since the vegetation layer of green roofs suffers physical and chemical changes over time, it can be expected that the age of green roofs influences runoff dynamics. Not many studies have investigated the effects of time on green roofs performances and furthermore they have varying results. Researchers such as Getter at al. (2007) evaluated organic matter content and physical properties of soil on a 5 years old green roof. It was found that organic matter resulted in increases from 2% to 4% in 5 years, while the pore space doubled, from 41% to 82%. On the contrary, German researches, as described by Mentens et al. (2006), demonstrated that green roof age did not affect runoff retention.

3.5 The Subsurface Runoff Coefficient of an extensive vegetated roof

The subsurface runoff coefficient, expressed as the ratio between the runoff from vegetated roof and the rainfall, is strongly affected both by the hydrological characteristics of the rainfall event (intensity, duration, precipitation depth, intra-event period) and by the physical characteristics of the green roof (substrate thickness, type of vegetation, conditions of soil moisture, age of the vegetated cover). The runoff coefficient is an extremely useful index to quantify the hydraulic efficiency of a green roof, for this reason has been investigated in numerous scientific studies.

Uhl and Schiedt (2008), in Muenster, DE, carried out a monitoring campaign on 18 green roofs with surface of 12 m^2 and 24.5 m^2 with different slopes and stratigraphies (installed on a roof of 500 m^2). The average annual runoff coefficient obtained from this study was 0.32. At the end, they showed that green roofs considerably reduce the annual and seasonal rain runoff : the annual runoff coefficient ranged between 23% and 38%. Palla et al. (2010) explored the performance of a green roof installed at the University of Genoa, IT, under Mediterranean climate conditions. The retained volumes, calculated as the percentage difference between the volume of rain and the discharged volume, ranged between 0% and 100%, with an average value of 51.5%. From this analysis an average value of the runoff coefficient 49.8% was achieved. Voyde et al. (2010) considered 91 events with a minimum rainfall depth of 2 mm and an inter-event time of 6 h, in an area with sub-tropical climate and they have found that the water retention efficiency of an extensive green roof in Auckland, NZ, was about 66% on average, with a subsurface runoff coefficient of 0.34. Stovin et al. (2012) analyzed the hydrologic performance of a test bed in Sheffield, UK, under temperate weather conditions. The study involved the analysis of 22 significant rain events, in 29 months of observations, with rainfall depth greater than 5 mm and a minimum inter-event time of 6 h. Analyzing rainfall data was obtained a cumulative total retention of 50.2%, and, therefore, an average annual subsurface runoff coefficient equal to 0.48. Gromaire et al. (2013) have made a study of 6 different green roofs with an area of 35 m^2, installed on an experimental site in the town of Trappes, 30 km from Paris. From the analysis of 34 rain events, with minimum rainfall depth of 1 mm and inter-event period of 1 hour, it was obtained a coefficient of annual runoff less than 0.5 for an extensive green roof. Locatelli et al. (2014), by analyzing three different extensive green roofs in Denmark, have implemented a model to quantify the hydrological response of the green roofs based on 22 years of observations. The average subsurface runoff coefficient obtained was between 0.43 and 0.68. Wong and Jim (2014), in Hong Kong, obtained a cumulative total retention between 11% and 14% depending on the substrate considered from the analysis of 63 rain events, with a minimum rainfall depth of 0.5 mm and the inter-event time of 6 h. Another study in the humid sub-tropical climate was carried out by Carter and Rasmussen (2006), which obtained a total cumulative retention of 62% for 72 mm of substrate, for green roof constructed at the University of Georgia.

In Table 3.4 it is shown a summary of the subsurface runoff coefficient values on a yearly basis observed in the mentioned literature studies.

Table 3.4 – Subsurface Runoff Coefficient (SRC) found in the literature studies

References	Climate Condition and Location	Subsurface runoff coefficient
Carter and Rasmussen	*Humid sub-tropical – Athens (GE)*	0.38
Uhl and Schiedt (2008)	*Continental – Muenster (DE)*	0.32
Palla et al. (2009)	*Mediterranean – Genova (IT)*	0.48
Voyde et al. (2010)	*Sub-tropical – Auckland (NZ)*	0.34
Stovin et al. (2012)	*Temperate – Sheffield (UK)*	0.48
Gromaire et al. (2013)	*Temperate – Trappes (F)*	0.36 - 0.50
Locatelli et al. (2014)	*Ocean - Odense and Copenaghen (DK)*	0.43 - 0.68
Wong and Jim (2014)	*Humid sub-tropical – Hong Kong (CN)*	0.86 - 0.89

While many studies have analyzed the subsurface runoff coefficient at seasonal and annual scales, only few have evaluated it at event-scale (Stovin et al., 2012; Palla et al., 2010). This study will focus on the analysis of the influence of hydrological parameters on the substrate runoff coefficient at event-scale for a specific case study.

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Chapter 4 – LYON CASE STUDY: Development and calibration of a green roof conceptual hydrological model

4.1 Introduction

As widely shown in the previous chapter, several studies have shown that green roofs have the capacity to significantly reduce runoff volumes and peaks of most frequent rainfall events, and delay their contribution to urban drainage networks (e.g. Carbone et al., 2014). However, the hydrological response of vegetated roofs to precipitation events is highly variable and strongly depends on climatic conditions and roof design (thickness of the substrate, technological characteristics of each single component, slope, vegetation species, etc.) (Czemiel Berndtsson, 2010).

Because of their morphological complexity, the analysis of green roofs behaviour requires specific modelling techniques accounting for the complex physical phenomena involved and enabling optimizing the green roof performance over a wide range of design types and different operating conditions.

New green roof technologies are developed, aiming to better control stormwater hydrological performance, by maximising retention, detention and evapotranspiration by means of additional layers, storage and water transfers between green roof layers and components. Among them, HYDROPACK® green roof systems (Vegetal i.D., 2014a) include an additional alveolus layer under the substrate layer to store additional water compared to traditional green roofs without increasing the substrate thickness: the water stored in the alveolus is then later available for evapotranspiration and reduces the green roof runoff. More recently, HYDROACTIVE® systems (formerly STOCK&FLOW®) (Vegetal i.D., 2014b, 2015) were developed as an evolution of HYDROPACK® with a supplementary storage reservoir under the alveolus layer, providing more water storage and using wicks, which, thanks to capillarity, allows backflow from the storage reservoir to the vegetation for evaporation.

The aim of the model presented in this part of the thesis is to reproduce at 1 minute time step the hydrological behaviour of various types of vegetated roofs by means of reservoirs and by activating specific processes and variables in the model: i) traditional extensive single substrate layer roofs, ii) specific HYDROPACK® and iii) new HYDROACTIVE® pre-fabricated green roofs.

The model, which mimics the physical structure of these green roofs, is adaptable to each type of green roof by activating different optional reservoirs and functions. The model will help designing and sizing future systems, according to a set of various performance indicators including retention efficiency, detention efficiency, peak attenuation, irrigation needs and periods of hydric stress.

This chapter presents the first model calibration results and performance indicators obtained for two cases: i) a HYDROPACK® system, with event calibration and ii) a traditional single layer green roof, with monthly calibration. Section 2 describes the two case studies and the complete model. Section 3 presents and discusses the results. Lastly, conclusions are drawn and next research steps are given.

4.2. Material and Method

4.2.1 Experimental sites

The model has been applied to two experimental sites: one pilot scale green roof and a full size single substrate layer green roof. As experiments were carried out independently from the model development, the available data sets do not perfectly coincide with the model data requirements. In particular, some parameters which were not experimentally measured during the monitoring campaigns have been calibrated. These assuption did not actually affect the validity of the main results achieved in this work.

4.2.1.1 HYDROPACK pilot scale green roof

The first experimental site is a 1m^2 HYDROPACK® green roof pilot scale unit. HYDROPACK® is a prefabricated green roof structure (Figure 4.1) manufactured by Le Prieuré - Vegetal i.D. The pre-cultivated vegetation is composed of sedum growing on the top of a 60 mm thick substrate layer. The substrate is a mix of lightweight aggregates and organic material, FLL guidelines compliant (FLL, 2008), that provides aeration, water retention and drainage. Under the substrate layer, there is first a geotextile, like in any standard green roof. Under the geotextile, a plastic box constitutes the alveolus layer. A fraction β (β = 0.30) of this layer is made of alveolus compartments storing water under the substrate layer. The water is entering into the alveolus by gravity from the substrate layer. The alveolus contain clay pellets which are in contact with the above geotextile, allowing the vegetation roots to take water from the alveolus. The clay pellets, in fact, representing a (small) water buffer for the roots which sometimes cross the geotextile filter, also facilitating their the development. The remaining fraction (1-β) is similar to the drainage layer in a standard green roof, i.e. it allows the gravity water from the substrate layer to be evacuated as the roof outflow through drainage holes. This additional water reserve in alveolus increases water retention and drought tolerance of the plants besides limiting runoff.

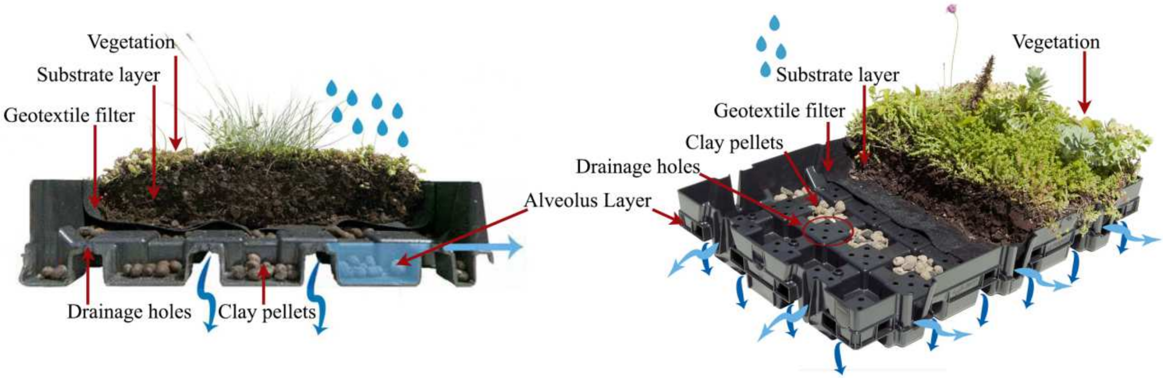

Figure 4.1. HYDROPACK® green roof structure. Left: lateral view. Dark blue arrows represent the drainage runoff from the substrate layer; light blue arrows represent the overflow from the alveolus when they are full; right: global view showing, from top to bottom, the vegetation, the substrate layer, the geotextile filter, the alveolus for water storage and the drainage layer between the alveolus (from: http://www.vegetalid.us/media/images/).

Figure 4.2. HYDROPACK® pilot-scale experimental installation (in the foreground) in Moisy, France (photo LGCIE-DEEP).

The pilot scale unit was installed in Moisy, France as a lysimeter with a weighing device (Figure 4.2). Data were collected by Le Prieuré - Vegetal i.D. from March 2011 to March 2012, with a one minute time step. The weighing system was used to calculate both the rainfall intensity P (positive gradient of the total mass) and the sum of the evapotranspiration ETR (from the vegetated fraction α of the roof) and evaporation EV (from the non-vegetated fraction 1-α of the roof) (negative gradient of the total mass). Only gradients at one minute time step are available in the data set. Consequently, there are no independent measurements of P and $EV+ETR$. Water depth H^A in the alveolus layer was measured independently with a bubbler sensor and subtracted from the total mass of the lysimeter to estimate the water level H^S in the substrate. After processing raw data files, the final data set contains the following information at one minute time step: i) rainfall intensity, ii) sum of evaporation and evapotranspiration and iii) water depth H^S in the substrate. In this study, H^A data were not used for calibration: it will be done in future research work with multi-objective calibration approaches.

In total, the data set initially included 93 rainfall events. After detection of gaps and missing values (Brimo, 2013), 74 rainfall events or periods are available for modelling purposes between March 2011 and March 2012. Only 50 events or periods from May 2011 to February 2012 with sufficient rainfall depth to observe significant variations of the water depth H^S were selected for model calibration: their duration and depth are shown in Figure 4.3 (the Hydrologic Characteristics of Rainfall Events are in the Annexed Table A-4.1). They range respectively from 66 min to 392 hours and from 0.9 to 63 mm. Separate successive rainfall events have been grouped together as rainfall periods when the effects of the successive events on the substrate water level were not independent of one another.

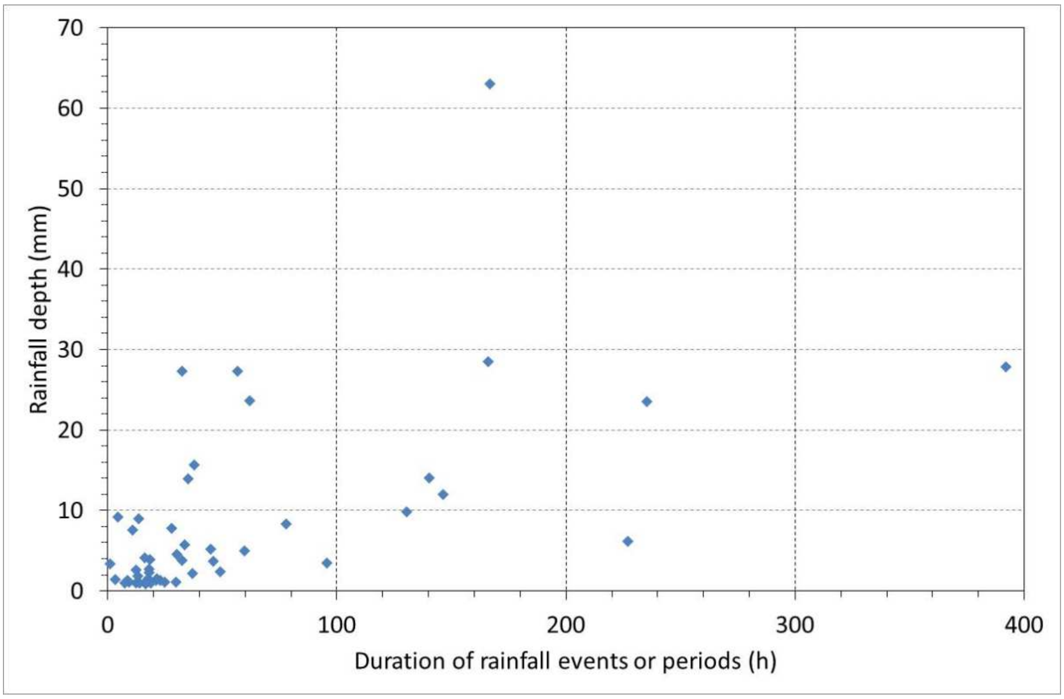

Figure 4.3. Duration and depth of the 50 rainfall events and periods in the HYDROPACK® data set used for calibration.

4.2.1.2 Lyon Congress Centre green roof

The second experimental site is one of the green roofs of the Congress Centre in Lyon, France. This 282.5 m^2 green roof was built in 1995 (Figure **4.4**). It is a traditional extensive green roof planted with sedum growing on a substrate with a depth varying between 40 and 140 mm. The substrate rests on a 50 mm high honeycomb-shaped drainage structure, with a geotextile filter as boundary under the substrate.

Figure 4.4. View of the Lyon Congress Centre green roof (photo LGCIE-DEEP).

The Congress Centre green roof was monitored by LGCIE-DEEP as part of the ECCLAIRA project (Yalamas, 2013). The following equipment was installed: one Précis-Mécanique 0.2 mm tipping bucket rain gauge and two Krohne Optiflux 2000 0 to 5.5 L/s magnetic flow meters located along the two vertical pipes evacuating the runoff from the roof. The vertical pipes were modified to create siphons as the magnetic flow meters need full pipes for measurement (Figure 4.5). All data were recorded in a data logger with a one minute time step. Validated data are available from September 2012 to May 2013, including 146 independent storm events or periods (two successive events are considered as independent of one another if there is at least two hours of dry weather between them and if the green roof outflow following the first event is back to zero before the second event starts) (Bertrand-Krajewski and Vacherie, 2014). Duration and depth of the 146 events or periods are shown in Figure 4.6: they range respectively from 2 min to 148 hours and from 0.2 to 52.4 mm. The longest event with a duration of 148 hours from 15 to 21 January 2013 corresponds to a quick 6-7 cm snowfall followed by slow melting during several days. Excluding this unusual event, the second maximum duration is 34 hours.

Figure 4.5. Monitoring of the Lyon Congress Centre green roof. Left: rain gauge; right:magnetic flow meter (photos LGCIE-DEEP).

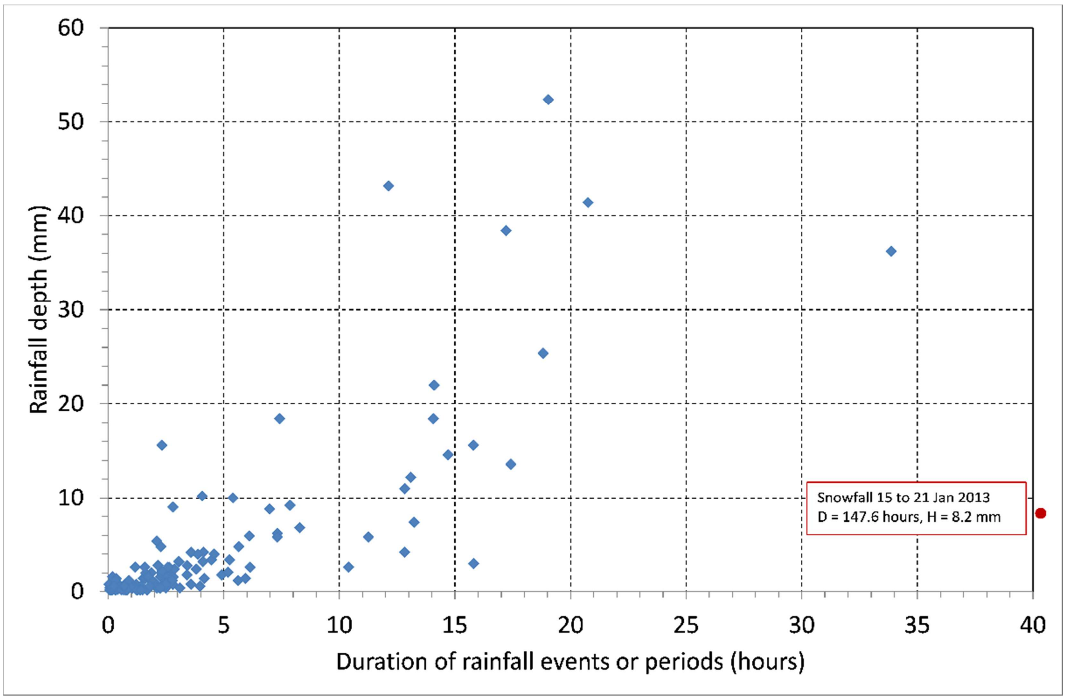

Figure 4.6. Duration and depth of the 146 rainfall events and periods in the Congress Centre data set.

No ETR measurements were done locally at the Congress Centre green roof during the monitoring. Daily ETR values have been provided by the French national meteorological office Météo France for the Bron weather monitoring station located 9 km south-east of the Congress Centre. In addition, hourly values of temperature, wind speed, atmospheric pressure, solar radiation and relative humidity were also provided by Météo France and used to calculate hourly ETR values by means of the Penman-Monteith formula as described in Zotarelli *et al.* (2014). The ETR hourly values have then been i) corrected in such a way that the daily sum of the hourly values is equal to the daily ETR values from Météo France considered as reference values, and ii) linearly interpolated at one minute time step.

The final data set then contains one minute time step records of: i) *in situ* rainfall intensity, ii) calculated potential evapotranspiration, iii) total outflow Q_{obs} evacuated by the green roof. It is organized as 9 monthly files and one full period containing all data from September 2012 to May 2013.

4.2.1.3 HYDROACTIVE® system

The HYDROACTIVE® prototype (formerly STOCK&FLOW®) complements the traditional green roofs solution with a further storage compartment to enable retaining an additional amount of rainfall. The water captured in HYDROACTIVE® is used to irrigate the plants above (plants uptake flow) while slowly being released from the roof to prepare for the next rain event. Figure 4.7 shows the HYDROACTIVE® blue-green roof structure.

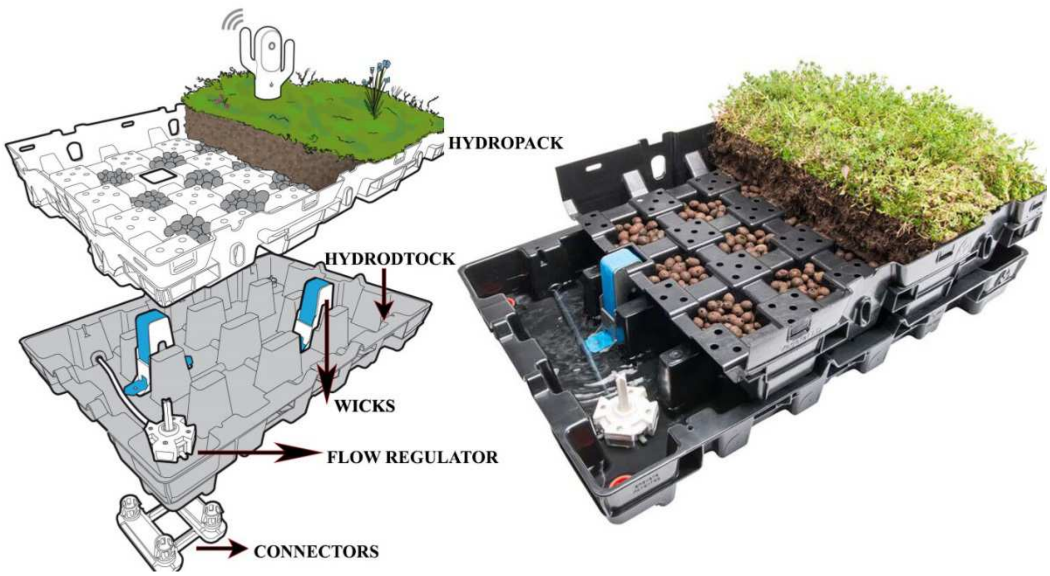

Figure 4.7. HYDROACTIVE® green roof structure.

1. it is designed to increase the delayed effect of rainfall runoff by the presence of the supplementary storage reservoir, which provide more water storage. This additional reservoir allows an increase of vegetation life in rainfall absence because the water stored satisfies irrigation requirements.

2. it is designed also to decrease the rainfall flow peaks thanks to a outflow controller, with the possibility of modulating the outflow. In this way it possible to know how much water goes into the sewer system.

3. through the wicks, it contributes to increase the evapotranspiration capacity by capillarity backflow (as shown in Figure 8 below): the water stored contributes to plants uptake then reducing needed irrigation demand.

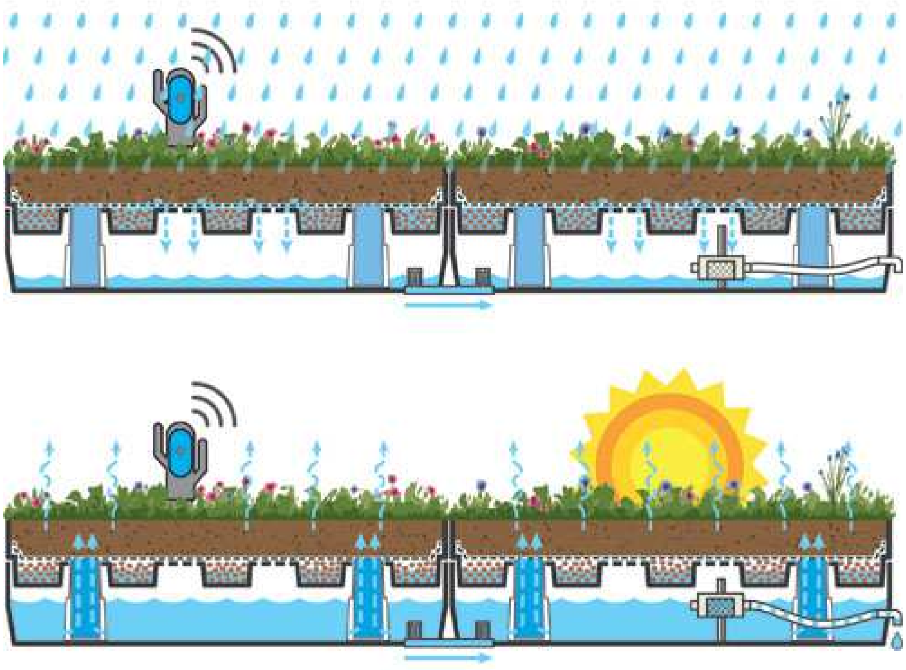

Figure 8. WICKS processes.

4.2.2 The model

The proposed model aims to simulate the hydrological behaviour of various types of green roofs: i) standard single layer green roofs, ii) HYDROPACK® systems (Vegetal i.D., 2014a) and iii) newly developed HYDROACTIVE® systems which include an additional underlying storage (Vegetal i.D., 2014b). It is a semi-detailed conceptual model based on water routing through up to four consecutive reservoirs, each reservoir representing one of the physical layers of real green roof systems and being characterized by a specific hydrological and/or hydraulic process represented by conceptual or semi-detailed equations. As HYDROPACK® and HYDROACTIVE® systems are proprietary systems, no previously published model was appropriate for our particular systems and objectives, and a specific model was thus developed.

The interception reservoir represents the fraction α of the roof covered by vegetation that intercepts an initial fraction of rainfall; the intercepted water than leaves this reservoir by evaporation (EV^I) from the only portion covered by plants. The substrate reservoir represents the soil where vegetation growth; it is filled by rainfall and emptied by 1) both evapotranspiration (ETR^S from the substrate) and evaporation (EV^S from the fraction 1-α not covered by vegetation), and 2) gravity flow into the alveolus and drainage layer. The alveolus reservoir is filled by gravity and emptied by vegetation roots in contact with clay pellets for evapotranspiration. In case the alveolus reservoir reaches its maximum capacity, any additional gravity inflow is evacuated as alveolus overflow. In the additional storage reservoir, further water storage, capillarity backflow to the substrate reservoir by means of wicks and regulated total outflow occurs. The schematic diagram of the complete model is shown in Figure 4.9, with notations given in Table 4.1. The alveolus reservoir and its related functions are activated in the model only for HYDROPACK® and HYDROACTIVE® systems. The storage layer with wicks, still under development, is activated only for HYDROACTIVE® systems.

In this phase of the study, only first applications with maximum three reservoirs are presented (interception, substrate and alveolus reservoirs), the part of the model relative to HYDROACTIVE® system is still in development and will be object of future research. An on-going research project (GEPETO project) will contribute to develop and test equations for the backflow through wicks Q_{BS} and the regulated outflow Q_{BG} for HYDROACTIVE® systems. More in detail, the aim of the GEPETO project (*Gestion des Eaux Pluviales En Toiture*), is to analyze the potential reduction of stormwater volumes to sewer systems through innovative blue-green roofs. It aims to build and monitor the experimental innovative blue-green roofs called HYDROACTIVE®, to show the efficiency in storage capacity, in two different climatic contexts in the catchment area managed by the Water Agency Rhone Mediterranean Corsica: the Temperate climate of Lyon and the Mediterranean climate of Marseille.

The model can be used either at event scale or for continuous simulations. At the present state the model requires local calibration based on experimental data sets, with rain (P) and evapotranspiration (ETR) as known input values (IV), plus initial conditions (IC) and parameters to be calibrated (CP) depending on the green roof type, and substrate water depth (H^S) or outflow from the green roof (Q) as outputs variables (OV) i.e. variables calculated by the model, used for calibration.

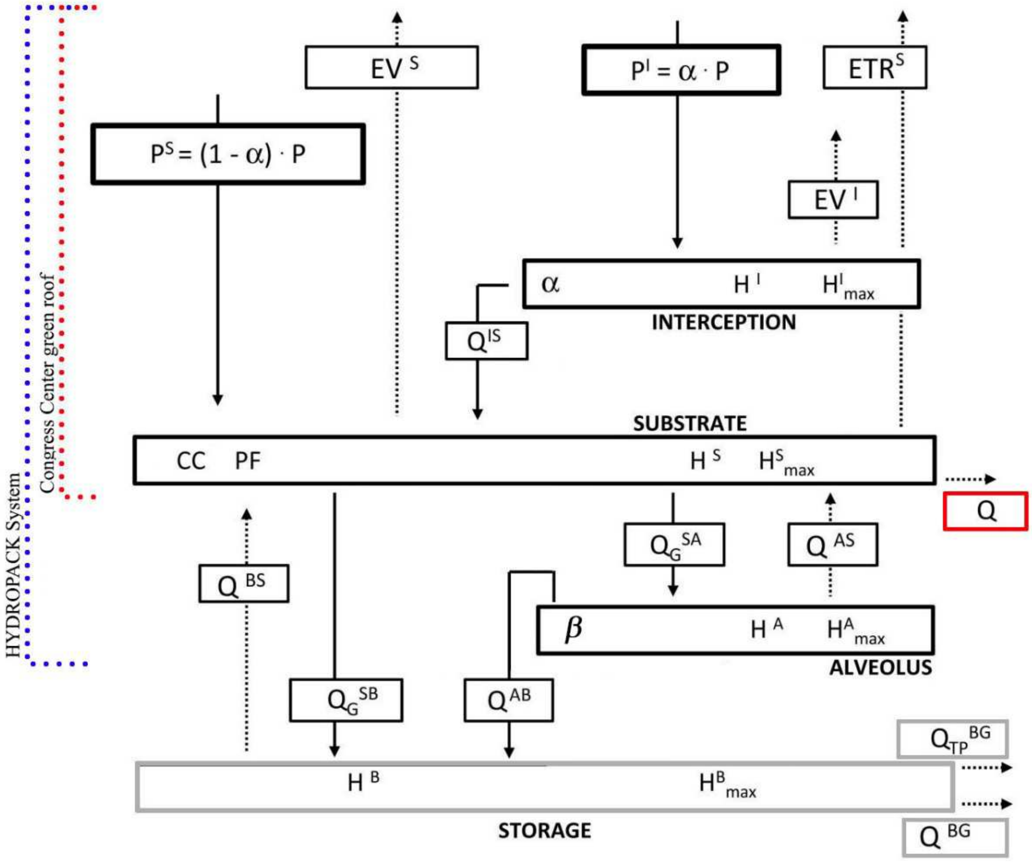

Figure 4.9. Schematic structure of the complete model with four reservoirs; the variable *Q* is only used for the Congress Center green roof. See notations in Table 4.1.

Table 4.1. Notations

Notations	Unit	Type	Definition
			Global variables
ETR	mm.h^{-1}	IV	Potential evapotranspiration rate
P	mm.h^{-1}	IV	Intensity of rainfall
			Interception reservoir
α	%	CP	Percentage of roof covered by vegetation
H^I	mm	OV	Water depth in the interception reservoir
H^I_0	mm	IC	Initial water depth in the interception reservoir at t = 0
H^I_{max}	mm	CP	Maximum water depth in the interception reservoir
Q_e^I	mm.h^{-1}	OV	Inflow to the interception reservoir
EV^I	mm.h^{-1}	OV	Evaporation rate from the interception reservoir
Q^{IS}	mm.h^{-1}	OV	Flow from the interception reservoir into the substrate reservoir
			Substrate reservoir
D	mm	FP	Depth of the substrate reservoir
CC	mm	CP	Field capacity of the substrate reservoir
PF	%	CP	Wilting point of the substrate reservoir
H^S	mm	OV	Water depth in the substrate reservoir
H^S_0	mm	IC	Initial water depth in the substrate reservoir at t = 0
H^S_{max}	mm	CP	Maximum water depth in the substrate reservoir
K_S	mm.h^{-1}	CP	Hydraulic conductivity
$K_{ETR}{}^S$	-	CP	Evapotranspiration correction coefficient
$K_{EV}{}^S$	-	CP	Evaporation correction coefficient
K^{SH}	-	CP	Wilting coefficient
Q_e^S	mm.h^{-1}	OV	Inflow to the substrate reservoir
ETR^S	mm.h^{-1}	OV	Evapotranspiration rate from the substrate reservoir
EV^S	mm.h^{-1}	OV	Evaporation rate from the part of the substrate not covered by vegetation
Q_g^S	mm.h^{-1}	OV	Gravity outflow from the substrate layer
Q_g^{SA}	mm.h^{-1}	OV	Part of the gravity outflow drained from substrate to the alveolus reservoir
Q_g^{SB}	mm.h^{-1}	OV	Part of the gravity outflow drained from substrate to the storage reservoir
Q_s^S	mm.h^{-1}	OV	Total outflow from the substrate reservoir
Q	mm.h^{-1}	OV	Total outflow from the substrate for the Congress Centre green roof
			Alveolus reservoir
β	%	CP	Percentage of alveolus surface under the substrate reservoir
H^A	mm	OV	Water depth in the alveolus reservoir
H^A_0	mm	IC	Initial water depth in the alveolus reservoir at t = 0
H^A_{max}	mm	CP	Maximum water depth in the alveolus reservoir
Q_e^A	mm.h^{-1}	OV	Inflow into the alveolus reservoir
Q^{AS}	mm.h^{-1}	OV	Backflow to the substrate reservoir from the alveolus reservoir
Q^{AB}	mm.h^{-1}	OV	Flow from alveolus reservoir into the storage reservoir
Q_s^A	mm.h^{-1}	OV	Total outflow from the alveolus reservoir
			Storage reservoir
H^B	mm	OV	Water depth in the storage reservoir
H^B_{max}	mm	CP	Maximum water depth in the storage reservoir
Q_e^B	mm.h^{-1}	OV	Inflow into the storage reservoir
Q^{BS}	mm.h^{-1}	OV	Backflow to the substrate reservoir from the storage reservoir through wicks
$Q_{TP}{}^{BG}$	mm.h^{-1}	OV	Overflow from the storage reservoir into the gutter
Q_s^B	mm.h^{-1}	OV	Total outflow from the storage reservoir

Q^{BG}	mm.h^{-1}	OV	Regulated outflow from the storage reservoir into the gutter

The model is developed by assuming that no rain water drains through the substrate to the drainage or alveolus layer as long as the water content is less than the field capacity in the substrate. Only for the HYDROPACK® pilot scale unit, due to the raw data availability, evaporation and evapotranspiration are neglected during rainfall events.

At t = 0 for each simulation, initial values (IV) for water depths H_0^I, H_0^S, H_0^A are given respectively for interception, substrate and alveolus reservoirs. For each time step and each reservoir, water balance is calculated to ensure mass conservation.

Water balance in the interception reservoir

A fraction of the rain is intercepted by vegetation and does not reach the substrate. It is evaporated later on. The flow Q^{IS} = 0 until the interception reservoir is full (H^I = H^I_{max}); then Q^{IS} is equal to the difference between rainfall intensity and evaporation from interception reservoir.

Inflow (i.e. rainfall) $Q_e^I(t)$ is calculated by:

$$Q_e^I(t) = \alpha\, P(t) \qquad \text{Eq. 1}$$

Evaporation of the intercepted fraction of the rain is calculated by (adapted from Deardorff, 1978)

$$EV^I(t) = min\left\{\alpha\, ETR(t)\left(\frac{H^I(t)}{H^I_{max}}\right)^{\frac{2}{3}}, \frac{60}{\Delta t}\, H^I(t)\right\} \qquad \text{Eq. 2}$$

The second term of Eq. 2 prevents the case where evaporation rate would exceed interception storage.

Water balance in the substrate reservoir

The total inflow to the substrate reservoir $Q_e^S(t)$ is the sum of the rain intensity over the not vegetated fraction (1-α) of the roof, the flow leaving the interception reservoir and the backflows from both alveolus and storage reservoirs:

$$Q_e^S(t) = (1 - \alpha)\, P(t) + Q^{IS}(t) + Q^{AS}(t) + Q^{BS}(t) \qquad \text{Eq. 3}$$

If the water storage in the substrate is lower than the field capacity ($H^S(t) < CC$), no water is drained by gravity into alveolus and storage reservoirs:

$$Q_g^{SA} = Q_g^{SB} = 0 \quad \text{Eq. 4}$$

If the field capacity is exceeded ($H^S(t) > CC$), a fraction of the water is drained by gravity from the substrate reservoir into alveolus and storage reservoirs while the rest remains in the substrate reservoir until it becomes completely saturated. The water flow drained by gravity is assumed to be proportional to the water depth in the substrate and is expressed by the Darcy equation:

$$Q_g^S(t) = \frac{K_s}{D} \max\{0, H^S(t) - CC\} \quad \text{Eq. 5}$$

The gravity flow is distributed in alveolus (Q_g^{SA}) and storage reservoirs (Q_g^{SB}) according to the alveolus surface fraction β:

$$Q_g^{SA}(t) = \beta\, Q_g^S(t) \quad \text{Eq. 6}$$

$$Q_g^{SB}(t) = (1-\beta) Q_g^S(t) \quad \text{Eq. 7}$$

This last portion of gravity flow is therefore drained into the storage reservoir through the drainage holes.

Water stress test

The difference (*CC*-*PF*) is the usable soil water reserve (*UR*), which is the amount of water stored in the plant's root zone that can be easily used by the vegetation. To prevent plant water stress an allowable depletion factor is used as a percentage of the total available water which may be safely depleted before water stress occurs; this factor varies but for sedum is usually around 40 % of the total available water which may be safely depleted before moisture stress occurs. For sedum, therefore, it is assumed that when the water depth in the substrate reservoir is below 40 % (K_{SH} = 0.4) of this water reserve, there is no passage of water from roots to plants and then the transpiration of the vegetation can be neglected (Rezaei and Jarret, 2005) and the model considers that the water depth in the substrate reservoir can decrease only by soil evaporation.

Consequently, if $H^S(t) < K_{SH}\ (CC - PF)$, the vegetation is submitted to water stress and EV^S, ETR^S, Q_g^{SA} and Q_g^{SB} are always null, except during dry periods when EV^S is calculated by:

$$EV^S = min\left\{ETR(t)\ K_{EV}^S \left(\frac{H^S(t)}{H_{max}^S}\right)^{\frac{2}{3}}, \frac{60}{\Delta t}\ H^S(t)\right\}$$ Eq. 8

Above these 40 %, based on the modified Lazzarin equation (Lazzarin *et al.*, 2005) evapotranspiration is calculated by the following equation:

$$ETR^S(t) = \alpha\ K_{ETR}^S \left(0.0632\ H^S(t)\ \frac{100}{H_{max}^S} + 0.4668\right) ETR(t)$$ Eq. 9

whereas evaporation from the not vegetated fraction (1-α) of the substrate is estimated by using the same assumption as for the interception reservoir. Evaporation follows an exponential decay with water storage during dry periods:

$$EV^S(t) = (1 - \alpha)\ ETR\ (t) K_{EV}^S \left(\frac{H^S\ (t)}{H_{max}^S}\right)^{\frac{2}{3}}$$ Eq. 10

Finally the total outflow $Q_s^S(t)$ from the substrate is determined by the following equation:

$$Q_S^S(t) = EV^S(t) + ETR^S(t) + Q_g^{SA}(t) + Q_g^{SB}(t)$$ Eq. 11

As there is no alveolus reservoir in the Congress Centre green roof, an additional equation is necessary in this case to estimate the total outflow $Q(t)$ leaving the substrate:

$$Q(t) = Q_g^{SA}(t) + Q_g^{SB}(t)$$ Eq. 12

$Q(t)$ will be compared later on to the discharge $Q_{obs}(t)$ observed at the outlet of the Congress Centre for model calibration.

Water balance in the alveolus reservoir

The inflow $Q_e^A(t)$ in the alveolus reservoir is given by the fraction of the water that is drained by gravity from the substrate reservoir when the macropores of the substrate are full (the field capacity is exceeded).

The backflow $Q^{AS}(t)$ to the substrate reservoir corresponds to the re-filling of the substrate reservoir by vegetation roots in contacts with clay pellets or immersed in the alveolus (some roots cross the geotextile filter) to compensate evaporation and evapotranspiration which occurred during the previous time step. It is given by:

$$Q^{AS}(t) = min\left\{\beta \cdot [EV^S(t-\Delta t) + ETR^S(t-\Delta t)], H^A(t)\frac{60}{\Delta t}\right\}$$ Eq. 13

Water balance in the storage reservoir

The inflow $Q_e^B(t)$ into the storage reservoir is given by:

$$Q_e^B(t) = Q_g^{SB}(t) + Q^{AB}(t)$$ Eq. 14

The backflow $Q^{BS}(t)$ from the storage reservoir to the substrate reservoir will be possible by capillarity thanks to wicks. The wicks are two plastic supports (their height is 50 mm and their width is about 25 mm) on which there is a particular microfiber that allow to the water to rise up from the storage to substrate reservoir. This part of the model is still under development in the GEPETO project and is not part of this study.

The regulated outflow Q^{BG} is either a constant value obtained by means of a specific small control orifice, e.g. set to 3 L/s/ha or, for a more a precise approach, a value varying as a power function of H^B which depends on the type of control system (power functions are determined experimentally in the on-going GEPETO project).

The total outflow from the storage reservoir is then given by:

$$Q_s^B(t) = Q^{BS}(t) + Q^{BG} + Q_{TP}^{BG}(t)$$ Eq. 15

with $Q_{TP}^{BG}(t)$ equal to zero, except if the storage reservoir is full.

4.2.3 Model calibration

The model is calibrated and tested using the data sets collected at both sites. The model parameters are calibrated i) at event scale using 50 (of 74) events or periods and ii) at month scale (including in total 146 rainfall events), for the HYDROPACK® and Congress Centre green roofs respectively. Each of the 2 green roof was calibrated according to 2 different objectives: in terms of water balance (with substrate water depth for the HYDROPACK®) and retention capacity (with roof runoff for the Congress Centre green roof).

The calibration is done by minimizing the objective function *FO* written as follows:

$$FO = \sum_{i=1}^{n}\left(X_{obs,i} - X_{mod,i}\right)^2$$ Eq. 16

with X_{obs} and X_{mod} respectively the observed (i.e. measured) values and modelled (i.e. calculated by the model) values, i the index from 1 to n and n the number of observed values. For the HYDROPACK® and the Congress Centre green roofs, the objective function to be minimized was respectively the sum of the squared i) substrate water depth H^S and ii) the total outflow Q. Minimizing FO is obtained by means of the *LsqNonLin* (Non Linear Least Squares) Matlab® function with the “trust-region-reflective” algorithm (Coleman and Li, 1996).

The Nash-Sutcliffe (NS) criterion (Nash and Sutcliffe, 1970) and the Root Mean Squared Error (RMSE) are used as model performance indicators:

$$NS = 1 - \frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{mod,i}\right)^2}{\sum_{i=1}^{n}\left(X_{obs,i} - \overline{X_{obs}}\right)^2} \qquad \text{Eq. 17}$$

$$RMSE = \left(\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{mod,i}\right)^2}{n}\right)^{\frac{1}{2}} \qquad \text{Eq. 18}$$

with $\overline{X_{obs}}$ the mean value of the $X_{obs,i}$.

NS values range between -∞ and 1.0 and allow comparing calibration and modelling as they are dimensionless. In this study, it is assumed that $NS \geq 0.6$ corresponds to a good match of model results to observed data. $NS = 1$ corresponds to a perfect match. $NS \sim 0$ indicates that the model predictions are not more accurate than the mean of the observed data. $NS < 0$ means that the model is performing poorly and cannot be considered as appropriate.

RMSE values have the same unit as the *X* values: the model performs better when *RMSE* values decrease and tend to zero.

4.3 Results and Discussion

4.3.1. HYDROPACK event scale modelling

The model calibration was done for 50 rainfall events. Fourteen parameters and input variables have been set and/or calibrated. Calibration was carried out with initial values and lower and upper boundaries defined according to green roof characteristics, pre-existing knowledge, preliminary tests and trials and errors. Their values are given in columns 2 to 4 of Table 4.2. Only the substrate depth *D* was set to a constant value of 60 mm after preliminary tests.

The mean values, standard deviations and coefficients of variation of all parameters and input variables are given in Table 4.2 for all 50 events in columns 5 to 7. Corresponding *NS* values are given in Figure 4.12.

Globally, the model performs well: *NS* is equal or higher than 0.6 for 39 events (78 % of the events), and higher than 0.97 for 23 (46 % of the events). Examples of results for two rainfall periods are shown in Figure 4.10 and Figure 4.11: the first period dated from the 8th to the 24th of January 2012 and includes several successive rainfall peaks with corresponding variations of the substrate water level in the range between 20 and 24 mm, while the second period dated 18 to 20 February 2012 shows a single rainfall peak with a very limited and rather flat response of the substrate water depth in the range between 26 and 28 mm. The model is able to simulate the dynamics of the substrate water depth at short time step for most events and periods.

Bad ($0 < NS < 0.14$) and even very bad (negative *NS* values) performances are observed for 9 events: 4 events in May and early June 2011, one at the beginning of September, and 4 events in February 2012. No information was reported in the data set indicating experimental problems or failures, but re-checking the raw data of May and early June 2011 indicates abnormally low response of the substrate water level despite significant rainfall depth, which may reveal a problem with the monitoring system. For the most critical events (lowest negative *NS* values) in February 2012, the Météo France climatologic records (available on the Météo France website) in Ouzouer, a small city 16 km away from Moisy, indicate that air temperatures were constantly negative from 1st to 12th February, with lowest values reaching -15°C on 9th February. These twelve days were exceptionally cold everywhere in the region (Jacq, 2012). Under such cold conditions, the HYDROPOACK® lysimeter weighing system was seriously disturbed: it recorded rainfall events from 5 to 11 February whereas Météo France records indicate the period was completely dry, except a significant snowfall (more than 10 cm locally) on 5th February (Jacq, 2012). The snow could not melt and flow through the substrate due to the very negative temperature. This posterior data analysis (temperature was not available in the HYDROPACK® data set) indicates that biased and not representative data were recorded in the beginning of February 2012.

However, as this information was not known by the authors before modelling was carried out, it was decided to keep the results for the 50 events as this provide interesting information about experimental conditions which may lead to bad model performance.

Whereas *NS* is dimensionless and convenient for comparisons, comparing event model performance is difficult to be done according to *RMSE* values as their order of magnitude varies with the absolute values of rainfall depth and water level in the substrate. However, *RMSE* values range from 0.01 to 1 mm, with a mean value of 0.16 mm, which is very low relatively to the substrate water level which typically range between 5 and 45 mm. The mean relative modelling uncertainty in the substrate water level H^S is typically ranging between 0.3 % and 3 %.

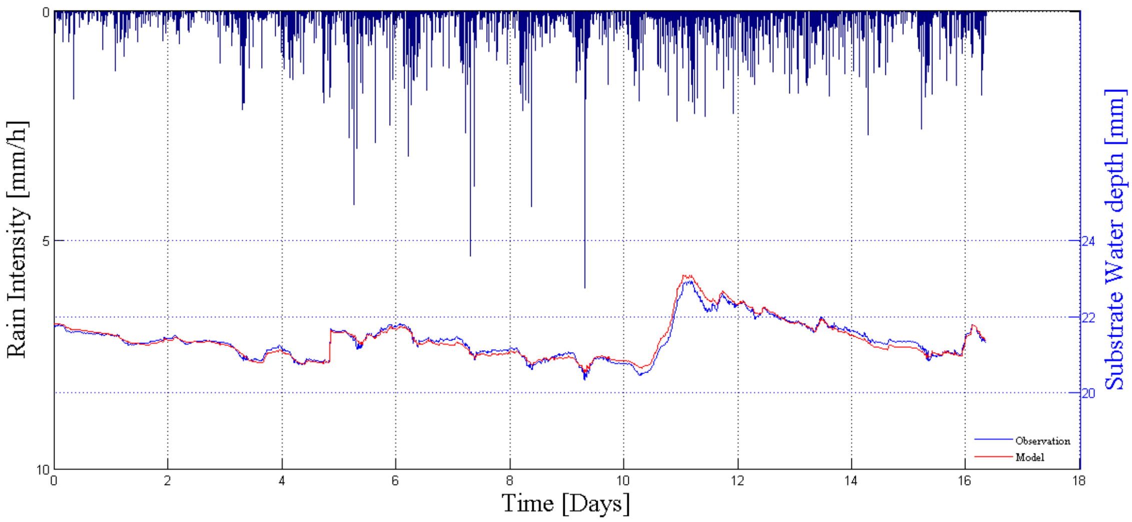

Figure 4.10. Calibration results: Rainfall intensity and modelled (in red) versus observed (in blue) substrate water depth H^S : 8-24 Jan. 2012, *NS* = 0.96, *RMSE* = 0.10 mm. For this event, H^S remains between the wilting point *PF* and the field capacity *CC*, i.e. within the soil water reserve.

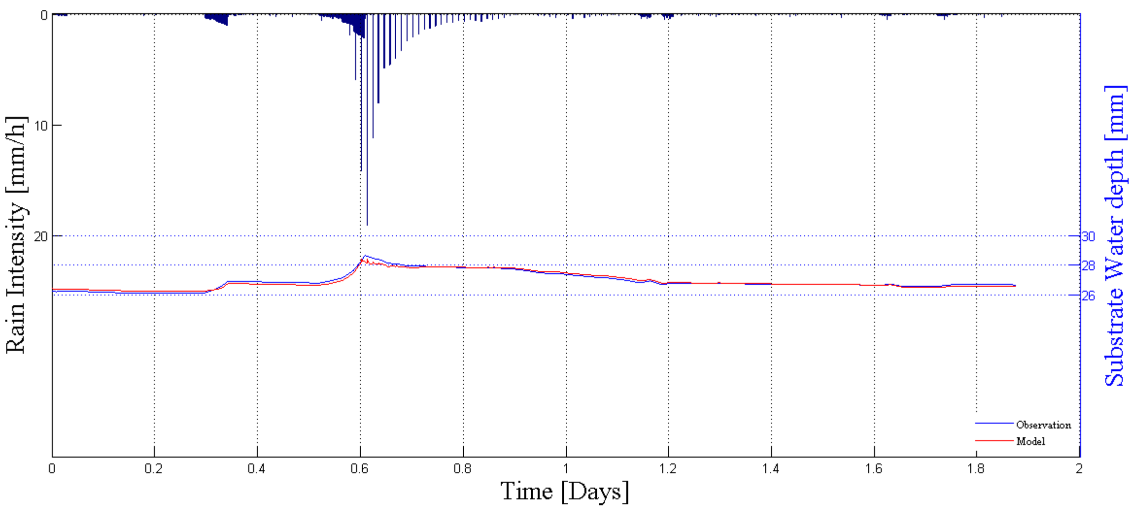

Figure 4.11. Calibration results: Rainfall intensity and modelled (in red) versus observed (in blue) substrate water depth H^S : 18-20 Feb. 2012, *NS* = 0.961, *RMSE* = 0.12 mm. The maximum value of H^S (26.40 mm) remains lower than the field capacity CC (28.13 mm).

Table 4.2 gives mean calibrated values of model parameters and input variables for all 50 events (columns 5 to 7) and for the 39 events with *NS* > 0.6 (columns 8 to 10).

Comparing both cases, it appears that excluding doubtful events with NS < 0.6 logically reduces the inter-event variability of parameters and initial conditions: standard deviations are usually lower in column 9 compared to column 6. Mean values are also slightly different (columns 5 and 8).

As a first approach, the coefficients of variation (column 10 in Table 4.2) can be used to estimate the relative sensitivity of the variables. Initial conditions are crucial for event scale calibration: they integrate the previous rainfall events and dry weather conditions which have led to a given state of the green roof when the rainfall of interest starts. The highest CV value (1.86) is observed for the initial water depth in the interception reservoir H_0^I. Nevertheless, this high value of CV is mainly due to the fact that the mean value of H_0^I is equal to 0.07 and close to zero: in practice, H_0^I is not as important as its CV may indicate, except for storm events with very small rainfall depth. For most events, H_0^A and H_0^S are crucial to obtain good modelling results: their CV values are respectively equal to 0.70 and 0.43.

Among the model parameters, the two most sensitive ones are the empirical coefficients K_{EV}^S and K_{ETR}^S, with respective CV values of 1.03 and 0.53. Previous authors indicated that such empirical coefficients are not an optimal solution (Voyde, 2011). Instead of setting *a priori* values, they were used as calibration parameters in this first version of the model. The variability of these parameters could partly reflect the seasonal variability of the green roof response to storm events due to changes of the green roof state (vegetation coverage, substrate conditions, vegetation state and evapotranspiration capacity…) which are not explicitly accounted for and represented in the model.

Other parameters are less sensitive (CV values between 0 and 0.5), except β the percentage of the alveolus coverage under the substrate with CV = 0.58. Initially, β was supposed to be a fixed value representing the geometry of the green roof system. However, *in situ* observations show that vegetation roots grow preferentially above the alveolus, and that even vegetation which is not planted just above alveolus tend to develop roots toward alveolus areas, as access to water is easier from alveolus compared to the substrate. Accordingly, another hypothesis could be formulated and should be tested with future experiments: β is not only a geometrical characteristic of the green roof system but, as roots develop with time, β may also evolve with vegetation and change over months and seasons.

Lastly, some parameters are constant in all simulations: H_{max}^{A}, PF and K^{SH}.

Table 4.2. Input variables and parameters values used for HYDROPACK® calibration. Columns 2 to 4: starting value, lower and upper boundaries. Columns 5 to 7: mean value, standard deviation and coefficient of variation for all 50 events. Columns 8 to 10: mean value, standard deviation and coefficient of variation for the 39 events with *NS* ≥ 0.6.

1	2	3	4	5	6	7	8	9	10
				all 50 events			events with *NS* > 0.6		
Variable	**Starting value**	**Lower boundary**	**Upper boundary**	**Mean**	**Std**	**CV**	**Mean**	**Std**	**CV**
H_0^I	0	0	1	0.16	0.28	1.84	0.07	0.13	1.86
H_0^S	32.5	0	0.8*D	20.14	9.13	0.45	16.9	7.28	0.43
H_0^A	0.8	0	10	1.47	1.07	0.73	1.57	1.10	0.70
H_{max}^I	0.4	0.3	1	0.40	0.20	0.48	0.42	0.21	0.51
H_{max}^S	36	20	0.8*D	40.94	6.17	0.15	39.9	6.16	0.15
H_{max}^A	15	0.5	15	15	0	0	15	0	0
D	60	Constant value		60	0	0	60	0	0
CC	24	0.1	30	21.48	7.28	0.34	19.5	6.87	0.35
PF	2	0	2	2	0	0	2	0	0
K^{SH}	0.4	0.1	0.8	0.40	0	0	0.40	0	0
K_S	2000	1000	3600	2264	873	0.39	2557	719	0.28
${K_{EV}}^S$	0.7	0	2	0.50	0.58	1.16	0.59	0.61	1.03
${K_{ETR}}^S$	1.2	0	2	0.53	0.38	0.72	0.63	0.34	0.53
α	0.7	0.5	0.9	0.57	0.13	0.23	0.58	0.14	0.24
β	0.3	0.1	0.6	0.35	0.19	0.54	0.29	0.17	0.58

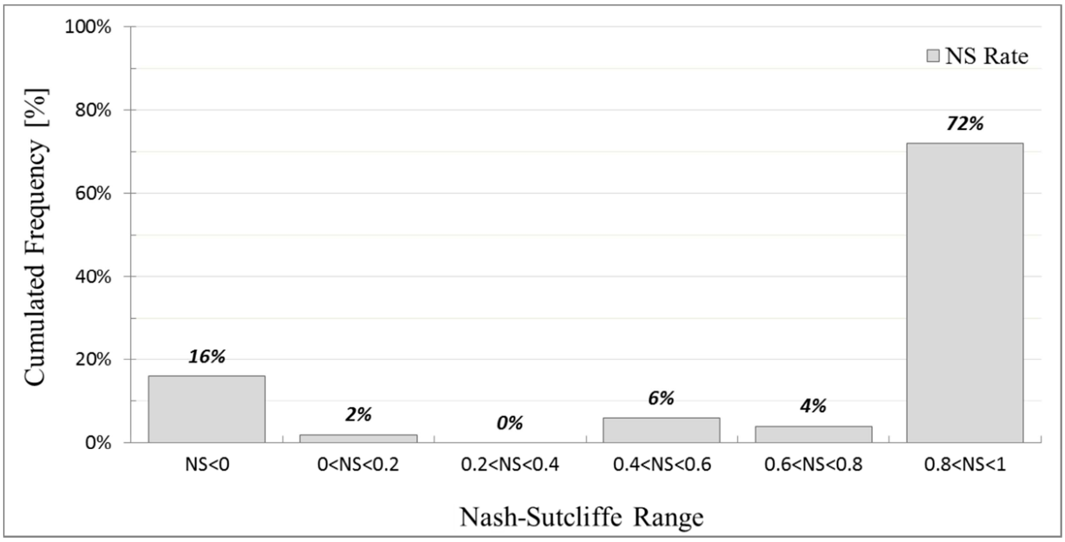

Figure 4.12. Cumulated distribution of *NS* values after calibration for all 50 events for the HYDROPACK® system.

Table 4.3. Matrix of correlation for the 39 events with *NS* > 0.6.

Variable	H_0^S	CC	H_{max}^S	K_S	${K_{EV}}^S$	${K_{ETR}}^S$
H_0^S	**1**					
CC	**0.81**	**1**				
H_{max}^S	0.44	**0.50**	**1**			
K_S	-0.36	-0.42	-0.01	**1**		
${K_{EV}}^S$	-0.25	-0.12	0.22	0.22	**1**	
${K_{ETR}}^S$	**-0.52**	**-0.51**	-0.41	0.00	0.17	**1**

In addition, coefficients of correlation r between model parameters and input variables for the 39 events with $NS > 0.6$ are given in Table 4.3. Only r values lower than -0.5 or higher than +0.5 are considered significant for the analysis: the four corresponding coefficients appear in bold characters in Table 4.3.

There are a positive correlation (r = 0.81) between CC (field capacity) and H_0^S, and (r = 0.5) between CC (field capacity) and H_{max}^S, two negative ones (r = -0.52) between H_0^S and K_{ETR} and (r = -0.51) between CC and K_{ETR} (ETR correction coefficient). The field capacity can be considered as a constant value representing the substrate characteristics. However, in the model calibration, it was decided to keep CC as a calibration parameter. The consequence is that when H_0^S increases to reflect the initial water content of the substrate at the beginning of the simulated storm event, CC also increases and K_S decreases to allow a high water content in the substrate. This interaction is also indicated by the negative correlation coefficient (r = -0.42) between CC and K_S which is just below the conventional threshold of significance (±0.5).

The other coefficients of correlations are below the significance threshold, indicating weak or no correlation between the model variables.

4.3.2. Lyon Congress Centre monthly continuous modelling

For the Lyon Congress Centre, model calibration was performed monthly with the 9 consecutive months from September 2013 to May 2013 and globally for the whole period in order to simulate the green roof outflow. Initial values are given at the beginning of each month (resp. the whole period) and the set of calibrated parameters is used without modification for all events in each month (resp. the whole period). Values of parameters and input variables used for calibration are based on preliminary tests and trials and errors. They are given in Table 4.4 (columns 2 to 4), as well as final calibrated values for the 9 months and for the whole period (columns 5 to 7). As there is nothing equivalent to the HYDROPACK® alveolus layer in the Congress Centre green roof, all alveolus components were replaced by zeros in the model and corresponding values do not appear in Table 4.4.

The Nash-Sutcliffe index (*NS*) and the Root Mean Square Error (*RMSE*) values are reported in Table 4.5.

Table 4.4. Input variables and parameters values used for Lyon Congress Centre calibration. Columns 2 to 4: starting value, lower and upper boundaries. Columns 5 to 7: mean value, standard deviation and coefficient of variation for all 9 months.

1	2	3	4	5	6	7
Variable	**Starting value**	**Lower boundary**	**Upper boundary**	**Mean**	**Std**	**CV**
H_0^I	0	0	1	0.04	0.13	2.81
H_0^S	32.5	0	0.8*D	29.70	12.87	0.43
H_{max}^I	0.4	0.3	1	0.65	0.31	0.48
H_{max}^S	36	20	0.8*D	54.90	22.22	0.40
D	140	Constant Value		140	0	0
CC	24	0.1	60	33.24	11.40	0.34
PF	2	0	10	2.00	0.00	0.00
K^{SH}	0.4	0.1	0.8	0.40	0.00	0.00
K_S	2000	1000	3600	1177.87	353.55	0.30
$K_{EV}{}^S$	0.7	0	2	0.53	0.61	1.15
$K_{ETR}{}^S$	1.2	0	2	1.02	0.40	0.39
α	0.7	0.5	0.9	0.73	0.13	0.18

Table 4.4 shows that *D* was set to a constant value equal to 140 mm, i.e. the maximum substrate depth. Previous simulations with flexible *D* values between 40 and 140 mm revealed that the highest value was systematically the most appropriate to reproduce the observations. The range 40 to 140 mm was given in reports describing the green roof built in 1995 but was not measured *in situ* during the experiments.

The CV values (column 7) are globally similar or lower than in the HYDROPACK® case, except for H_0^I (CV = 2.81) but here again this high value is mainly due to the fact that the mean H_0^I value (0.04) is close to zero. One should note that the CV values are based on 9 monthly calibrations only while CV values in Table 4.2 are based on 39 events calibrated individually, which very likely leads to a larger dispersion of calibrated variables.

The most variable parameters remain the same as at event scale: the initial condition H_0^S (CV = 0.43), and the empirical coefficients K_{EV}^S and K_{ETP}^S, with respective CV values of 1.15 and 0.39. As in the previous case, PF and K^{SH} remain equal to their initial values.

Table 4.5. Experimental data, *NS* and *RMSE* values after calibration for the 9 months and the whole period for the Lyon Congress Centre green roof. Italic values correspond to poor calibration performance (*NS* < 0.6).

Period	Number of rainfall events	Rainfall depth [mm]	Outflow volume [mm]	Retention efficiency [%]	*NS* [-]	*RMSE* [mm/h]
September 2012	6	67.4	43.7	35.1	0.663	0.46
October 2012	17	37.4	3.5	90.6	*-0.022*	0.04
November 2012	10	122.2	101.6	16.9	0.740	0.27
December 2012	29	42.2	22.6	46.4	*0.299*	0.15
January 2013	13	43.5	23.9	45.1	*-0.033*	0.18
February 2013	19	45.8	27.9	39.1	*0.254*	0.17
March 2013	15	52.6	13.9	73.5	*0.371*	0.09
April 2013	22	101.2	52.8	47.8	0.695	0.16
May 2013	15	111.8	88.0	21.3	*0.582*	0.32
Sept 2012 - May 2013	146	624	378	39.4	0.591	0.22

Table 4.5 shows *NS* values which may be grouped in two categories: i) good modelling performance (*NS* values close to and higher than 0.6) for 4 months (Sept. 2012, Nov. 2012, April 2013 and also May 2013) and for the whole period Sept. 2012 to May 2013, ii) poor modelling performance (*NS* values lower than 0.4) for 5 months (Oct. 2012, Dec. 2012, Jan., Feb. and March 2013). Figure 4.13 and Figure 4.14 show one example from each category, respectively November 2012 and February 2013.

In November 2012, the ten observed rainfall events correspond to a monthly rainfall depth of 122.2 mm and the monthly outflow volume is equivalent to 101.6 mm. The corresponding retention efficiency is 16.9 %, which is the lowest measured value. November 2012 was very rainy and outflow was significant. Four events generate outflow: Figure 4.13 shows that the model is able to reproduce rather well the dynamics of the observations (*NS* = 0.74), with a lower performance for the second event on 8-9 November. For this second event, the model under-estimates the initial runoff; and over-estimates the peak; this may due to the fact that the model is not able to accurately predict the available Retention capacity of the substrate layer at the beginning of the second event. A separate individual calibration for this second event (results not shown here) reveals a much better ability of the model to simulate the observed values. The main hypothesis to explain the lower ability of the model is that the initial conditions at the beginning of the second event are not well predicted by the global monthly calibration.

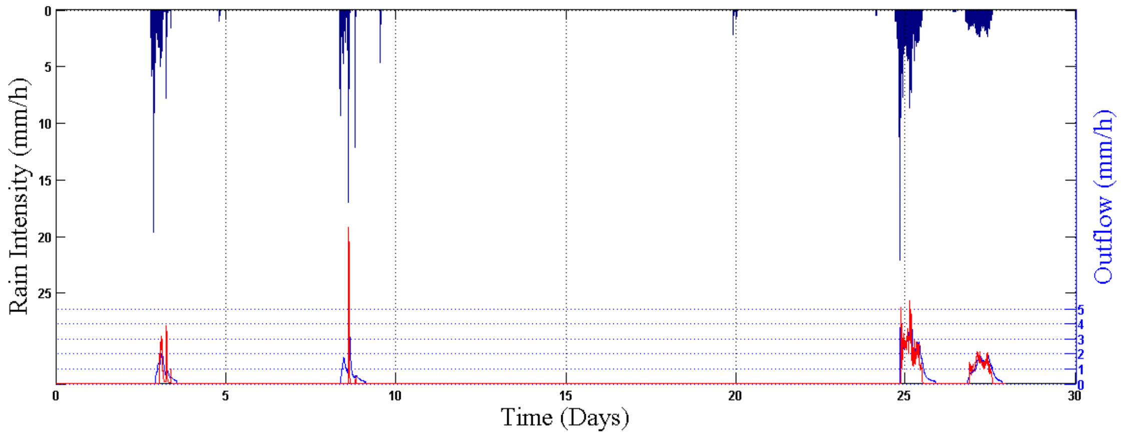

Figure 4.13. Calibration results: Rainfall intensity and modelled (in red) versus observed (in blue) outflow Q^S : November 2012, *NS* = 0.74, *RMSE* = 0.27 mm/h.

In February 2013, the 19 observed rainfall events correspond to a monthly rainfall depth of 45.8 mm and the monthly outflow volume is equivalent to 27.9 mm. The corresponding retention efficiency is 39.1 %, which is equivalent to the mean efficiency over the whole period (39.4 %). Figure 4.14 shows that seven events generate measurable outflow during the first half of the month but that the model is able to reproduce only the last one. For the six previous events, the model does not generate overflow at all. This explains the corresponding low *NS* value equal to 0.25.

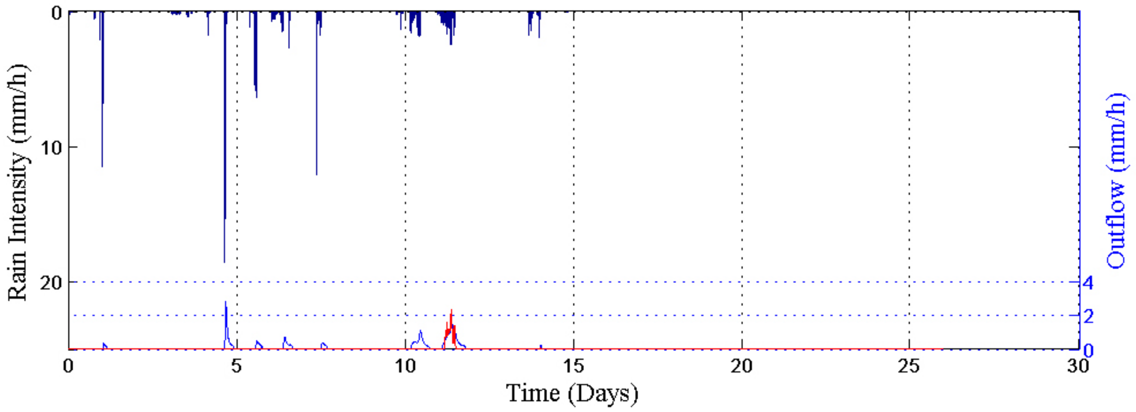

Figure 4.14. Calibration results: Rainfall intensity and modelled (in red) versus observed (in blue) outflow Q^S : February 2013, *NS* = 0.25, *RMSE* = 0.17 mm/h.

A more detailed analysis of the data and figures for all 9 months indicates that:

i) *NS* values are near or above 0.6 for months with rainfall depth above 60 mm, significant rainfall intensities, and observed outflow peaks greater than 3 mm/h.

ii) Reciprocally, *NS* values are lower than 0.4 for months with rainfall depth under 60 mm, low rainfall intensities and observed outflow peaks less than 3 mm/h.

iii) For all measured outflow periods, the modelled outflow diminishes and is back to zero at the end of rainfall events faster than measurements. In case of significant events (months with $NS > 0.6$), outflow peak values are slightly greater than the measured ones.

iv) For small and low events (months with $NS < 0.4$), the model underestimates the outflow and frequently does not generate any outflow.

Consequently, it appears that the model is able to satisfactorily reproduce the observations when rainfall intensity and depth are large enough. The fact that outflow systematically ends earlier than observations could be explained by three complementary assumptions. The first one is linked to the fact that the model considers an instantaneous water transfer from the substrate bottom to the outflow measurement point: this is acceptable for a 1 m^2 roof like the HYDROPACK® pilot scale system, but it is too simplistic for the 282.5 m^2 Congress Centre green roof with long distances between the extremities of the green roof and the outflow measurement point.

The second hypothesis is linked to the fact that the outflow volume is frequently underestimated, especially for small rainfall events and low intensities. The green roof periphery is equipped with a narrow path, approximately 0.3-0.4 m wide, between the green roof and the external wall of the building (see Figure 4.5 left). This impervious path also collects rainfall and the runoff is evacuated by the same pipes as the water leaving the green roof substrate. This additional runoff, which is not included in the present model including only the green roof area, is generated even for small storm events. This additional contribution is measured by the flowmeter. For small events, most rainfall may be intercepted by the green roof, but this additional runoff from the peripheral path may create low but detectable outflow peaks. This may explain the difference between modelling results and measurements.

The third hypothesis is linked to the estimation of ETR. The rainfall is measured locally on the green roof, but ETR is calculated from hourly meteorological data measured in Bron, 9 km away from the city centre where the Congress Centre green roof is located, and then linearly interpolated to a 1 minute time step. Maybe true local (but unknown) and remote ETR estimation may differ significantly at 1 minute step. In addition, ETR was calculated by using the global radiation (available data) and not the net radiation, which may contribute to overestimate ETR (DiGiovanni *et al.*, 2013), which has a greater relative influence for small rainfall events with low rainfall intensities. In theory, this could be compensated by the empirical coefficients K_{EV}^{S} and K_{ETR}^{S} but further tests should help to improve the model.

After the above calibration tests, the 9 month observation period was then divided into two sub-periods: Sept. 2012 to Jan. 2013 (5 months) for calibration, and Feb. to May 2013 (4 months) for verification. The verification was carried out using as input parameters the values obtained by the calibration for 5 months. Compared to NS value for the whole period of 9 months (NS = 0.59), the efficiency grew for the calibration sub-period (NS = 0.64) and slightly decreased for the verification sub-period (NS = 0.50).

4.4 Conclusions and Perspectives

A conceptual hydrological model is proposed for both traditional and innovative multi-layer green roofs. The structure of the model is generic, based on reservoirs, transfer functions and mass balances, and can be adapted to each type of green roof by activating specific reservoirs and functions in the model. The model aims to simulate the dynamics of green roof hydrological processes with 1 minute time step for time scales ranging from one rainfall event to one year or more.

Like any conceptual model, a site specific calibration is required. The first version of the model was calibrated with data sets for two cases: i) a 1 m^2 HYDROPACK® pilot scale green roof system, ii) a 282.5 m^2 single substrate layer traditional green roof.

In the first case, calibration was carried out at event scale for the water level H^S in the substrate with a data set of 50 individual events. For 39 events with reliable data, the model was able to simulate the dynamics of H^S, with *NS* values equal or higher than 0.6. For the last 9 events, the model did not performed satisfactorily, due to doubts in data reliability (4 events) and/or to exceptional negative temperature conditions and snowfall (4 events). At event scale, the most sensitive variables in the model are the initial conditions, which vary from event to event and depend in a complex way on the succession of antecedent of rainfall events and dry weather periods. The two empirical coefficients K_{EV}^{S} and K_{ETR}^{S}, which are used to fit evaporation and evapotranspiration processes, are the most sensitive model parameters.

In the second case, calibration was carried out at month scale for the total outflow Q^S from the green roof, for 9 months individually and for the whole period Sept. 2012 –

May 2013. For 4 individual months and for the whole period, the model was able to simulate correctly the dynamics of Q^S with *NS* values close to or higher than 0.6. For the other 5 months, which show much smaller rainfall events with lower depth and intensities, the model performs less satisfactorily, with *NS* values lower than 0.4. The analysis of the results allowed to propose possible explanations (additional external runoff, distant instead of local ETR data). Most sensitive model variables and parameters are the same as in the first case.

Further research work will include the following points:

i) Development of specific equations to simulate new HYDROACTIVE® green roofs with additional storage, regulated outflow and backflow to the substrate by means of wicks.

ii) Model testing, multi-objective calibration and multivariate sensitivity analysis with new and more comprehensive and accurate data sets which will be collected in 2015-2016 in two experimental sites in France (GEPETO project) for both HYDROPACK® and HYDROACTIVE® systems.

iii) Improvements of the model to account for the first findings obtained with the above two case studies:

  a. Alternative functions to replace the empirical coefficients K_{EV}^{S} and K_{ETR}^{S};
  b. Discretisation of large green roofs into elementary units and propagation of flow between elementary units and to the roof outlet to better account for flow peak attenuation and delay.

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Chapter 5 – UNICAL Case Study: Development of a SIGMA DRAIN Model for an extensive Vegetated Roof

5.1 Introduction

The use of LID (Low Impact Development) as storm water management techniques has assumed increased importance in recent years (Sitzenfrei et al., 2013). Despite the benefits are large and well known, the transition to sustainable urban drainage systems is very slow (Piro et al., 2012). The lack of adequate modeling and analysis tools for is a limiting factor in the diffusion of such systems (Elliott & Trowsdale, 2007).

Green roof represent one of the most diffused LID, but due to their morphological complexity, green roof's analysis requires specific modeling techniques that take into account the complex physical phenomena involved. Storm water management performance of a green roof may differ in various climatic regions due to the specific precipitation climatology, building practices and green roof materials.

A modelling approach for the simulation of green roof rainfall-runoff will be presented in this chapter. From a practical point of view, the modelling part of this research is intended to provide a tool for practitioners, regulators and policymakers requiring objective quantitative performance data, to inform on the development of stormwater management strategies, and to improve decision-making and design of sustainable stormwater drainage systems in a Mediterranean climate conditions.

The overall aim of the present phase of the research is to investigate the hydrologic response of the green roof installed at University of Calabria on a rainfall event basis. The first specific objective is to implement a conceptual model to simulate the hydrologic behavior of the system; which is calibrated and validated based on experimental data collected at the green roof site. The second objective is to characterize the hydrologic performance of the green roof system based on suitable synthetic variables (such as the retained volume, peak flow reduction, and delay in starting runoff). Therefore, the expected result of this phase of the research is to develop - and demonstrate the value of - a conceptual model to understanding the influence of both climate and roof configuration on the hydrologic performance of green roof systems.

More in detail, after an initial description of the experimental site, the SIGMA DRAIN (SD) model conceptualization, in paragraph 5.2.3, will address a mathematical description of the governing flow equations and the selected hydraulic model. An initial specification of the boundary conditions, the hydrological process parameters and the soil hydraulic parameters will be presented in paragraph 5.2.3.2. After this, the model parameters will be calibrated . In the final validation phase (paragraph 5.3.1) of the model, green roof model simulations will be compared to green roof modeled with HYDRUS-1D software - used as a benchmark - outside the calibration period in order to demonstrate whether the SD model gives a reasonable representation of the hydrological/hydraulic behaviour of the considered green roof.

5.2 Materials and method

In order to investigate the hydrologic response of a green roof in the Mediterranean climate, the University of Calabria, within the Project “Integrated and Sustainable Management service for the water-energy cycle in urban drainage systems” (PON01_02543) of the National Operational Program - Research and Competitiveness 2007/2013, co-financed by the European Regional Development Fund and the National Resources Grant, has designed and implemented a full-scale experimental green roof in the University of Calabria, Italy.

Fig. 5.1 The Green Roof Experimental site at University of Calabria

5.2.1 Experimental site

The study was performed on the experimental site at the Cube 46/C of University of Calabria (Unical), Italy. The test site, situated on a fifth-floor terrace of a campus’s building, is located in a Mediterranean climate region, characterized by a hot-dry summers and cool-wet winters a strongly seasonal rainfall with an annual average of 1000 mm. High temperatures during the summer average 27°C (Carbone et al. 2015 a).

The vegetated roof consists of four compartments, each one with an equal area of around 50 m^2 and a slope of 1%, which vary in their stratigraphy, composition elements and the presence, or not, of vegetation species.

Fig. 5.2 The 4 compartments of the Unical Experimental site.

Sectors 1 and 2 are vegetated and consist of the following stratigraphy: 1) native Mediterranean vegetation species as *Carpobrotus edulis*, *Dianthus gratianopolitanus*, *Cerastium tomentosum* ; 2) a soil substrate of 8 cm; 3) a ‘egg box’ drainage and storage layer in polystyrene (with a storage capacity of 11 L/m^2) and in pe-ad (with a storage capacity of 8.7 L/m^2), respectively for the first and second compartment. A fine fibrous membrane was also placed between the substrate and the underlying drainage layer. The cross section of the 2 stratigraphies is shown in Figure 5.3. On sector 3 vegetation is spontaneous, thanks to the seeds carried by wind and grown on the substrate (Carbone et al. 2015 a).

Fig. 5.3 A View and the Cross Sections of Sectors 1 and 2 of the Unical Experimental site; on the right and on the left respectively.

The soil, consisting of volcanic lapillus, pumice, broken bricks and zeolites, enriched with organic matter, including peat, composted plant residues, is extremely draining and clay-free, with a good resistance to compaction and volume reduction (Carbone et al., 2014a). This mineral terrain substrate is built to comply with Italian regulation (UNI 11235): (1) anchoring the root; (2) preventing standing water on the surface; (3) water and nutritional supply; (4) root respiration and life of the microorganisms present.

Finally, the fourth compartment represents the reference roof (a conventional roof), covered by a pre-existing waterproofing layer and equipped with four temperature sensors and a flow meter device at the outlet section.

In this study only one of the four sectors was considered, in detail the one characterized by the drainage and storage layer in polystyrene. A picture and a transverse stratigraphy of the considered compartment is shown in Figure likewise (Fig. 5.4).

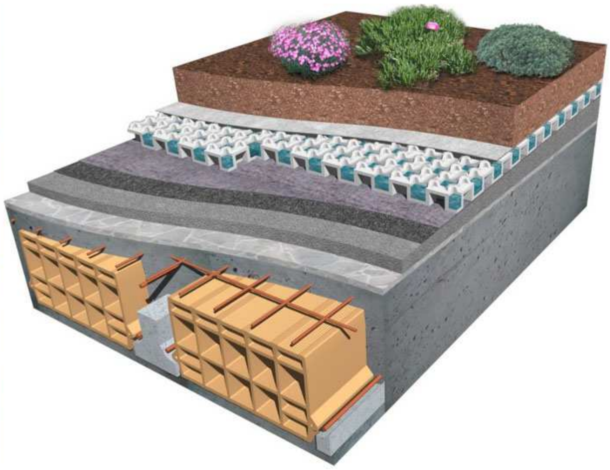

Fig. 5.4 A picture and a transverse stratigraphy of the compartment considered in this study.

The experimental site is a modern technological system fully equipped with hydraulic and thermal sensors; in addition to the green roof monitoring equipment, a *MeteoSense 2.0* weather station (developed and produced by Netsens s.r.l.) was installed atop the roof to monitor environmental conditions on site and in real time. The weather station, which provides climatic measurements at 5 minutes time steps, is equipped also with a *Rain collector* with a 0.2 mm resolution and tipping bucket principle.

5.2.2 Data Analysis

Precipitation data, consisting of rainfall depth recorded with minute frequency, were collected from two different sites: Green Roof of University of Calabria (Italy) and Green Roof of the Lyon Congress Center (France), located respectively in Mediterranean and Temperate climate conditions. In order to analyze the influence of hydrologic parameters on the efficiency of the green roof, under different climate conditions, it was needed to define each rainfall event in the data sets with time resolution of 1 minute.

For both sites, despite having both rain gauge a resolution of 0.2 mm, only events with rainfall depth greater than 2 mm were selected, based on the assumption that rainfall events less than 2 mm are unlike to produce runoff from a conventional roof (Voyde et al., 2010; Stovin et al., 2012).

Moreover, in a second phase, it was needed to estimate the specific inter-event time to define each independent rainfall event. To separate a storm event from the other, *Minimum Inter-event Time* (MIT) criterion was chosen. Minimum Inter-event Time is defined as the elapsed time between the end of a storm event and the beginning of the next so that a rain event can be considered independent from the consequent one. Often the choice of a particular value of MIT was related to physical parameters changes that competed in the definition of independent rainfall events (Carbone et al., 2015 b). This value therefore has never been unique but closely related to the type of analysis or observation of a particular natural phenomenon; for example Stovin et al. (2012) consider a period equal to 6 hours, as it was done by the authors such as VanWoert et al. (2005), Getter et al. (2007) and Voyde et al (2010). However, the use of 6 h is not universal.

It is clear that the way in which a storm event is defined will significantly influence any conclusions reached about the overall retention and detention performance of the green roof. For example, short Antecedent Dry Weather Periods (ADWPs) between storm events (period with no rain) may result in lower mean retention per event than for longer ADWPs. Conversely, if the smallest events are completely excluded from analysis, many events with 100% retention will be eliminated, and the mean retention percentage per storm event may be reduced as a consequence (Stovin et al., 2012).

In this study, individual events were defined as being separated by continuous dry periods of at least two hours; rainfall events separated by less than 2 hours were merged and considered as single event. Using this value of MIT and considering a volume threshold of 2 mm, a number of rainfall events were selected from each datasets. In specific, under these conditions, a total of 70 and 50 rainfall events, recorded respectively at Unical and Lyon site, were identified and then used in the analysis. Since the experimental site is installed in an area with a Mediterranean climate, characterized by precipitations which mostly result distributed in the autumn and winter season, the data collected in the period between September and April were considered.

More in detail, 70 rainfall events, during the whole period between September 2013 and April 2014, were identified for the experimental site at Unical; their duration and depth are shown in the Figure below.

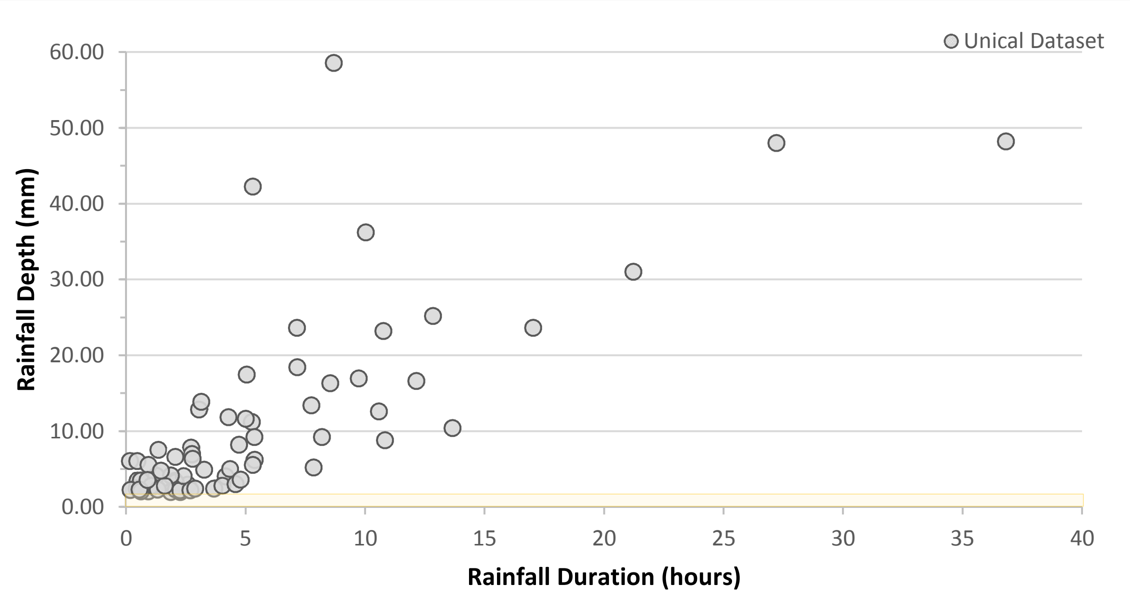

Figure 5.5 Duration and depth of the 70 rainfall events of the Unical data set used for analysis.

The Lyon data set, instead, includes 50 rainfall events collected between September 2012 and April 2013; their duration and depth are reported in the Figure below.

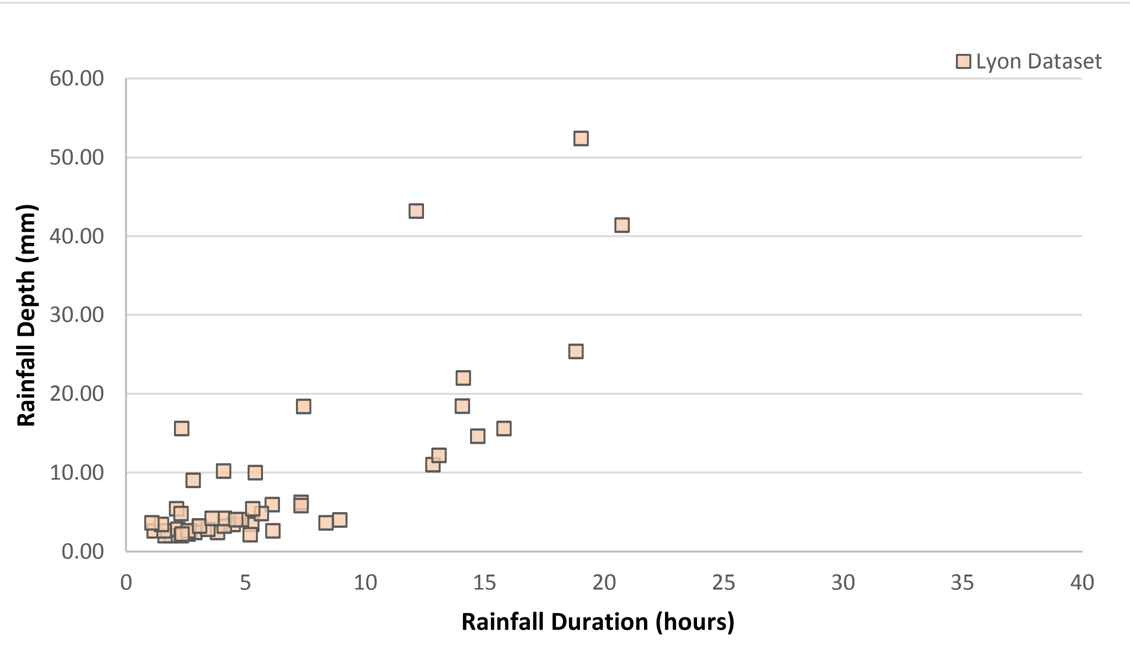

Figure 5.6 Duration and depth of the 50 rainfall events of the Lyon data set used for analysis.

For each event the following five storm parameters were evaluated: Rainfall Depth (mm, h tot); Rain Duration (hours, d); Mean Rainfall intensity (mm/h_i); Antecedent Dry weather period (hours_ADWP). The main hydrological characteristics of selected rainfall events, are reported in the annexed Tables (Table A-5.1 and Table A-5.2), respectively for the two scenarios (Italy and France).

5.2.3 SIGMA DRAIN Model

The *SIGMA DRAIN* conceptual model, is a new tool developed to simulate the hydraulic response of the extensive vegetated roof installed at the University of Calabria, realized using the calculation engine of EPA-SWMM (Storm Water Management Model) software (Rossman, 2010) for the simulation of the hydrological and hydraulic phenomena, while being completely independent of the user interface. The design criterion adopted has been to build a tool completely independent from the EPA-SWMM user interface, but which, for robustness and reliability requirements, continues to use its powerful calculation engine.

The *SIGMA DRAIN* model idealizes the green roof as a system consisting of three individual components in series, each of them corresponding to the main technological modules of the vegetated roof: 1) surface layer, 2) substrate layer and 3) drainage and storage layer.

The surface layer, exposed to the atmosphere and covered by vegetation, is conceptualized as sub-catchment; it is defined by the real size of the vegetated roof surface (area and % slope), and is characterized by a specific permeability of the soil dependent on fraction of vegetation coverage. The following soil and drainage layers are schematized through two reservoir elements, which describe respectively the percolation in the substrate and the transport through the drainage layer. A mass balance equation is applied to each block, taking into account the specific physical phenomena that occur in each module and the flow is instead regulated by the Richard’s equation. Structure of the model is showed in the Figure 5.7 below.

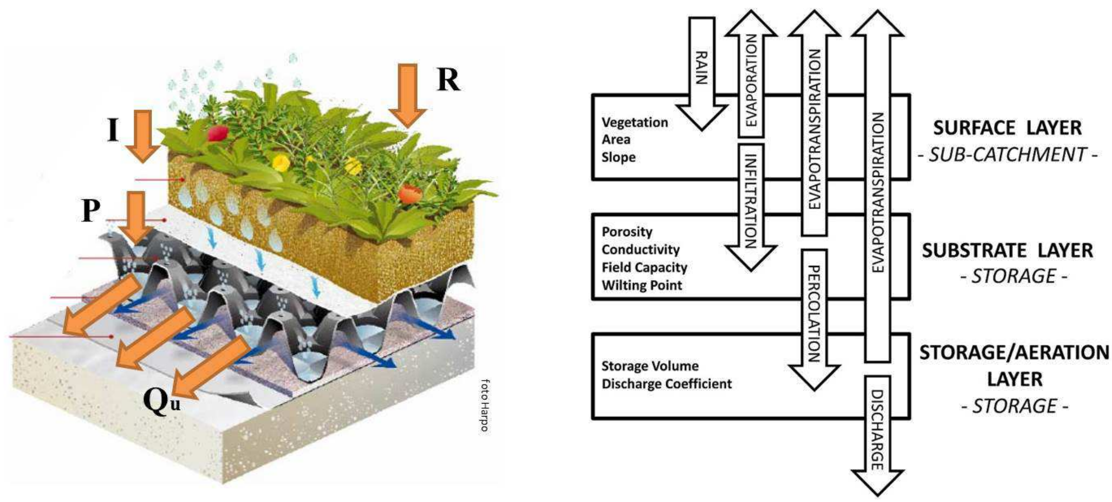

Fig. 5.7 Schematic structure of the SIGMA DRAIN Model. Where *R* is the Precipitaton, *I* the Infiltration; *P* the Percolation and Q_u the Outflow

Since the hydraulic/hydrologic behavior of a green roof is most influenced by soil layer characteristics (especially at event scale), the surface layer has not been considered in the modelling. In this specific case, the sub-catchment surface is characterized by an impermeability equal to 100%, in order to collect the entire rainfall volume, and deliver it to the substrate layer. In this way, the rainfall volume will become the input for the underlying substrate layer.

In this study, also evaporation (EV) and evapotranspiration (ETR) contributions are not considered, because the model calibration and validation are made at event scale, therefore when it rains EV and ETR are considered void.

This section of the paragraph will provide an overview of all governing equations for the conceptual model.

Water balance in the substrate reservoir

Precipitation data are used as a direct input for the model. The incoming flux to the substrate reservoir (q_1) equals the total precipitation collected from the surface layer. The flow from the substrate layer (*Storage 1*) to the drainage layer (*Storage 2*) is controlled by a Percolation equation (q_2), which was formulated from Darcy's Law for unsaturated flow, in which the unsaturated hydraulic conductivity (K) depends on the volumetric water content (θ); it increases with increasing soil moisture to its maximum value at saturation (the saturation hydraulic conductivity K_s).

In the case that only vertical flow of water (1-dimensional) is considered, the Darcy law for unsaturated porous medium can be written as:

$$q = -K(\theta)\frac{\partial h}{\partial z} \quad \text{Eq. 1}$$

Where:

- q = specific discharge rate or flux [LT^{-1}]
- $K(\theta)$ = unsaturated hydraulic conductivity [LT^{-1}]
- θ = Volumetric water content or moisture content [L^3L^{-3}]
- h = Total hydraulic head for unsaturated soil [L]

Since the hydraulic head for unsaturated soil h [L] is the sum of the negative water pressure head ψ [L] and z [L], the elevation head (positive downward), this can be transformed into:

$$q = -K(\theta)\frac{d[\psi(\theta)-z]}{dz} \xrightarrow{yields} q = K(\theta)\left[1-\frac{\partial\psi(\theta)}{\partial z}\right]$$ Eq.2

by using the chain rule Eq. 2 becomes:

$$q = K(\theta)\left(1-\frac{\partial\psi}{\partial\theta}\frac{\partial\theta}{\partial z}\right)$$ Eq.3

The two derivatives in Eq. 3 are values related to soil type and for this reasons they can be assumed constants. In particular, the tension slope - the slope of the *soil water retention curve* (SWRC) - is approximated to a constant C_1, while the slope of the average distribution of the moisture along the substrate is assumed to be equal to a constant C_2. This latter is express as the difference between the moisture content θ corresponding to the Field Capacity (θ_{cc}) and the Wilting Point (θ_w) (in the *Storage 1*), divided by the average substrate depth, (s/2). Thus:

$$\begin{cases} \frac{\partial\psi}{\partial\theta} = C_1 \\ \frac{\partial\theta}{\partial z} = \frac{(\theta_{cc}-\theta_r)}{\left(\frac{s}{2}\right)} = C_2 \end{cases}$$ Eq. 4

By substituting Eq. 4 in Eq. 3:

$$q = K(\theta)(1 - C_1 \cdot C_2)$$ Eq. 5

and by grouping the two constants in a single one:

$$C_3 = (1 - C_1 \cdot C_2)$$ Eq. 6

can be simplified as:

$$q = K(\theta) \cdot C_3$$ Eq. 7

Following Eq. 7, flow in substrate layer is related to the unsaturated hydraulic conductivity, which is a function of the soil water content. The most important aspect in this type of model is the correct definition of the unsaturated hydraulic conductivity *K(θ)*. When direct measurements of *K(θ)* are not obtainable it is possible to estimate using more easily measured properties such as particle size distributions. In this formulation, *K(θ)* is defined as:

$$K(\theta) = K_s \cdot K_r(\theta)$$ Eq. 8

where K_s is the saturated hydraulic conductivity and K_r *(θ)* is the relative hydraulic conductivity. Several relations based on experimental data are presented in literature to compute the relative hydraulic conductivity, the most employed, also used for this study, is the Van Genuchten (Van Genuchten, 1980) soil hydraulic function with the statistical pore distribution model of Mualem (Mualem, 1976), express as:

$$K_r(S_e) = S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad \text{Eq. 9}$$

Where:

- $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$ is the effective degree of saturation [-], with θr and θs respectively the residual and saturated water contents [L^3L^{-3}];
- *l* is an empirical parameter that represents the effects of tortuosity and pore connectivity, and is usually assumed to be =0.5 (Mualem, 1976), although this is not general agreement [-];
- $m = \left(1 - \frac{1}{n}\right)$ is the dimensionless parameters of the retention curve of soil water.

Althrough several *K(θ)* parametric relationship have been proposed and successfully used in the literature (Kutílek & Nielsen, 1994), an exponential model was selected for its simplicity and the good fitting obtained. The Mualem-van Genuchten equation (Eq. 9) can be interpolated with an exponential function of the type:

$$K_r(\theta) \cong a\, S_e{}^b \qquad \text{Eq. 10}$$

Therefore, by substituting the last two equations (Eq. 8 and Eq. 10) in the expression of the specific flux (Eq. 7), the following relation is obtained:

$$q = K_s \cdot C_3 \cdot (a\, Se^b) \qquad \text{Eq. 11}$$

Since the water level in the substrate reservoir (*Storage 1*) over the weir *h'(t)* can be related to the value of the effective degree of saturation (S_e) by using the following equation:

$$h'(t) = S_e(t) \cdot n \cdot s \quad \xrightarrow{yields} \quad S_e(t) = \frac{h'(t)}{n \cdot s} \qquad \text{Eq. 12}$$

where n is the porosity [L^3L^{-3}] and s is the substrate depth [L]. Combining Eq. 12 with Eq. 11 leads to:

$$Percolation = q_2 = K_s \cdot C_3 \cdot a \cdot \left(\frac{1}{n \cdot s}\right)^b \cdot h'^{\,b} \qquad \text{Eq. 13}$$

By grouping all known terms into a single parameter (α), the expression can be simplified in the form:

$$q_2(t) = \alpha \cdot h'^{\beta} \qquad \text{Eq. 14}$$

where:

- $\beta = b$
- $\alpha = K_s \cdot C_3 \cdot a \cdot \left(\frac{1}{n \cdot s}\right)^b \cdot A = K_s \left(1 - \frac{\partial \psi}{\partial \theta}\frac{\partial \theta}{\partial z}\right) \cdot a \cdot \left(\frac{1}{n \cdot s}\right)^b \cdot A$

where K_s is the saturated hydraulic conductivity [LT^{-1}]; n is the soil porosity [L^3L^{-3}]; s is the substrate depth [L]; A the reference surface of the green roof [L^2]; h' is the water level in the substrate reservoir over the weir [L]; the two derivatives, as previously mentioned, define the tension slope of the SWRC and the slope of the average distribution of the moisture along the substrate. Not least, the parameters a and b, are the parameters of the exponential function (Eq.10), which takes account of the variation of Kr as a function of the effective degree of saturation S_e.

Last equation (Eq. 14) control the outflow rate of the substarte reservoir element and depends on the properties of the layer considered. Parameter α and β can be calculated directly if the soil water retention curve and the saturated hydraulic conductivity are known, or can be calibrated on experimental data. In this study, parameters of the proposed model have been calculated using soil water retention curve and the saturated hydraulic conductivity already calculated by using UMS HYPROP® system which use the evaporation method, according to Wind/Schindler, to determine retention curves of soil samples (Paragraph 5.2.3.2).

Water balance in the drainage reservoir

The percolation rate (q_2) is the input for the third module relating to the drainage layer (*Storage 2*), which is represented by a storage tank with geometrical characteristics dependent on the particular technology used. The relationships used to describe the hydraulic behavior of this module are the mass balance equation (Eq. 15) and the discharging equation (Eq. 16) written as follows:

$$\frac{dW}{dt} = Q_e - Q_u = q_2 - q_3 \qquad \text{Eq. 15}$$

where W is the accumulated volume [L^3], t is the time [T], Q_e is the inflow [L^3T^{-1}] - in this case the Percolation rate - and Q_u is the outflow [L^3T^{-1}].

$$q_3 = Q_u = \mu \cdot L \cdot h \cdot \sqrt{2gh} \qquad \text{Eq. 16}$$

where Qu is the flow rate eluted from the vegetated roof, μ is the discharging coefficient, L is the width of the storage and h'' is the water level in the Drainage Layer (*Storage 2*) over the weir.

Now that the SIGMA DRAIN model has been conceptualized, in order to estimate its reliability, it was first calibrated and then validated with the software HYDRUS-1D. An initial specification of the HYDRUS-1D model, of the boundary conditions, and of the soil hydraulic parameters determination will be presented in the next two paragraphs.

5.2.3.1 HYDRUS-1D model for vegetated roofs

The HYDRUS-1D computer code is a physically based model for the simulation of one-dimensional vertical flow of water in variably saturated porous media (Šimůnek et al. 2009). The physical background offers the opportunity to better understand the green roof functioning. The software program numerically solves the Richards equation for saturated-unsaturated water flow and it is one of the best documented and most widely used codes (Carbone et al., 2015 b). HYDRUS-1D can be adopted and used in a variety of locations, since geographical and meteorological parameters can be modified easily. On top of these advantages the software is freely available and scientifically verified. The version of HYDRUS referred to in this study is HYDRUS-1D, version 4.08 (Šimůnek et al. 2009).

The governing flow equation of the infiltration process is the one-dimensional form of the Richards' equation:

$$\frac{\partial\theta(\psi)}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi) \cdot \left(\frac{\partial\psi}{\partial z} + 1\right)\right] \qquad \text{Eq.17}$$

where θ is the volumetric water content [-]; ψ is the suction or pressure head [L]; K is the unsaturated hydraulic conductivity [LT^{-1}]; z is the vertical spatial coordinate [L]; t is the time [T]. Richards has extended Darcy's law to unsaturated flow (Eq. 1), with the provision that the unsaturated hydraulic conductivity K is a function of the water pressure head ψ. (Hillel, 1982). The differential form of the Richard's equation (Eq.17) shows that the hydraulic conductivity (K), the moisture content (θ) and the water pressure head (ψ), are mutually dependent. In particular, the unsaturated soil hydraulic properties (θ and K) are in general highly nonlinear functions of the suction head (Šimůnek et al. 2009).

When one wants to numerically solve the Richards equation, which has three unknown variables (K, θ and ψ), two more equations are required. The relationship between the moisture content and the water pressure head $\theta(\psi)$ is called the *soil water retention function*. The relationship between the hydraulic conductivity and the water pressure head $K(\psi)$ is called the *hydraulic conductivity function*. Several scientists have attempted to develop analytical solutions for the relationship between the hydraulic conductivity, moisture content and water pressure. To describe the unsaturated hydraulic conductivity function of a substrate in terms of volumetric water content, the Van Genuchten (1980) soil-hydraulic functions, with the statistical pore distribution model of Mualem (1976), are implemented.

The Van Genuchten relationships can be written as:

$$\theta(\psi) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha\psi|^n\right]^m} & \psi < 0 \\ \theta_s & \psi \geq 0 \end{cases} \qquad \text{Eq. 18}$$

where $\theta(\psi)$ is the measured volumetric water content [L^3L^{-3}] at the suction head. The parameters θr and θs - as already previously seen - are residual and saturated water contents [L^3L^{-3}], respectively; a, n and m are empirical parameters (Van Genuchten, 1980). More in detail:

- α (>0) is a parameter related to the inverse of the air-entry pressure [L^{-1}];
- n (>1) is a measure of the pore-size distribution [-];
- m is equal to: $m = \left(1 - \frac{1}{n}\right)$

therefore the volumetric soil-water content, as defined by Eq. 18, only contains four independent parameters (θr, θs, α, n), which have to be estimated from observed soil-water retention data.

Combination of Eq. 18 with Mualem's (1976) pore-size model yields the following closed-form expression for unsaturated hydraulic conductivity (van Genuchten, 1980), as a function of saturated hydraulic conductivity K_s [LT^{-1}] and effective degree of saturation S_e [-]:

$$K(\psi) = K_s\, S_e^l \left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad \text{Eq. 19}$$

l [-] is an empirical parameter that represents the effects of tortuosity and pore connectivity, and is usually assumed to be =0.5 (Mualem, 1976), although this is not general agreement.

The soil hydraulic properties are expressed by several parameters for the soil water retention and hydraulic conductivity function. The considerations above therefore require five parameters (θr, θs, α, n, and K_s) to describe the water retention; whose values mainly depend on the soil type.

Since simulation accuracy of the green roof rainfall-runoff on experiment-scale depends, to a large extent, on the accuracy of parameter determination, in the next section will be determinate the soil hydraulic parameters for the green-roof experiment soil at University of Calabria.

5.2.3.2 Model Calibration

Before the model can be used to reliably simulate green roof runoff at acceptable accuracy, it is necessary to go through a stage of model parameter calibration.

In view of its reliability, HYDRUS-1D has been used in the literature as a benchmark for the validation of different alternative models (Celia et al., 1990; Zlotnik et al., 2007), and therefore, it was used in this study as well for comparing the outflow rates from the SIGMA DRAIN model. The outflow is one of the most important hydraulic characteristics in the analysis of a green roof exposed to rainfall; it provides information on the retention and peak attenuation capacity of the green roof, and for these reasons, accurate modelling of the green roof outflow is particularly needed (Carbone et al., 2015 c).

In order to perform the comparison between the two models, boundary conditions used to implement the HYDRUS-1D code and the input parameters required by software, must be defined. There is little potential for lateral water flow in the green roof system due to the relatively thin substrate layer, the small roof gradient (1%), and the fact that effluent is drained via a non-substrate drainage layer (Bond & Thompson, 2013); therefore, only one-dimensional (1D) flow in the vertical direction was assumed. Boundary conditions of interest for 1D vertical flow are only the top and bottom boundaries. In this study, two Neumann boundary conditions have been applied. These conditions specify the value of the flux in the direction normal to the boundary considered.

For the upper boundary, the infiltration process has been simulated by imposing a Neumann condition, specifying the value of the flux. Precisely, when dealing with infiltration fluxes at the soil surface, the most widely used boundary condition is the *soil-atmosphere interface condition*: it's possible to switch from unsaturated soil condition ($\psi < 0$) to saturated soil ($\psi = 0$), and are given by:

$$\begin{cases} \left| -K(\psi)\frac{\partial \psi}{\partial z} - K(\psi) \right| = P & \psi_{z=0} < 0 \\ \psi_{z=0} = 0 & \end{cases} \qquad \text{Eq. 20}$$

with P the precipitation.

If the applied flux is larger than the saturated hydraulic conductivity, then positive pressures appear at the surface, which corresponds to the formation of ponding on the soil surface. At this point the boundary condition switches to the Dirichlet boundary condition. However, as stated previously, green roof substrates are designed to avoid the formation of ponding on the surface, which is why the Neumann boundary condition has been implemented (Carbone et al., 2015 c).

For the lower boundary, a *free-drainage condition* has been used. This condition, also a Neumann type, represents vertical flow of water through the bottom of the soil towards a distant groundwater table.

As mention in the previous paragraph (5.2.3.1), the transport of water through the green roof substrate is governed by the Richard’s equation, which relates change in soil moisture content with time to pressure head and hydraulic conductivity. HYDRUS allows their users to choose between six types of hydraulic models for the soil hydraulic properties (PC-PROGRESS 2008). These hydraulic models can be split up into two main groups (Durner et al. 1999): i) Unimodal, single-porosity models and ii) Bimodal, dual-porosity models.

In this study a dual-porosity model was considered. Dual-porosity model conceptualizes the soil as a two interacting regions, one referred to the macro-pore network and the other associated with the micro-pores inside soil aggregates (Šimůnek et al., 2003). Dual-porosity models assume that water flow is restricted to the macro-pores, and that water in the matrix (intra-aggregate pores or micro-pores) does not move at all. Thus, micro-pores represent immobile pockets that can exchange, retain and store water, but do not permit convective flow (Šimůnek et al., 2003).

The soil hydraulic parameters (θr, θs, α, n, and K_s) required in the dual porosity model mainly depend on the soil type. In this study, the green roof substrate properties were analyzed during a laboratory experiment to evaluate its hydraulic characteristic using the UMS HYPROP® system. HYPROP® (*HYdraulic PROPerty analyser*) is a fully automated measuring and evaluation device to determine the hydraulic properties of soil samples (UMS, 2015). Indeed, using HYPROP®, is possible to measure simultaneously the water retention curve and the unsaturated hydraulic conductivity function in the range between water saturation and close to the permanent wilting point. Empirical van Genuchten shape parameters (α and n) of the hydraulic conductivity function come directly from the retention curve. HYPROP® is working based on the evaporation method according to Wind (1968) in Schindler's model (1980).

As stated before the HYDRUS-1D software has been applied in order to assess its performance in predicting hydrological behavior of the green roof experimental site and, by using Schindler's model, were estimated the input soil parameters required by HYDRUS-1D. In the table below (Table 5.1), in addition to the soil hydraulic parameters, are also listed the physical characteristics of the experimental site green roof, useful to calculate the α parameter of the Eq. 14.

Table 5.1. Hydraulic Parameters of the green roof substrate

Parameter	Unit	Value	Definition
			Soil Hydraulic Parameters
θ_r	[-]	0.096	Soil Residual Water Content
θ_s	[-]	0.574	Saturated Soil Water Content
α	[1/cm]	0.8	Parameter related to the inverse of the air-entry pressure
n	[-]	1.499	Parameter related to the pore-size distribution
K_s	[cm/min]	4.916	Saturated hydraulic conductivity
θ	[-]	0.2	Initial Moisture Condition

			Green roof Physical Parameters
s	[cm]	8	Substrate depth
A	[m^2]	50	Reference Green Roof Area

The initial moisture condition for the green roof media was assumed to be constant over the whole soil profile, and specifically, it was set equal to 0.2, as the field capacity value (θ_{cc}). The residual water content (θ_r) is defined as the water content at some large negative value of the pressure head, e.g. at the permanent wilting point (-15 Bar). Using these values for field capacity and wilting point, HYDRUS-1D has been used to predict runoff for the soil.

Finally, numerical simulation with the HYDRUS-1D software have been conducted, using measured rainfall data as precipitation input, to calibrate the model. The model is calibrated with 3 rainfall events characterized by different rainfall depths, observed from the monitoring campaign carried out in the Unical experimental site, whose the main characteristics are summarized in the Table 5.2.

Table 5.2 Hydrologic characteristics of rainfall events selected for the Calibration

#	Rainfall Event [*dd/mm/yyyy*]	Starting Time [*hh:mm*]	Rainfall Depth [*mm*]	Peak Intensity [*mm/h*]	Duration [*hours*]
13	11/11/2013	h 00:27	58.6	96	8.7
29	26/12/2013	h 20:27	17.5	12	5.05
44	11/02/2014	h 22:58	25.2	24	12.8

The calibration strategy involved comparing the results, in terms of outflow, modeled with HYDRUS-1D and SIGMA DRAIN conceptual model. The goodness of fit between HYDRUS-1D and SIGMA DRAIN modeled data, was determined by the Pearson coefficient, R^2.

In the figure below (Fig. 5.8) are shown the calibration results, obtained for the Event 13 (dated 11 November 2013), by varying the parameters *a* and *b* of the exponential function (Eq.10). It can be noticed the same tendency for all the three evaluated variations, that well interpolates the HYDRUS-1D trend. Were selected the values corresponding to the curve which better approximates the one obtained with HYDRUS-1D model (continuous line), corresponding to a Pearson Coefficient value of 0.91.

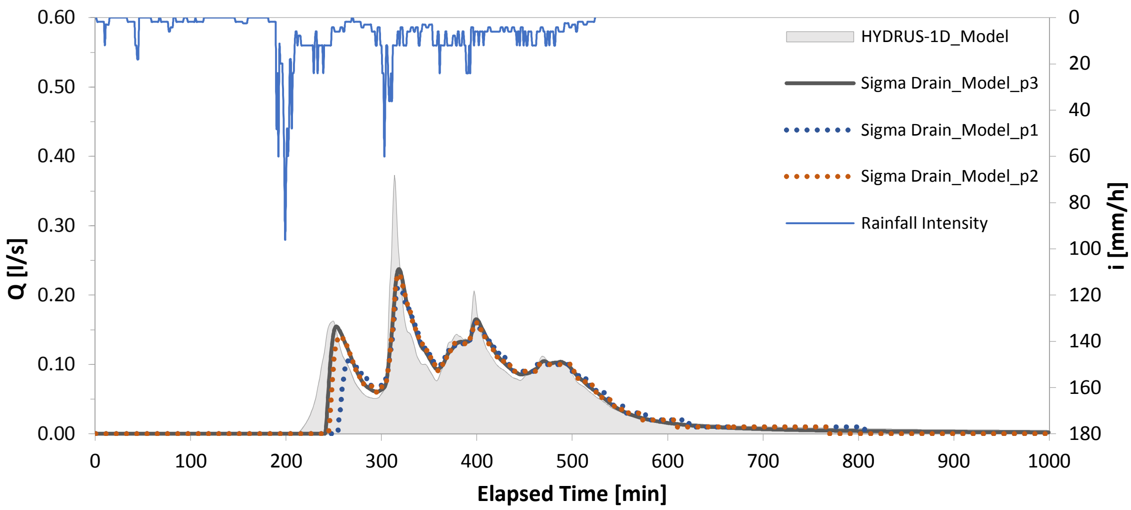

Fig. 5.8 Comparison between HYDRUS-1D and SIGMA DRAIN model for event 13 (11 November 2013)

5.2.3.3 Model performance evaluation

In order to verify the accuracy of a model it is necessary to perform a statistical evaluation to ensure the results validity. The SIGMA DRAIN Model hydrological performances were evaluated comparing runoff rate between SIGMA DRAIN model and HYDRUS-1D.

For a quantitative assessment of the model performance, several statistical indices were found and their description and discussions on their suitability, has been widely discussed in the literature (Moriasi et al., 2007); for this research three statistical indices were selected.

The Nash-Sutcliffe efficiency coefficient (NS) is a normalized statistic that indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007), and is one of the most widely used indices for characterizing the overall fit of hydrographs (Servat et al., 1990; Nash & Sutcliffe, 1970). The NS is computed as follows:

$$NS = 1 - \left[\frac{\sum_{i=1}^{n}\left(Q_i^{hyd} - Q_i^{SD}\right)^2}{\sum_{i=1}^{n}\left(Q_i^{hyd} - Q_{mean}^{hyd}\right)^2}\right] \qquad \text{Eq. 21}$$

Where, Q_i^{hyd} is the ith value of HYDRUS model, Q_i^{SD} is the ith value of SIGMA DRAIN model, and Q_{mean}^{hyd} is the mean value of HYDRUS model, for n total number of observations. NS coefficient values range between -∞ and 1.0, with NS=1 being the perfect agreement. In this research values between 0.5 and 1.0 are considered satisfactory, corresponds to a good match of the SIGMA DRAIN model results to HYDRUS-1D results.

Percent bias (PBias) measures the average tendency of the model to overestimate or underestimate the counterpart (Gupta et al., 1999). PBias was selected for its ability to clearly indicate poor model performance, and is calculated as follow:

$$PBias\ (\%) = \frac{\sum_{i=1}^{n}\left(Q_i^{hyd} - Q_i^{SD}\right)}{\sum_{i=1}^{n}\left(Q_i^{hyd}\right)} \cdot 100 \qquad \text{Eq. 22}$$

The optimal value of PBias is 0.0, with low-magnitude values indicating good performance of the model, negative values indicate model overestimation bias, while positive values means model underestimation bias (Gupta et al., 1999). In this study PBias values ranging between 0% and 40% are considered good.

While Root Mean Square Error (RMSE) is one of the most widely used error statistic index, in this research an RMSE-observation standard deviation ratio (RSR) was selected (Moriasi et al., 2007) to evaluate model performance. RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by Legates and McCabe (1999). The RSR is calculated as the ratio of the RMSE and the standard deviation of reference data, as shown in Eq. 23 (Servat et al., 1990):

$$RSR = \frac{RMSE}{STDEV_{hyd}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Q_i^{hyd} - Q_i^{SD}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Q_i^{hyd} - Q_{mean}^{hyd}\right)^2}\right]} \qquad \text{Eq. 23}$$

The RSR varies from the optimal value of 0.0, which means zero RMSE or residual variation and therefore perfect model simulation, to a large positive values; the lower the RMSE, and the better the model simulation performance. In this research values lower than 0.5 are considered satisfactory.

These three statistical index are able to describe the model general performance, although the objectives of single rainfall event or multi-event simulation are the accurate determination of peak flow rate and runoff reduction, which are extremely important for flood estimation and forecasting.

5.2.4 Multi Linear Regression Analysis

In this study the Multiple Linear Regression Analysis was used in order to:

- statistically define the most influencing hydrological factors on the hydraulic efficiency of the experimental green roof located at University of Calabria;
- get regression equations that an engineer could use for a preliminary study on the performance of the green roof, without the implementation of the conceptual model.

The Multiple Linear Regression Analysis is used to assess the association between two or more independent variables and a single continuous dependent variable. The multiple linear regression equation is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_P X_P + \varepsilon \qquad \text{Eq. 24}$$

where Y is the predicted or expected value of the dependent variable, X_1 through X_p are p distinct independent or predictor variables, β_0 is the value of Y when all of the independent variables (X_1 through Xp) are equal to zero, β_1 through β_P are the estimated regression coefficients, and ε is the residual term which translates the inability of the model to accurately reproduce the observed reality.

In multiple linear regression problems, certain tests of hypotheses about the model parameters are useful in measuring model adequacy. In this section three types of hypothesis tests may be carried out:

1. *Test for significance of regression*: this test checks the significance of the whole regression model. More in detail, this is a test to determine whether a linear relationship exists between the response variable Y and a subset of the predictor variables X_1, X_2,..X_p..
2. *t-Test*: this test checks the significance of individual regression coefficients in the presence of all other explanatory variables.
3. *F-Test*: this test can be used to simultaneously check the significance of a number of regression coefficients.

In this study each test was used, but in this section, wanting to quantify the influence of hydrological parameters on runoff, it focuses particular attention on the *t Test*. The hypothesis statements to test the significance of a particular regression coefficient β_j are:

$H_0: \beta_j = 0$

$H_1: \beta_j \neq 0$ with $j = 1, \dots, p$

the statistic test for this test is based on the *t* distribution:

$$t = \frac{\widehat{\beta_J}}{s.e.(\widehat{\beta_J})} \quad \text{Eq. 25}$$

where the standard error, $s.e.\widehat{\beta_J}$, is obtained. The analyst would fail to reject the null hypothesis if the test statistic lies in the acceptance region:

$$-t_{\frac{\alpha}{2},n-2} < t < +t_{\frac{\alpha}{2},n-2} \quad \text{Eq. 26}$$

In this study the independent variables are the hydrological parameters, such as precipitation depth, rainfall duration and rainfall intensity, while the dependent variable is the runoff depth.

In order to evaluate the significance of each regression coefficient a *t*-test was used. A p-value of 0.05 was considered in this study. To define how close the data are to the fitted regression line, the R^2 coefficient is used. This is the first coefficient that give a general information about the regression equation. R^2 is always between 0 and 100%: 100% indicates that the model explains all the variability of the response data around its mean. In general, higher is the R^2, and better the model fits the data.

This analysis is carried out by firstly defining the subsurface runoff coefficient at event scale, by using 1-minute rainfall data as input data in the SIGMA DRAIN conceptual model. The subsurface runoff coefficient is computed as the ratio between the total runoff depth and the total rainfall depth during the event. The data set from Unical, Italy is used to obtain the multi-regression relationships, which were, then, validated with the data set from Lyon, France.

5.3 Results and Discussions

This paragraph is divided in three main sub sections: the first one is relate to the Model validation both at event and multi-events scale; in a second part the analysis of hydraulic efficiency of green roof performance is carried out and finally, the results of multi linear regression analysis are shown.

5.3.1 Model Validation Results

After the model calibration, the validation strategy involved comparing the HYDRUS-1D and SIGMA DRAIN runoff hydrographs. The model validation differs from the model calibration in the sense that the parameters will not be adjusted anymore.

More in detail, this procedure was carried out prior at event scale and then, by combining consecutive events, at multi-event scale, as shown below.

5.3.1.1. Event Scale Modelling

Ten measured rainfall events, characterized by different rainfall depths, were selected for the validation of the proposed SIGMA DRAIN model. The rainfall data were collected from the monitoring campaign carried out at the Unical experimental site, whose the main characteristics are summarized in the Table below (Table 5.3).

Table 5.3 Hydrologic characteristics of the rainfall events selected for Validation

#	Rainfall Event [*dd/mm/yyyy*]	Starting Time [*hh:mm*]	Rainfall Depth [*mm*]	Peak Intensity [*mm/h*]	Duration [*hours*]
5	16/09/2013	h 03:18	42.2	144	5.3
16	15/11/2013	h 14:13	16.9	12	9.7
17	22/11/2013	h 23:31	36.2	60	10.0
20	24/11/2013	h 07:35	18.4	24	7.2
24	30/11/2013	h 10:59	48.0	24	27.2
35	20/01/2014	h 17:39	48.3	48	36.8
38	31/01/2014	h 23:34	31.0	24	21.2
41	03/02/2014	h 01:17	23.6	6	17.0
56	24/03/2014	h 00:07	23.2	36	10.8
61	27/03/2014	h 23:44	16.6	24	12.2

The hyetograph and the corresponding hydrographs measured with HYDRUS-1D (grey area) and simulated with SIGMA DRAIN (solid line) models, for few rainfall event examined in this section of the study, are illustrated in the Figures below.

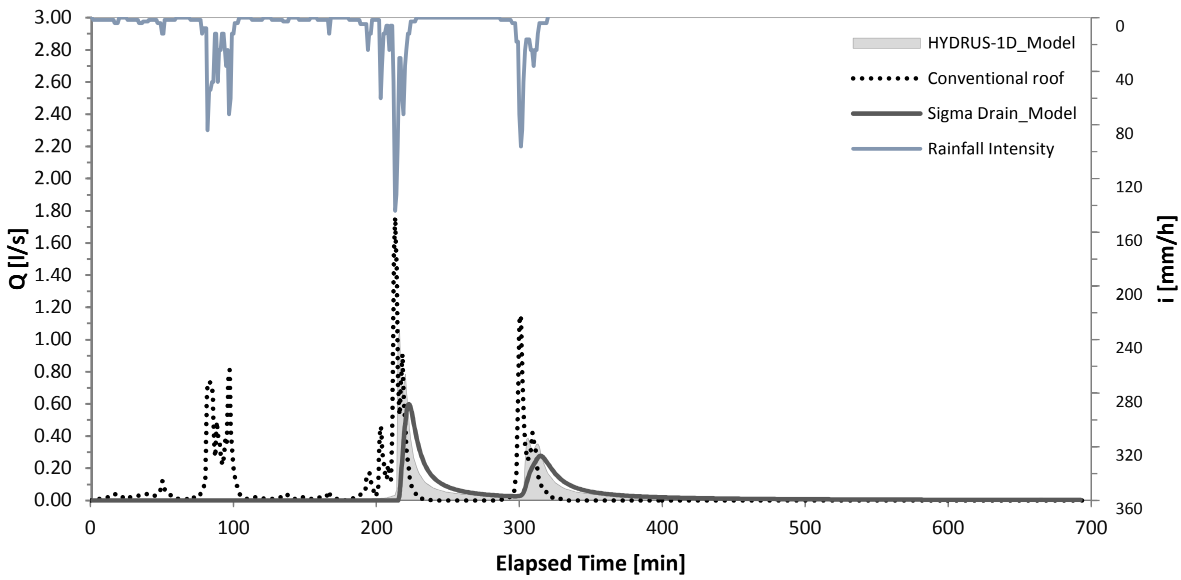

Fig. 5.9 Hyetographs and corresponding SIGMA DRAIN and HYDRUS-1D hydrographs for rainfall event n.5 (16 September 2013) .

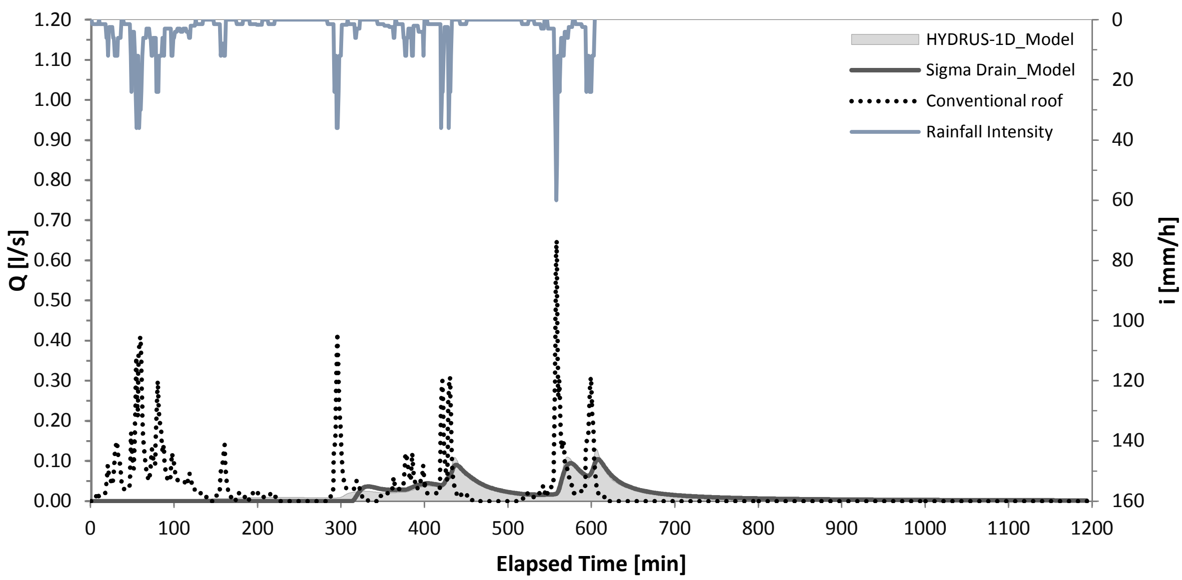

Fig. 5.10 Hyetographs and corresponding SIGMA DRAIN and HYDRUS-1D hydrographs for rainfall event n 17 (22 November 2013)

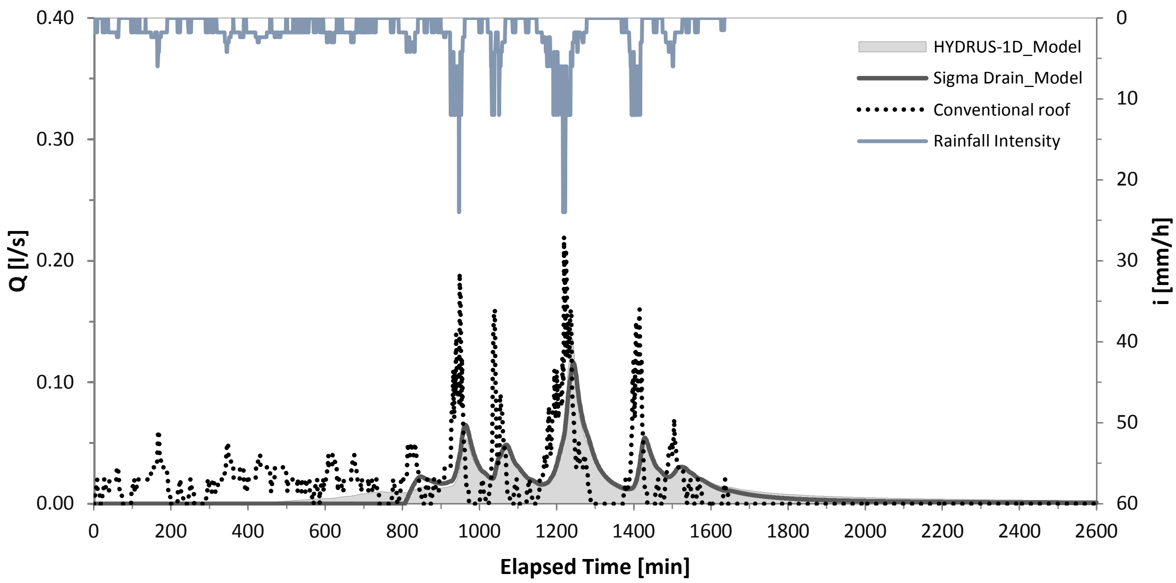

Fig. 5.11 Hyetographs and corresponding SIGMA DRAIN and HYDRUS-1D hydrographs for rainfall event n 24 (30 November 2013)

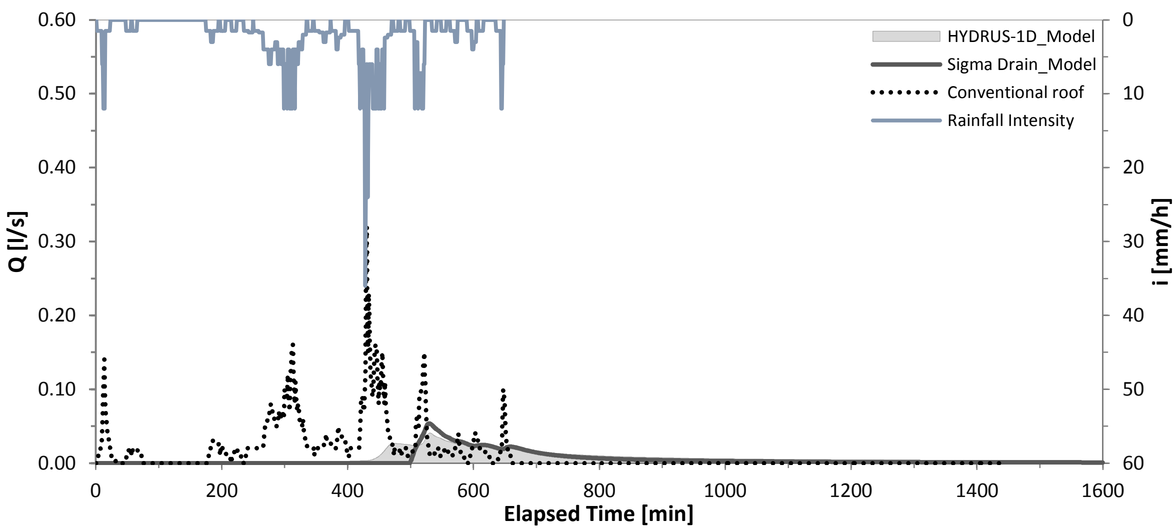

Fig. 5.12 Hyetographs and corresponding simulated hydrographs with SIGMA DRAIN and HYDRUS-1D results, for rainfall event n 56 (24 March 2014), and comparison with Conventional roof

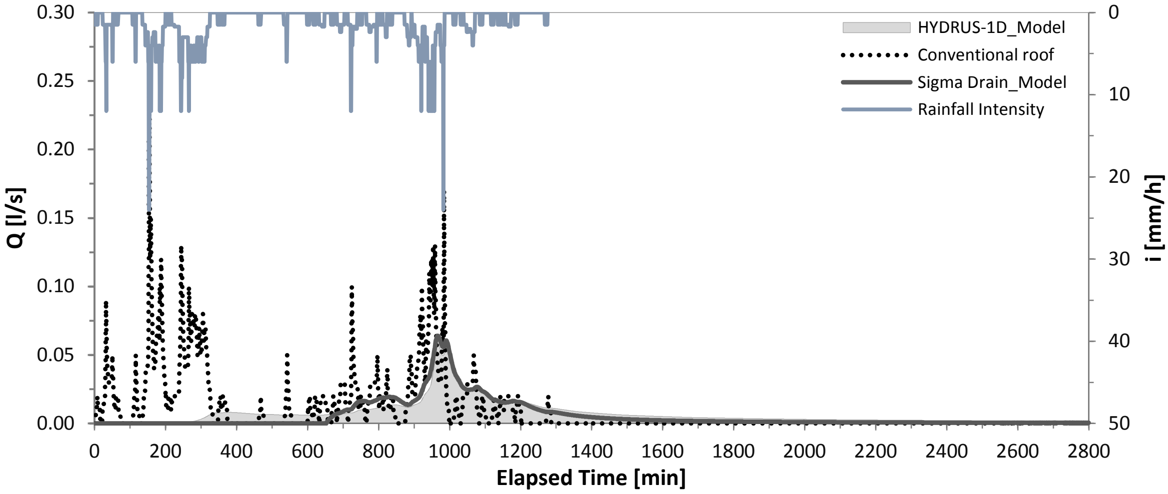

Fig. 5.13 Hyetographs and corresponding simulated hydrographs with SIGMA DRAIN and HYDRUS-1D results, for rainfall event n 38 (31 January 2014), and comparison with Conventional roof

In Table 5.4, the NS, Pbias and RSR performance indicators are reported with respect of the Sigma Drain conceptual model.

Table 5.4 Performance indicators of comparison between the SIGMA DRAIN model and HYDRUS-1D.

#	Rainfall Event [*dd/mm/yyyy*]	Rainfall Depth [*mm*]	Peak Intensity [*mm/h*]	Runoff Peak Flow [*l/s*]	NS	Pbias [%]	RSR
5	16/09/2013	42.2	144	0.6	*0.5*	*11.9*	*0.7*
16	15/11/2013	16.9	12	0.01	-0.3	66.9	1.2
17	22/11/2013	36.2	60	0.1	*0.9*	*21.3*	*0.3*
20	24/11/2013	18.4	24	0.02	0.2	59.5	0.9
24	30/11/2013	48.0	24	0.1	*0.9*	*12.8*	*0.2*
35	20/01/2014	48.3	48	0.04	*0.8*	*12.1*	*0.4*
38	31/01/2014	31.0	24	0.06	*0.8*	*22.4*	*0.4*
41	03/02/2014	23.6	6	0.02	0.2	*23.7*	0.9
56	24/03/2014	23.2	36	0.05	*0.7*	*37.9*	*0.6*
61	27/03/2014	16.6	24	0.01	-0.6	60.7	1.3

Results obtained from the validation events, illustrated in Table 5.4 and Figures (from 5.9 to 5.12), reveal the suitability of the SIGMA DRAIN model to well approximates the model HYDRUS-1D and therefore correctly describe the hydrologic behavior of the green roof, for precipitation above 20 mm, while for events with rainfall depth lower than 20 mm, the performance of the model are not satisfactory. As proof of this consideration:

- the Nash-Sutcliffe coefficient, for these events, is always major than 0.5;

- Pbias indicates that the SIGMA DRAN model performs very well with a constant overestimation ranging between 11.9 % and 37.9 %;
- RSR is under 0.5 value for 5 of the 7 rainfall events above 20 mm.

Such behavior can be attributed to the fact that in the SIGMA DRAIN model, differently from HYDRUS-1D, the initial water content of the substrate is not taken into account. To verify this, as shown in the next paragraph, simulations by combining more consecutive events were conducted, proving that the antecedent hydrologic-hydraulic conditions prior the event are relevant in assessing the response of the model.

Another goal of the study was also to determine if runoff from the modeled green roof was significantly less than that from a conventional, impervious roof type. In particular, this procedure is based on three variables: runoff attenuation, peak flow reduction and delay in starting time of runoff. Peak discharge reduction and runoff attenuation is often far more important for stormwater management because the total rainfall volume and rainfall duration is often not the problem, it is the rate that the incoming water needs to be treated (Van Woert, et al., 2005).

The peak flow reduction or hydrograph attenuation is a very important objective in stormwater management, because this could enable a size-reduction of the hydraulic structures within the stormwater drainage system, or could provide capacity for future urban development (Carter & Rasmussen, 2006). In this study is expressed as the percentage difference between the reference roof peak flow and the green roof peak flow (modelled with SIGMA DRAIN).

The runoff attenuation is calculated as the absolute percentage difference between the runoff volume from the conventional roof and the discharged volume from the green roof.

Moreover, the delay in starting outflow was also determined as the difference in time between the starting time of green roof runoff and the reference impervious roof.

In order to calculate these parameters, a model of the impervious roof was implemented so that the reference rooftop behavior is made available for comparison purposes. The reference impervious rooftop is simulated by employing the EPA Storm Water Management Model (Rossman, 2010). For the impervious roof, all rainfall was assumed to become runoff (1 mm rainfall = 1 mm of runoff).

By observing the figures of validation above, it is also possible to evaluate the performance of the extensive green roof installed at Unical and modeled with SIGMA DRAIN (solid line), compared to traditional roof (dotted line).

The quantitative assessment of model performance is summarizes in Table 5.5, where are reported the percentage peak flow reduction, the runoff volume attenuation and the delay in starting runoff time on an event basis.

Table 5.5 Green Roof Hydrologic performance compared to the Conventional Roof.

#	Rainfall Event [*dd/mm/yyyy*]	Rainfall Depth [*mm*]	Green Roof Runoff Flow [*l/s*]	Peak Flow Reduction [*%*]	Runoff Attenuation [*%*]	Delay in Starting Runoff Time [*hours*]
5	16/09/2013	42.2	23.0	66.2	35.1	3.5
16	15/11/2013	16.9	2.9	93.8	83. 7	11.7
17	22/11/2013	36.2	18.8	83.9	38.7	5.2
20	24/11/2013	18.4	3.9	93.3	74.6	6.7
24	30/11/2013	48.0	27.8	47.2	29.2	13.3
35	20/01/2014	48.3	29.2	91.9	21.5	9.2
38	31/01/2014	31.0	15.7	73.3	42.0	10.8
41	03/02/2014	23.6	8.9	70.0	56.5	11.9
56	24/03/2014	23.2	8.2	83.2	58.8	8.2
61	27/03/2014	16.6	2.8	96.0	80.7	11.5

Results reveal that the green roof installed at Unical, exhibits:

- A peak flow reduction ranging between 47% and 96%, with an average value of 80%, compared to a conventional roof.
- A runoff volume attenuation ranges between 21% and 83%, with an average value of 49%, compared to a conventional roof.
- As expected, the effluent hydrograph from Green roof exhibits a lag with regard to the hydrograph from the traditional roof for each rainfall event, with a range between 3.5 and 13.3 hours, with a mean values of 9 hours.

5.3.1.2. Multi-event Modelling

On the basis of the above considerations, whereby the antecedent hydrologic-hydraulic conditions prior the event are relevant in assessing the response of the model, nine multi-event simulations were carried out.

The multiple events were defined by combining two or more consecutive events, and include individual events varying in the rainfall depth, with the aim to evaluate the green roof response also for low precipitations (with rainfall depth < 20 mm), which individually have not produced runoff. The main characteristics of each Multi rainfall event are summarized in the annexed Table A-5.3.

For example, looking at the figures below (Fig. 5.14 and 5.15), referring respectively to the multi events n.3 and n.7, it may be observed what has been said until now. Both events considered, include mainly events with rainfall depth less than the threshold of 20 mm, as described in detail in the Table A-5.4 annexed, in which are shown the hydrological characteristics and the results in terms of runoff depth of each individual rainfall event.

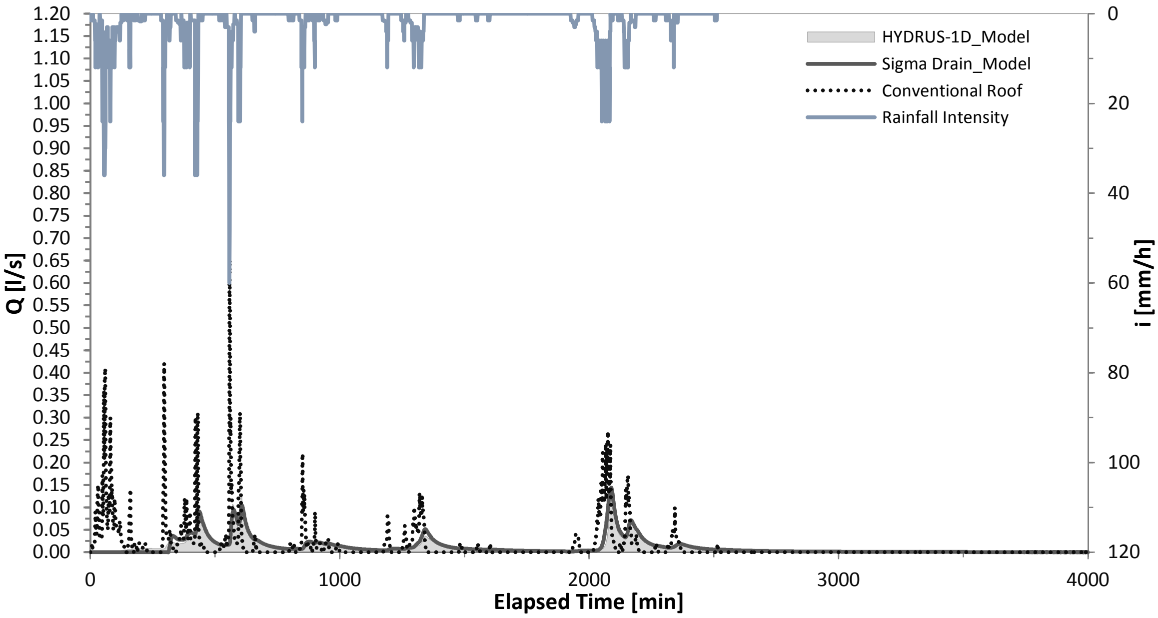

Fig. 5.14 Hyetographs and corresponding simulated hydrographs with SIGMA DRAIN and HYDRUS-1D results, for the Multi-Event n.3, and comparison with Conventional roof

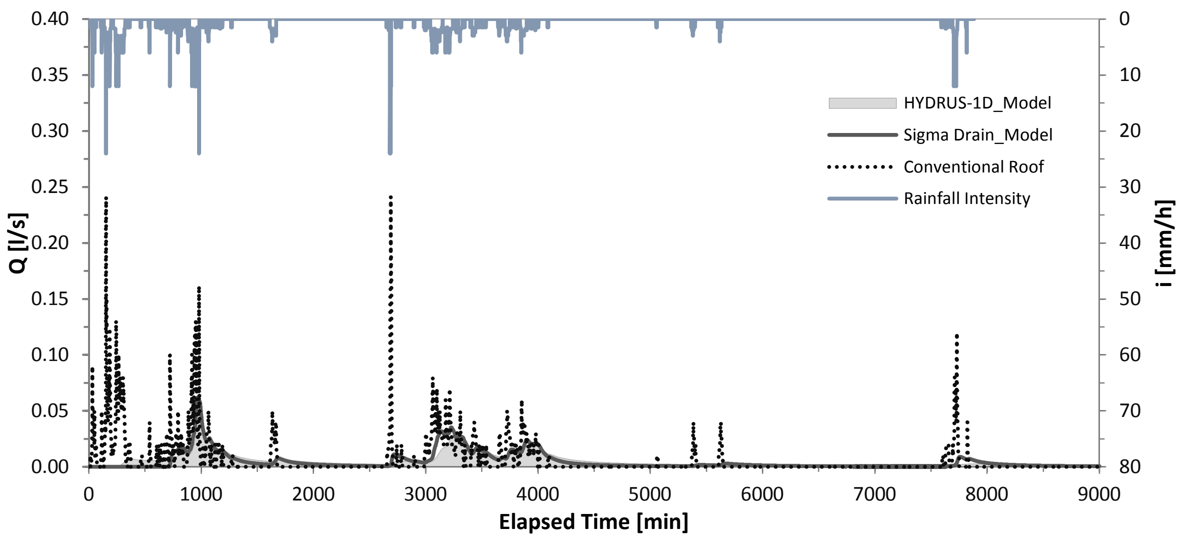

Fig. 5.15 Hyetographs and corresponding simulated hydrographs with SIGMA DRAIN and HYDRUS-1D results, for the Multi-Event n. 7, and comparison with Conventional roof

From a cross-reference of tables and figures, it is evident how small events that individually did not produce runoff, when grouped with others, produce a runoff. This assumption is proved also by the NS values reported in the Annexed Table A-5.3, which reached an average value of 0.8.

Also at multi-event scale, it was evaluated the performance of the modeled green roof (solid line) compared to traditional roof (dotted line). The Results in terms of runoff volume attenuation and the delay in starting runoff time are summarizes in Table A-5.3. Results reveal that the green roof installed at Unical, exhibits:

- A runoff volume attenuation ranges between 14% and 47%, with an average value of 24%, compared to a conventional roof.
- A delay in starting runoff time with a range between 4 and 40 hours, with a mean values of 14 hours.

From these data it clearly emerges that a green roof system is able to significantly reduce storm water runoff generation in Mediterranean regions in terms of runoff volume reduction, peak attenuation and increase of starting runoff time. If these results are transferred to the spatial scale of the urban watershed, green roof installations can become helpful tool to prevent flooding phenomena in the urban areas and to limit the impact of storm water on waste water treatment plants (Carter & Rasmussen, 2006; Palla et al., 2008).

5.3.2 Analysis of hydraulic efficiency of green roof based on event scale data

After the validation process, in order to analyze the influence of the hydrologic parameters on the green roof efficiency, the runoff from the green roof was evaluated.

By analyzing the 70 rainfall events recorded on the experimental site at Unical (Italy), and the 50 rainfall events at the Congress Center in Lyon (France), through the SIGMA DRAIN conceptual model, it was possible to obtain the runoff volumes delivered from the green roof for each rainfall event.

Consequently, based on these values, the relative subsurface runoff coefficient (SRC) and the retention capacity (VR) of the green roof implemented at Unical, were evaluated. While the subsurface runoff coefficient was expressed as the ratio between the runoff volume from vegetated roof and the rainfall volume, the retention capacity (VR) of the green roof, was evaluated as the inverse of the SRC, using the following equation:

$$VR\ (\%) = \left(1 - \frac{Runoff\ depth\ [mm]}{Rainfall\ depth\ [mm]}\right) \cdot 100 \qquad \text{Eq. 27}$$

Literature values of the retention ratio can often not be directly compared; several studies use different time intervals for assessing the retention performance of green roofs.

In particular, the results obtained in terms of runoff, subsurface runoff coefficients (SRC) and retention capacity (VR), for each rainfall events, are shown in the Tables A-5.4 and A-5.5 (in the Annex).

A similar behavior for both scenarios (Unical and Lyon), is evident by comparing the results provided by SIGMA DRAIN in terms of runoff: it has been estimated a threshold rainfall depth of 13 mm, below which the green roof retains almost the totality of the event.

Carrying out a more detailed analysis of the values reported in the annexed tables (Tab. A-5.4 and A-5.5), for event higher than 13 mm, it is possible to notice a strong proportionality between rainfall and runoff depths: to small events with redoubt rainfall depth correspond law runoff depth values. The Runoff depth as a function of the Precipitation depth for the two sites is reported in the Figure below (Fig. 5.16).

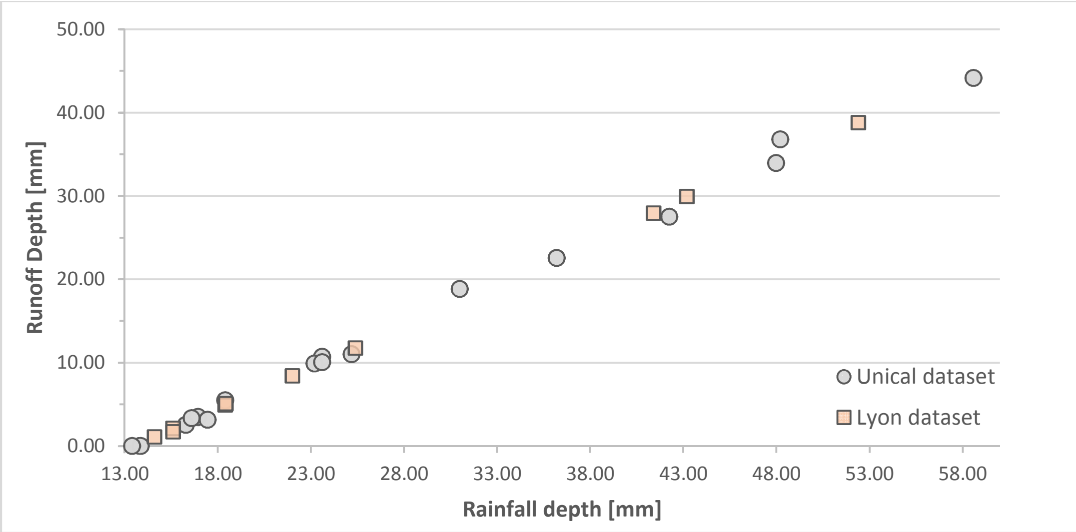

Figure 5.16: Relationship between rainfall and runoff depth

Analogous observations to those already done are found from the analysis of subsurface runoff coefficient and retention capacity as a function of the rainfall depth.

Figure 5.17 shows how the distribution of the subsurface runoff coefficient, as a function of rainfall depth, is similar for both rainfall data sets. Indeed, the surfurface runoff coefficient values rise as the rainfall increases, until an asymptotic value of around 75% is reached.

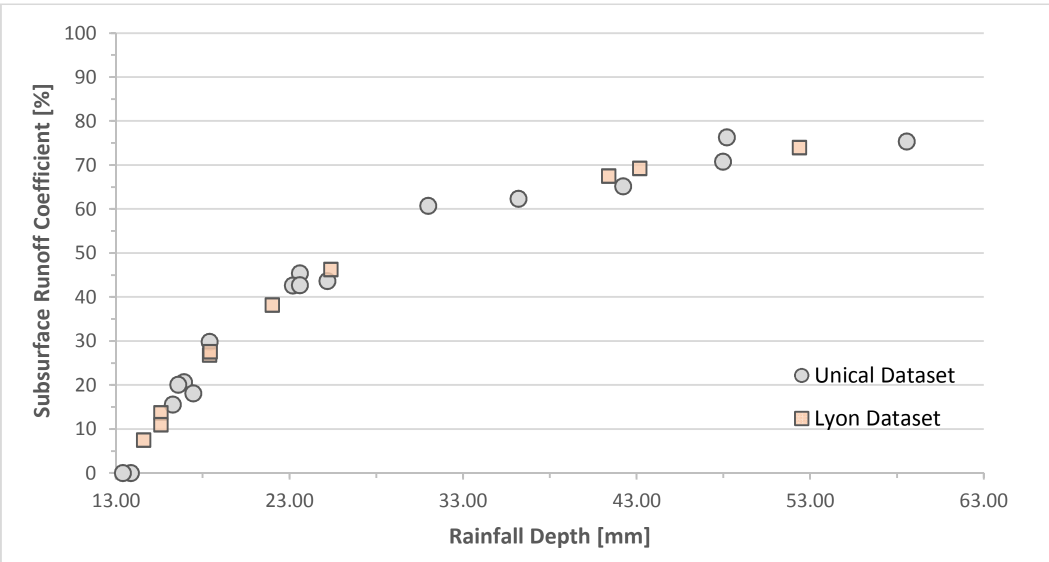

Figure 5.17: Relationship between subsurface runoff and precipitation depth

As expected, the two parameters are strongly correlated and exhibits an opposite trend of the results in Figure 5.3, in which the retention percent is strongly related to the precipitation depth. In fact, as previously said, retention percent is the inverse of the subsurface runoff coefficient and it represents the amount of water that the green roof retains after a rainfall event. Specifically, Figure 5.18 shows that the retention percent exponentially drops as the rainfall depth increases.

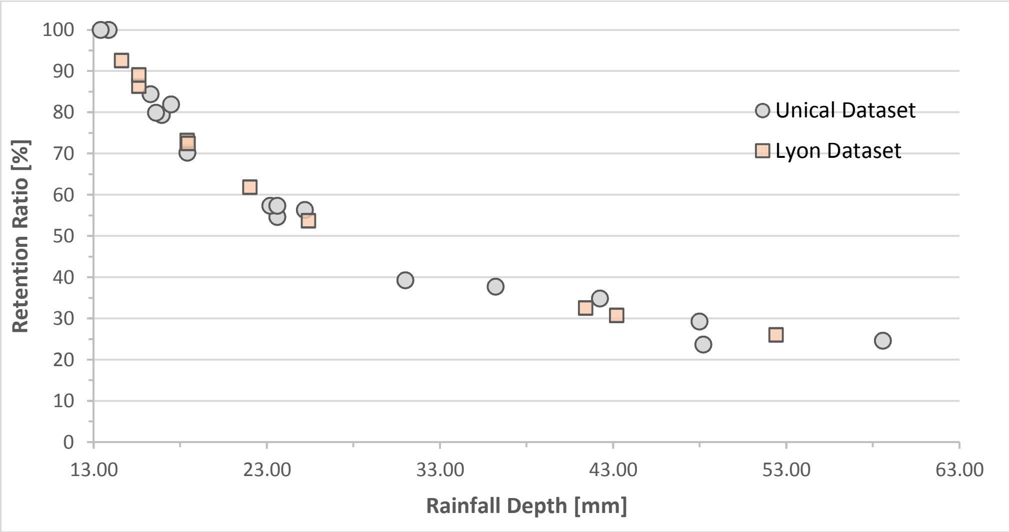

Figure 5.18: Relationship between retention and precipitation depth

Looking both the figures, it can be observe that:

- For precipitation higher than 13 mm, the green roof system presents a mean value of SRC equal to 46% and 38% for Unical and Lyon dataset, respectively;
- For events with a rainfall depth higher than 30 mm, the Subsurface runoff coefficient is higher than 60 % for both datasets;
- The retention capacity of the green roof considered varies between 25 % and 100 % for all the events, with a mean values of 63%.

All these three plots (Figure 5.15, 5.16 and 5.17) show that the results from the two sites area follow the same trend, suggesting that this green roof package, developed at University of Calabria, under Mediterranean climate conditions, has a good hydraulic performance also in a different climate, as the Temperate one, in which the Lyon data were recorded.

5.3.3 Regression Analysis results

The focus of this part of the study concerns the analysis about the effect of hydrologic parameters on the hydraulic efficiency of the experimental green roof, located in Mediterranean area. A multiple linear regression analysis, using the rainfall data collected from the experimental site at University of Calabria, was evaluated.

The results of the multiple linear regression analysis are summarized in Table 5.6, where the t-statistics (significant at p = 0.05) are presented in the same order as the parameters in the equation.

Table 5.6 Multiple Linear Regression Analysis for rainfall data collected at University of Calabria.

REGRESSION EQUATION		*R^2*	*T-STATISTIC*
$RD = -4.10 + 0.71PD$	*(Eq. 28)*	*0.9*	*24.7*
$LNVR_{\%} = -4.92 - 0.18\ LNPD - 0.02D$	*(Eq. 29)*	*0.7*	*-4.7, -4-.0*
$VR = 1.13 - 0.03D - 0.03I$	*(Eq. 30)*	*0.7*	*.10.9, -4.2*

The first relationship (Eq. 28) correlates the runoff depth (RD) from with the rainfall depth (PD) and presents a R^2 equal to 0.9; this finding is in agreement with the results previously seen in Fig. 5.15, which shows a strong correlation between these two parameters.

The second equation (Eq. 29) was defined by considering how the Retention capacity (%) could be express as a function of rainfall depth (PD) and rainfall duration (d). Although this relationship exhibits a R^2 equal to 0.7, the *t-statistic* of both parameters were characterized by a low significance level.

In the regression equation (Eq. 30), the retention capacity (VR) was obtained by using the rainfall duration (*d*) and intensity (*i*), with an R^2 equal to 0.7.

In agreement with Stovin et al. (2012), and with the previous consideration in the paragraph (5.3.1.1), the antecedent dry weather period (ADWP) was not found to be a good predictor of retention.

Validation

The multi-regression relationships, reported in Table 5.6, are validated by using the rainfall data recorded at Congress Center in Lyon (Table A-5.2).

In the validation process, the SIGMA DRAIN model was used as a reference to verify the soundness of the data obtained from the statistical relationship.

The results of the statistical relationships are compared with those obtained from the SIGMA DRAIN model - loaded with the 1-minute rainfall data as well - are shown in the Figures below (Fig. 5.19, Fig. 5.20 and Fig. 5.21).

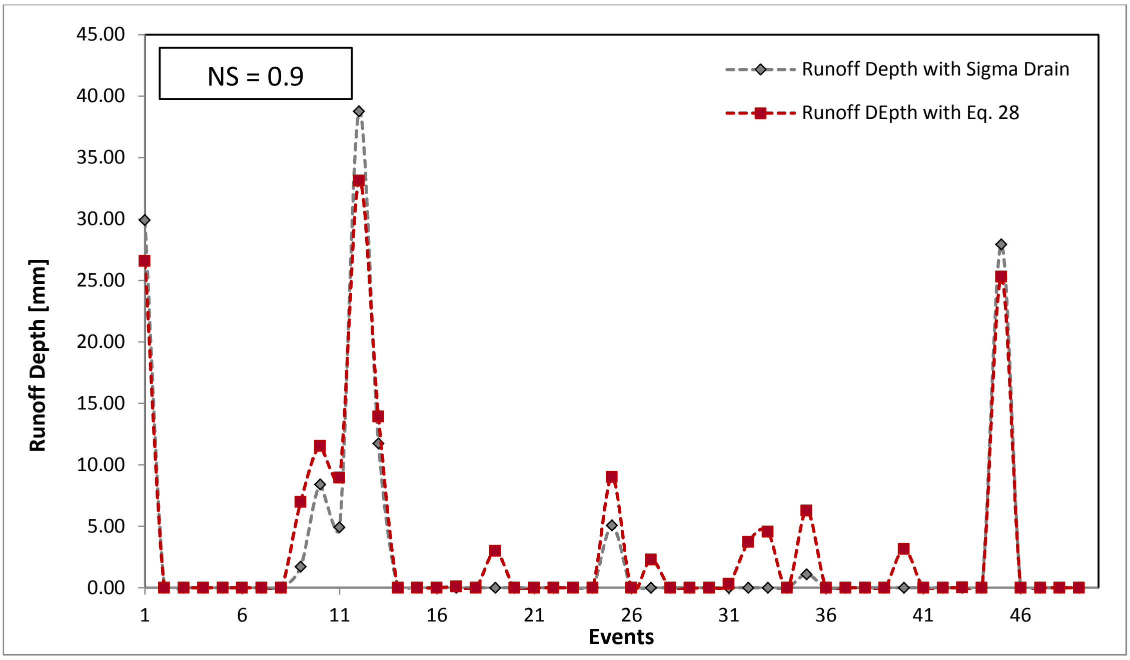

Figure 5.19: Runoff Depth predicted by the Eq. 28 and modelled with SIGMA DRAIN model, with Lyon dataset.

The runoff obtained from the regression relationships (Eq. 28), for the entire data set is similar to the runoff provided through SIGMA DRAIN model, corresponding to a NS value equal to 0.9. In particular is possible to notice how the runoff depth obtained by the Eq. 28, generally overestimates the SIGMA DRAIN values, except for events with a rainfall depth higher than 40 mm (as events 2, 13 and 46 of Lyon dataset, Table A-5.2).

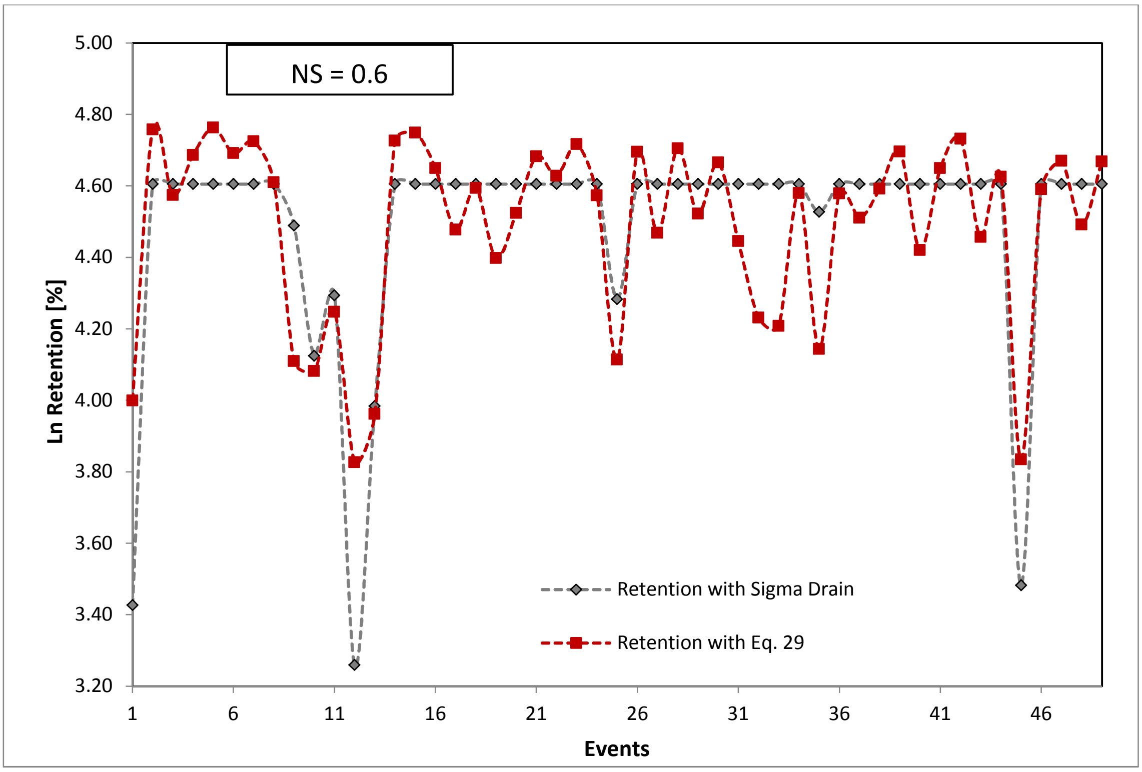

Figure 5.20: Runoff Depth predicted by the Eq. 29 and modelled with SIGMA DRAIN model, with Lyon dataset.

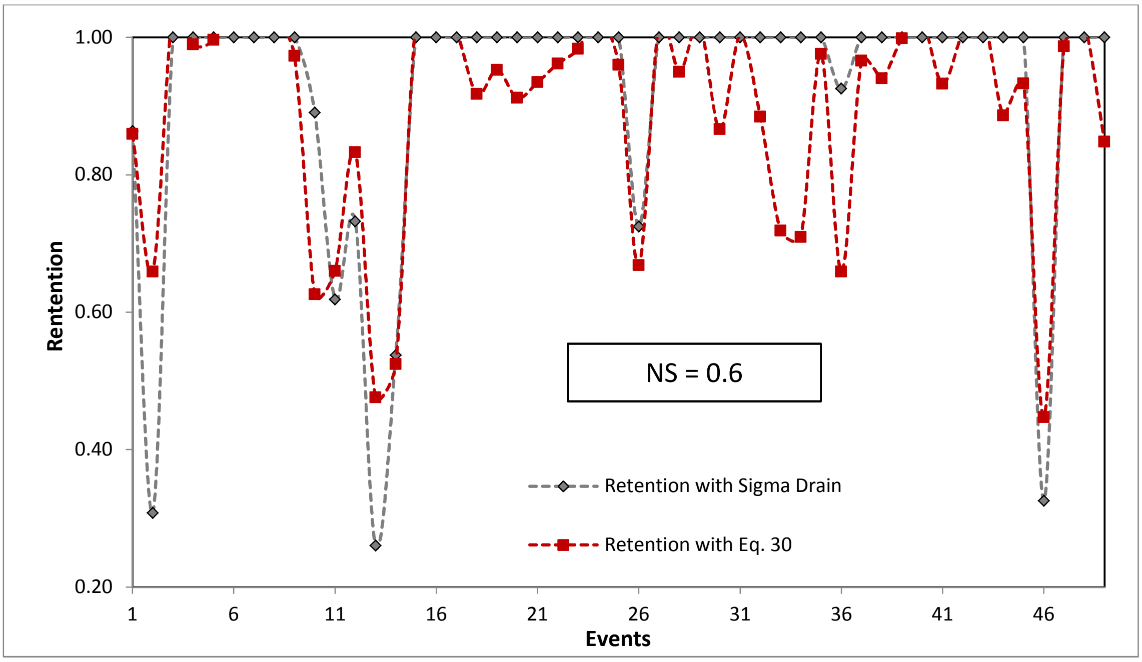

Figure 5.21: Runoff Depth predicted by the Eq. 30 and modelled with SIGMA DRAIN model, with Lyon dataset.

The retention capacity, in above Figures (Fig. 5.19 and 5.20) obtained by Eq. 29 and Eq. 30 respectively, for the entire data set are similar to the values obtained through SIGMA DRAIN model, both present a NS value of 0.6.

In conclusion, it can be said that the three relationships were validated and, therefore, it is possible to use them, by considering rainfall data recorded at 1- minute time steps and characterized by a precipitation depth of at least 2 mm and an intra-event of 2 hours, both in Mediterranean and in Temperate climate conditions. These equations can be used to preliminarily predict the runoff depth and the retention capacity, for a given rainfall events, when more advanced model are not available.

5.4 Conclusions and Perspectives

The hydrological behavior of an experimental green roof in Mediterranean area was examined on an event scale and, by combining consecutive events, at multi-event scale.

Results obtained from the validation at event scale, reveal the suitability of the SIGMA DRAIN model to well approximates the model HYDRUS-1D - used as a benchmark - and therefore correctly describe the hydrologic behavior of the green roof, for precipitation above 20 mm, while for events with rainfall depth lower than 20 mm, the performance of the model are not satisfactory. More in details, as proof of this consideration, the Nash-Sutcliffe coefficient, one of the performance indicators used in the study, is always >0.5 only for events with a rainfall depth higher than 20 mm. Such behavior was attributed to the fact that the initial water content of the substrate is not taken into account by the SIGMA DRAIN model, differently from HYDRUS-1D. As good evidence of this, the results of multi-event simulations, with an average value of NS equal to 0.8, have shown that the antecedent hydrologic-hydraulic conditions prior the event are relevant in assessing the response of the model. From the simulations results it is clear how small events that individually did not produce runoff, when grouped with others, produce a runoff. At event scale, the most sensitive variables in the model are therefore the initial conditions, which vary from event to event and depend in a complex way on the succession of antecedent of rainfall events and dry weather periods.

Another goal of the study was to determine if runoff from the modelled green roof was significantly less than that from a impervious roof type; for this purpose three variables were evaluated: runoff attenuation, peak flow reduction and delay in starting time of runoff compared to a conventional roof. The performance of the green roof installed at University of Calabria, as a device for stormwater control appear very good, with an average runoff volume attenuation of 49% and 24 % at event scale and multi-event scale, respectively, and an average peak flow reduction of 80 %, compared to the impermeable roof.

After validation procedure, the model was loaded with datasets collected in two different sites (Unical, in Italy and Lyon, in France), in order to analyze the influence of the hydrologic parameters on the green roof efficiency. A similar behavior for both scenarios (Unical and Lyon) is evident by comparing the results provided by SIGMA DRAIN in terms of runoff: the two sites area follow the same trend, suggesting that this green roof package, developed at University of Calabria, under Mediterranean climate conditions, has a good hydraulic performance also in a different climate, as the Temperate one, in which the Lyon data were recorded.

Furthermore, to statistically determine the significance of the hydrological parameters on the event runoff coefficient, the multiple linear regression analysis was applied. Indeed, the investigation revealed that the parameters that most influence the retention capacity of vegetated roof are the rainfall depth, the duration and intensity, according to which, the substrate moisture condition changes. The relationships founded and validated with Lyon dataset, can be used to preliminarily predict the runoff depth and the retention capacity, for a given rainfall events, when more advanced model are not available.

From these data it clearly emerges that a green roof system is able to significantly reduce storm water runoff generation in Mediterranean regions in terms of runoff volume reduction, peak attenuation and increase of starting runoff time. In the framework of the assessment of the environmental benefits, it is necessary to transfer the single green roof installation to spatial scale of the watershed, to prevent flooding phenomena in the urban areas and to limit the impact of storm water on waste water treatment plants.

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Chapter 6 – GENERAL CONCLUSIONS

6.1 Conclusions

The progressive increase of impermeable surfaces and environmental changes in urban areas have produced drastic changes in the natural hydrological cycle. The hydrological effects of urbanization affect the rainfall-runoff regime of many cities in the world. During rainfall events, the infiltration rate and evapotranspiration in highly urbanized watersheds have significantly dropped and, as a result, an increase of runoff volumes and peak flow rates has occurred. The reduction of green areas and ‘sealing’ surface not only produce negative effects from a hydrological-hydraulic perspective, but also from an energy point of view contributing to modifying the urban microclimate and generating heat islands in our cities.

While traditional stormwater drainage systems are often able to effectively serve the function of flood control, they increase downstream peak flows and do not provide a habitat to support a healthy aquatic ecosystem. In order to improve this situation, water managers introduced the concept of Low Impact Development. The goal of this concept is to maintain or re-establish predevelopment site hydrology.

Green roofs may represent a sustainable solution for minimizing the impact of urbanization on the hydrologic cycle and for sustainably managing water resources in urban environment. Green roofs are designed to capture, temporarily retain and infiltrate stormwater and to promote evapotranspiration (ET). So far, green roofs have been broadly investigated from a hydraulic perspective, thus analyzing the runoff volume reduction and the peak flow mitigation provided by such measures.

Several studies have shown that green roofs effectively control surface runoff in urban drainage systems reducing overall stormwater volumes and peak flow rates. From the studies found in literature, the hydraulic efficiency of a green roof strongly depends on the hydrological parameters of the rainfall events, such as precipitation depth, antecedent dry weather period, duration and intensity of the event. Most of the studies provided an annual or a seasonal subsurface runoff coefficient, varying from 0.32 to 0.89.

Based on the knowledge gap in the understanding of quantitative hydrological effects of green roofs the experimental green roof installed at Unical was chosen as a case study for this research. The main objectives of the research were to:

- define, improve and implement a methodology for the design of green roofs by using data from two different geographical areas and climate conditions in order to identify some key factors for the characterization of the response of green roof system.
- develop and calibrate a green roof conceptual model, which mimics the physical structure of an innovative green roof system;
- determine the quantitative hydrological performance of the experimental green roof installed at Univeristy of Calabria, in Mediterranean area;
- verify that the green roof performance are better than those of a conventional roof, impervious type;
- establish the influencing hydrological factors on the hydraulic efficiency of the Unical green roof;
- determine multi-regression equations, specific for the site of interest, which can be useful for preliminary design consideration, in the case a detailed model of a green roof is not available

The hydrological behavior of an experimental green roof in Mediterranean area was examined on an event scale and, by combining consecutive events, at multi-event scale.

Results obtained from the validation at event scale, reveal the suitability of the SIGMA DRAIN model to well approximates the model HYDRUS-1D - used as a benchmark - and therefore correctly describe the hydrologic behavior of the green roof, for precipitation above 20 mm. Such behavior was attributed to the fact that the initial water content of the substrate is not taken into account by the SIGMA DRAIN model, differently from HYDRUS-1D. As good evidence of this, the results of multi-event simulations, with an average value of NS equal to 0.8, have shown that the antecedent hydrologic-hydraulic conditions prior the event are relevant in assessing the response of the model. From the simulations results it is clear how small events that individually did not produce runoff, when grouped with others, produce a runoff. At event scale, the most sensitive variables in the model are therefore the initial conditions, which vary from event to event and depend in a complex way on the succession of antecedent of rainfall events and dry weather periods.

Moreover was determine the runoff from the modelled green roof and was compared with that from a impervious roof type. To better evaluate the performance of the experimental green roof three variables were evaluated: runoff attenuation, peak flow reduction and delay in starting time of runoff compared to a conventional roof. The performance of the green roof installed at University of Calabria, as a device for stormwater control appear very good, with an average runoff volume attenuation of 49% and 24 % at event scale and multi-event scale, respectively, and an average peak flow reduction of 80 %, compared to the impermeable roof.

In order to analyze the influence of the hydrologic parameters on the green roof efficiency, the model was loaded with two different datasets. A similar behavior for both scenarios is evident by comparing the results in terms of runoff: the two sites area follow the same trend, suggesting that this green roof package, developed at University of Calabria, under Mediterranean climate conditions, has a good hydraulic performance also in a different climate, as the Temperate one, in which the Lyon data were recorded.

Finally, to statistically determine the significance of the hydrological parameters on the event runoff coefficient, the multiple linear regression analysis was applied. The investigation revealed that the parameters that most influence the retention capacity of vegetated roof are the rainfall depth, the duration and intensity, according to which, the substrate moisture condition changes. The relationships founded and validated with data collected in Lyon, located in Temperate climate condition, can be used to preliminarily predict the runoff depth and the retention capacity, for a given rainfall events, when more advanced model are not available.

From these data it clearly emerges that green roof system is able to significantly reduce storm water runoff generation in Mediterranean regions in terms of runoff volume reduction, peak attenuation and increase of starting runoff time in comparison to an impervious surface.

In the framework of the assessment of the environmental benefits, it is necessary to transfer the single green roof installation to spatial scale of the watershed, to prevent flooding phenomena in the urban areas and to limit the impact of storm water on waste water treatment plants.

Furthermore, it is important to understand mechanisms used by each stormwater management device to ensure that their application will support environmental processes. The results of this study characterize the impervious response of a green roof and show that it can contribute in a positive way, in conjunction with other stormwater management devices and low impact development techniques, to reducing impervious area. That is, green roofs can play an important role in returning the hydrologic cycle and water balance of developed areas toward pre-development ratios, providing a benefit to the environment.

6.2 Possible Future Develompents

Despite the achievements presented in this work, there is still space for improvements.

In an urban environment, vegetated roofs are sustainable systems, which provide a variety of valuable benefits, such as the reduction of stormwater volumes and the mitigation of urban heat island, strongly linked to their evaporative processes. The evapotranspiration (ET) is one of the most important processes of the hydrological cycle, but it also represents one of the most difficult hydrological phenomena to quantify due to the complex interaction between the ground surface, vegetation and atmosphere. Since the ET provides a beneficial effect in green roofs, by enhancing the water loss, an accurate estimation of evapotranspiration is essential to predict such a positive aspect.

Based on these considerations, and because only few studies had evaluated the evapotranspiration (ET) phenomena from a vegetated roofs, a possible future perspective of this research could be an accurate computation of evapotranspiration (ET) from vegetated roofs, using on-site meteorological data, to properly predict the benefits of such systems.After a first evaluation of the ET of the experimental green roof, located at the University of Calabria (Italy), the time variation of water content in the substrate, measured in the experimental green roof, will be used to quantify the water loss due to the ET.

Both case studies evaluated (HYDROPACK and SIGMA DRAIN) have shown that at event scale, the most sensitive variables in the model are the initial substrate water conditions, which vary from event to event and depend in a complex way on the succession of antecedent of rainfall events and dry weather periods. Therefore, it will important to evaluate specifically the water content in the substrate and put it in relation with the hydrological and meteorological parameters, that affect its variability. This study will aim to determine a relationship between this parameters, specific for the site of interest, which could be useful for preliminary design consideration or to assess the irrigation needs of the green roof. In agreement with what mentioned above, this factors also effects the water loss due to the ET.

Finally, since few literature studies have shown that green roofs are more effective when diffused at watershed scale, or when are installed in synergy with other solutions (as, e.g. permeable pavements, filter strips, etc.), the research will address the integration of these different LID solutions, at the watershed scale, both to reduce the risk of flooding and also to provide a many other environmental benefits.

Appendix A-4.1: Hydrologic characteristics of Rainfall events Imax has recorded with 3 min time interval

No.	Events	Rainfall		
	No.	Date	I_{max}	d
#	#	[d/m/y h:m]	[mm/h]	[Hours]
6	1	09/05/2011 11:02	19.14	13.5
7	2	10/05/2011 07:05	19.34	4.7
10	3	27/05/2011 04:11	1.71	3.3
11	4	30/05/2011 07:47	2.68	18.3
12	5	31/05/2011 18:02	1.50	12.4
13	6	07/06/2011 01:59	10.43	35.0
14	7	12/06/2011 17:59	0.96	8.7
15	8	13/06/2011 13:47	6.28	12.3
16	9	16/06/2011 09:14	2.09	21.0
17	10	17/06/2011 11:05	3.24	17.7
18	11	18/06/2011 11:05	9.88	1.1
19	12	18/06/2011 18:47	1.10	13.9
20	13	22/06/2011 19:56	1.38	29.8
22	14	26/06/2011 19:17	4.26	227.0
23	15	06/07/2011 13:08	6.35	49.0
24	16	12/07/2011 03:14	6.00	10.8
25	17	16/07/2011 15:50	9.47	56.8
26	18	25/07/2011 10:44	20.42	33.8
27	19	01/08/2011 14:08	0.78	9.4
29	20	04/08/2011 12:50	2.64	30.2
30	21	06/08/2011 18:41	21.63	61.9
31	22	09/08/2011 09:41	9.27	146.4
33	23	20/08/2011 08:50	15.06	165.9
35	24	30/08/2011 12:14	5.83	235.3
36	25	12/09/2011 10:41	3.87	18.4
38	26	15/09/2011 21:50	1.63	18.2
39	27	17/09/2011 09:32	9.02	28.1
40	28	18/09/2011 15:41	7.44	16.1
41	29	22/09/2011 08:44	0.95	18.7
42	30	25/09/2011 06:38	1.03	24.9
59	31	01/11/2011 08:59	17.56	167.0
64	32	15/11/2011 10:29	1.70	46.0
66	33	19/11/2011 11:11	1.39	21.6
68	34	21/11/2011 10:05	1.89	22.9
70	35	25/11/2011 09:29	0.49	95.6
71	36	03/01/2012 12:05	47.38	32.6
72	37	04/01/2012 22:08	3.57	77.8
73	38	08/01/2012 06:26	2.13	392.2
74	39	24/01/2012 15:29	1.42	18.0
75	40	25/01/2012 10:26	3.35	140.4
76	41	31/01/2012 09:05	1.09	16.4
77	42	01/02/2012 03:29	1.29	16.4
78	43	01/02/2012 20:50	1.79	59.8
79	44	04/02/2012 09:56	2.27	13.3
80	45	05/02/2012 04:26	7.12	37.9
81	46	06/02/2012 21:05	2.85	32.4
82	47	09/02/2012 10:32	2.74	7.6
83	48	09/02/2012 19:32	1.16	36.9
86	49	12/02/2012 21:44	3.92	130.6
87	50	18/02/2012 11:32	6.36	45.0

Table A-5.1: Rainfall events characteristics by using 1-minute data from University of Calabria, Italy

#	Rainfall Event (*dd/mm/yyyy*)	Starting Time (*hh:mm*)	Rainfall Depth (*mm*)	Rainfall Duration (*hours*)	Rainfall Intensity (*mm/h*)	ADWP (*hours*)
1	09/09/2013	17:25	6.0	0.2	36.2	-
2	12/09/2013	12:25	12.8	3.1	4.2	66.8
3	12/09/2013	17:35	2.0	2.3	0.9	2.1
4	13/09/2013	06:32	3.5	0.5	7.2	10.7
5	16/09/2013	03:18	42.2	5.3	8.0	68.3
6	16/09/2013	12:02	2.4	0.5	5.4	3.4
7	30/09/2013	12:32	7.8	2.7	2.9	336.1
8	01/10/2013	05:28	3.5	0.6	5.6	14.2
9	16/10/2013	12:01	13.9	3.2	4.4	366.0
10	16/10/2013	19:06	2.5	1.6	1.6	3.9
11	05/11/2013	07:49	8.8	10.8	0.8	467.1
12	05/11/2013	21:20	2.9	2.6	1.1	2.7
13	11/11/2013	00:27	58.6	8.7	6.7	120.5
14	11/11/2013	13:22	6.2	5.4	1.2	4.2
15	13/11/2013	02:47	5.2	7.9	0.7	32.0
16	15/11/2013	14:13	16.9	9.7	1.7	51.6
17	22/11/2013	23:31	36.2	10.0	3.6	167.6
18	23/11/2013	12:44	4.9	3.3	1.5	3.2
19	23/11/2013	19:01	6.9	2.8	2.5	3.0
20	24/11/2013	07:35	18.4	7.2	2.6	9.8
21	24/11/2013	17:13	2.0	1.9	1.1	2.5
22	25/11/2013	22:48	7.5	1.4	5.6	27.7
23	26/11/2013	07:33	4.1	1.3	3.2	7.4
24	30/11/2013	10:59	48.0	27.2	1.8	98.2
25	03/12/2013	04:27	16.3	8.6	1.9	38.3
26	09/12/2013	16:16	2.4	3.7	0.7	147.3
27	15/12/2013	17:43	3.4	2.0	1.7	141.8
28	26/12/2013	13:06	8.2	4.7	1.7	257.4
29	26/12/2013	20:27	17.5	5.1	3.5	2.6
30	31/12/2013	10:51	3.2	2.1	1.6	105.4
31	13/01/2014	10.45	6.6	2.1	3.2	309.8
32	14/01/2014	10:14	6.0	0.5	12.9	21.4
33	15/01/2014	12:33	2.3	2.1	1.1	25.9
34	19/01/2014	06:56	9.2	8.2	1.1	88.3
35	20/01/2014	17:39	48.2	36.8	1.3	26.5
36	28/01/2014	13:24	2.2	0.2	12.2	150.9
37	28/01/2014	21:27	2.2	2.3	1.0	7.9
38	31/01/2014	23:34	31.0	21.2	1.5	71.9
39	02/02/2014	02:25	2.1	0.9	2.2	7.0
40	02/02/2014	19:43	4.0	4.2	1.0	16.4
41	03/02/2014	01:17	23.6	17.0	1.4	1.4
42	06/02/2014	06:04	4.1	2.4	1.7	59.8
43	08/02/2014	09:32	2.2	2.7	0.8	49.1
44	11/02/2014	22:58	25.2	12.9	2.0	82.7
45	12/02/2014	22:.43	4.2	1.9	2.2	10.9
46	21/02/2014	09:26	2.8	1.1	2.6	200.8
47	01/03/2014	14:36	2.8	4.0	0.7	196.1
48	02/03/2014	00:19	5.6	5.3	1.0	5.7
49	04/03/2014	03:34	11.2	5.3	2.1	46.0
50	04/03/2014	15:11	9.2	5.4	1.7	6.4
51	05/03/2014	18:20	2.1	0.6	3.3	21.8
52	05/03/2014	21:09	2.4	2.9	0.8	2.2
53	06/03/2014	17:37	13.4	7.8	1.7	17.6
54	08/03/2014	13:43	2.3	1.3	1.7	36.4
55	15/03/2014	04:28	5.0	4.4	1.1	157.4
56	24/03/2014	00:07	23.2	10.8	2.2	207.3
57	24/03/2014	13:54	11.8	4.3	2.8	3.0
58	24/03/2014	20:28	2.3	0.6	4.0	2.3
59	27/03/2014	02:27	11.6	5.0	2.3	53.4
60	27/03/2014	16: 41	3.0	4.6	0.7	9.2
61	27/03/2014	23:44	16.6	12.2	1.4	2.5
62	04/04/2014	15:45	2.8	1.6	1.7	171.9
63	05/04/2014	11:42	6.4	2.8	2.3	18.3
64	05/04/2014	21:37	12.6	10.6	1.2	7.1
65	15/04/2014	20:17	23.6	7.2	3.3	228.1
66	16/04/2014	13:53	5.5	0.9	5.9	10.5
67	23/04/2014	14:04	3.5	0.9	3.9	167.3
68	28/04/2014	05:45	10.4	13.7	0.8	110.8
69	29/04/2014	07:38	4.8	1.5	3.3	12.2
70	29/04/2014	15:45	3.6	4.8	0.7	6.7

Table A-5.2: Rainfall events characteristics by using 1-minute data from Lyon Congress Center, France

#	Rainfall Event (*dd/mm/yyyy*)	Starting Time (*hh:mm*)	Rainfall Depth (*mm*)	Duration (*hours*)	Rainfall Intensity (*mm/h*)	ADWP (*hours*)
1	24/09/2012	04:42	15.6	2.3	6.7	-
2	26/09/2012	11:11	43.2	12.2	3.6	52.2
3	29/09/2012	05:54	2.0	1.9	1.1	54.6
4	30/09/2012	09:34	5.4	2.1	2.6	25.8
5	07/10/2012	00:11	2.4	3.8	0.6	156.5
6	08/10/2012	22:08	2.0	1.6	1.2	42.1
7	10/10/2012	02:05	2.8	2.2	1.3	26.3
8	12/10/2012	06:11	2.6	1.2	2.2	49.9
9	26/10/2012	13:33	3.4	4.5	0.8	342.2
10	26/10/2012	23:01	15.6	15.8	1.0	5.0
11	04/11/2012	14:07	22.0	14.1	1.6	190.3
12	10/11/2012	03:13	18.4	7.4	2.5	119.0
13	26/11/2012	10:58	52.4	19.1	2.8	384.3
14	28/11/2012	12:24	25.4	18.8	1.3	30.4
15	04/12/2012	02:54	2.2	2.6	0.8	115.7
16	14/12/2012	15:59	2.0	2.3	0.9	250.5
17	15/12/2012	00:16	3.2	3.1	1.0	6.0
18	16/12/2012	19:48	5.9	6.1	1.0	40.5
19	20/12/2012	13:23	3.4	5.3	0.6	83.5
20	22/12/2012	12:44	10.0	5.4	1.8	42.1
21	01/01/2013	09:48	4.8	5.7	0.8	231.7
22	10/01/2013	07:34	2.1	5.2	0.4	208.1
23	10/01/2013	21:45	3.2	4.1	0.8	9.0
24	14/01/2013	00:07	2.6	1.6	1.6	70.3
25	15/01/2013	12:15	4.0	4.8	0.8	34.5
26	27/01/2013	12:04	18.4	14.1	1.3	283.0
27	01/02/2013	23:26	2.6	2.7	1.0	117.3
28	05/02/2013	15:52	9.0	2.8	3.2	85.8
29	06/02/2013	12:34	2.4	2.9	0.8	17.9
30	07/02/2013	01:49	3.6	8.4	0.4	10.4
31	08/02/2013	09:22	2.8	3.4	0.8	23.2
32	11/02/2013	04:20	6.2	7.3	0.8	63.5
33	11/02/2013	23:36	11.0	12.9	0.9	11.9
34	17/03/2013	21:14	12.2	13.1	0.9	800.8
35	23/03/2013	23:48	4.2	4.1	1.0	133.5
36	28/03/2013	05:10	14.6	14.7	1.0	97.2
37	29/03/2013	07:15	4.0	4.6	0.9	11.4
38	30/03/2013	03:33	5.4	5.3	1.0	15.7
39	30/03/2013	18:44	4.8	2.3	2.1	9.9
40	08/04/2013	08:36	2.6	2.6	1.0	203.6
41	11/04/2013	18:02	10.2	4.1	2.5	78.8
42	19/04/2013	00:44	3.2	3.1	1.0	170.6
43	19/04/2013	11:51	2.2	2.4	0.9	8.0
44	20/04/2013	03:38	5.8	7.3	0.8	13.4
45	26/04/2013	10:43	2.6	6.2	0.4	143.8
46	26/04/2013	21:20	41.4	20.8	2.0	4.5
47	28/04/2013	11:59	4.2	3.6	1.2	17.9
48	29/04/2013	13:56	3.4	1.5	2.3	22.4
49	29/04/2013	18:14	4.0	9.0	0.4	2.8
50	30/04/2013	19:02	3.6	1.1	3.3	15.9

Table A-5.3 - Green Roof Hydrologic performance compared to the Conventional Roof at Multi Event Scale

#	Rainfall Events (*dd/mm/yyyy*)	Rainfall Depth (*mm*)	Green Roof Runoff Flow (*l/s*)	Runoff Attenuation (*%*)	Delay in Starting Runoff Time (*hours*)	NS
1	12/09/2013 12/09/2013 13/09/2013 16/09/2013 16/09/2013	62.6	40.6	22.1	18.6	0.5
2	11/11/2013 11/11/2013 13/11/2013 15/11/2013	87.0	61.4	14.4	3.9	0.9
3	22/11/2013 23/11/2013 23/11/2013 24/11/2013 24/11/2013	67.2	46.5	17.9	5.2	0.9
4	30/11/2013 01/12/2013	63.4	41.5	19.8	21.0	0.8
5	26/12/2013 26/12/2013 31/12/2013	29.2	14.5	41.8	10.6	0.8
6	19/01/2014 20/01/2014	57.6	39.5	20.6	39.9	0.8
7	31/01/2014 02/02/2014 02/02/2014 03/02/2014 06/02/2014	60.8	44.7	18.1	11.9	0.8
8	24/03/2014 24/03/2014 24/03/2014 27/03/2014 27/03/2014 27/03/2014	74.2	58.8	16.2	8.5	0.7
9	15/04/2014 16/04/2014	29.0	12.8	46.7	5.5	0.6
RANGE				*14.4 ÷46.7*	*3.93 ÷40.0*	*0.5 ÷ 0.9*
MEAN				*24.2*	*13.9*	*0.8*
ST. DEVIATION				*11.7*	*11.4*	*0.1*

Table A-5.4: Sigma Drain Model results, using rainfall data recorded at Univeristy of Calabria (Italy)

#	Rainfall Events (*dd/mm/yyyy*)	Rainfall Depth (*mm*)	Runoff Depth (mm)	SRC (*%*)	VR (*%*)
1	09/09/2013	6.0	0.0	0	100
2	12/09/2013	12.8	0.0	0	100
3	12/09/2013	2.0	0.0	0	100
4	13/09/2013	3.5	0.0	0	100
5	16/09/2013	42.2	27.5	65	35
6	16/09/2013	2.4	0.0	0	100
7	30/09/2013	7.8	0.0	0	100
8	01/10/2013	3.5	0.0	0	100
9	16/10/2013	13.9	0.0	0	100
10	16/10/2013	2.5	0.0	0	100
11	05/11/2013	8.8	0.0	0	100
12	05/11/2013	2.9	0.0	0	100
13	11/11/2013	58.6	44.2	75	25
14	11/11/2013	6.2	0.0	0	100
15	13/11/2013	5.2	0.0	0	100
16	15/11/2013	16.9	3.5	21	79
17	22/11/2013	36.2	22.6	62	38
18	23/11/2013	4.9	0.0	0	100
19	23/11/2013	6.9	0.0	0	100
20	24/11/2013	18.4	5.5	30	70
21	24/11/2013	2.0	0.0	0	100
22	25/11/2013	7.5	0.0	0	100
23	26/11/2013	4.1	0.0	0	100
24	30/11/2013	48.0	34.0	71	29
25	03/12/2013	16.3	2.5	16	84
26	09/12/2013	2.4	0.0	0	100
27	15/12/2013	3.4	0.0	0	100
28	26/12/2013	8.2	0.0	0	100
29	26/12/2013	17.5	3.2	18	82
30	31/12/2013	3.2	0.0	0	100
31	13/01/2014	6.6	0.0	0	100
32	14/01/2014	6.0	0.0	0	100
33	15/01/2014	2.3	0.0	0	100
34	19/01/2014	9.2	0.0	0	100
35	20/01/2014	48.2	36.8	76	24
36	28/01/2014	2.2	0.0	0	100
37	28/01/2014	2.2	0.0	0	100
38	31/01/2014	31.0	18.8	61	39
39	02/02/2014	2.1	0.0	0	100
40	02/02/2014	4.0	0.0	0	100
41	03/02/2014	23.6	10.7	45	55
42	06/02/2014	4.1	0.0	0	100
43	08/02/2014	2.2	0.0	0	100
44	11/02/2014	25.2	11.0	44	56
45	12/02/2014	4.2	0.0	0	100
46	21/02/2014	2.8	0.0	0	100
47	01/03/2014	2.8	0.0	0	100
48	02/03/2014	5.6	0.0	0	100
49	04/03/2014	11.2	0.0	0	100
50	04/03/2014	9.2	0.0	0	100
51	05/03/2014	2.1	0.0	0	100
52	05/03/2014	2.4	0.0	0	100
53	06/03/2014	13.4	0.0	0	100
54	08/03/2014	2.3	0.0	0	100
55	15/03/2014	5.0	0.0	0	100
56	24/03/2014	23.2	9.9	43	57
57	24/03/2014	11.8	0.0	0	100
58	24/03/2014	2.3	0.0	0	100
59	27/03/2014	11.6	0.0	0	100
60	27/03/2014	3.0	0.0	0	100
61	27/03/2014	16.6	3.3	20	80
62	04/04/2014	2.8	0.0	0	100
63	05/04/2014	6.4	0.0	0	100
64	05/04/2014	12.6	0.0	0	100
65	15/04/2014	23.6	10.1	43	57
66	16/04/2014	5.5	0.0	0	100
67	23/04/2014	3.5	0.0	0	100
68	28/04/2014	10.4	0.0	0	100
69	29/04/2014	4.8	0.0	0	100
70	29/04/2014	3.6	0.0	0	100

Table A-5.5: Sigma Drain Model results, using rainfall data recorded at the Lyon Congress Center (France)

#	Rainfall Event (*dd/mm/yyyy*)	Rainfall Depth (*mm*)	Runoff Depth (mm)	SRC (*%*)	VR (*%*)
1	24/09/2012	15.6	2.1	14	86
2	26/09/2012	43.2	29.9	69	31
3	29/09/2012	2.0	0.0	0	100
4	30/09/2012	5.4	0.0	0	100
5	07/10/2012	2.4	0.0	0	100
6	08/10/2012	2.0	0.0	0	100
7	10/10/2012	2.8	0.0	0	100
8	12/10/2012	2.6	0.0	0	100
9	26/10/2012	3.4	0.0	0	100
10	26/10/2012	15.6	1.7	11	89
11	04/11/2012	22.0	8.4	38	62
12	10/11/2012	18.4	4.9	27	73
13	26/11/2012	52.4	38.8	74	26
14	28/11/2012	25.4	11.8	46	54
15	04/12/2012	2.2	0.0	0	100
16	14/12/2012	2.0	0.0	0	100
17	15/12/2012	3.2	0.0	0	100
18	16/12/2012	5.9	0.0	0	100
19	20/12/2012	3.4	0.0	0	100
20	22/12/2012	10.0	0.0	0	100
21	01/01/2013	4.8	0.0	0	100
22	10/01/2013	2.1	0.0	0	100
23	10/01/2013	3.2	0.0	0	100
24	14/01/2013	2.6	0.0	0	100
25	15/01/2013	4.0	0.0	0	100
26	27/01/2013	18.4	5.1	28	72
27	01/02/2013	2.6	0.0	0	100
28	05/02/2013	9.0	0.0	0	100
29	06/02/2013	2.4	0.0	0	100
30	07/02/2013	3.6	0.0	0	100
31	08/02/2013	2.8	0.0	0	100
32	11/02/2013	6.2	0.0	0	100
33	11/02/2013	11.0	0.0	0	100
34	17/03/2013	12.2	0.0	0	100
35	23/03/2013	4.2	0.0	0	100
36	28/03/2013	14.6	1.1	7	93
37	29/03/2013	4.0	0.0	0	100
38	30/03/2013	5.4	0.0	0	100
39	30/03/2013	4.8	0.0	0	100
40	08/04/2013	2.6	0.0	0	100
41	11/04/2013	10.2	0.0	0	100
42	19/04/2013	3.2	0.0	0	100
43	19/04/2013	2.2	0.0	0	100
44	20/04/2013	5.8	0.0	0	100
45	26/04/2013	2.6	0.0	0	100
46	26/04/2013	41.4	27.9	67	33
47	28/04/2013	4.2	0.0	0	100
48	29/04/2013	3.4	0.0	0	100
49	29/04/2013	4.0	0.0	0	100
50	30/04/2013	3.6	0.0	0	100