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EXPERIMENTAL STUDY AND QUALITATIVE AND QUANTITATIVE MODELLING OF SUSTAINABLE URBAN DRAINAGE SYSTEMS (SUDS)

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Antonello Mancuso

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Abstract

Climate changes have become always more frequent, increasing the interest of researchers in finding the causes and, above all, the structural or non-structural solutions to solve the problem. Economic development together with rapid population growth constantly increase the demand of goods and services. As the same as drought, also precipitation became more intense and frequent, even with more ever short duration. These events for their heavy impact are called ‘extreme rainfall events’. The actual management of urban waters is unsustainable thus, foregoing reasons lead to an imperative need to develop new urban ecosystems, requiring a rethink of traditional development techniques. Traditional urban drainage systems are designed to rapidly collect and convey overland flows to the treatment plants, without taking into account of their qualitative characteristics. In order to reach the aim of the qualitative and quantitative control of stormwater in urban areas, a possible way is the widespread implementation in urban areas of ‘blue-green infrastructure’ that provide an holistic and integrated approach to the problem. They are one step beyond other ‘classic’ sustainable urban drainage measures such as LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems) or BMPs (Best Management Practices), allowing to emphasize their beneficial effects. Use of BGC as a part of sustainable drainage system concept is a winning approach, that allow managing and treatment of stormwater runoff within urban areas, using practices made of green and blue components. Generally green components are represented by any kind of existing vegetation (floral plants, grass, hedges) while the blue one by lakes, ponds, rivers and canals (natural or artificial). Together, these infrastructures allow to create a network between them at regional scale. The real behaviour of these structures is not yet properly modelled. Most of the software currently used in urban hydrology (SWMM by EPA, Music by eWater CRC, etc…) model in a reasonable way the hydraulic behaviour of infiltration practices (such as bioretention cells, infiltration trenches, vegetated filter strips, porous pavement) using a simple mass balance approach. Generation, inflow and transport of pollutants are, instead, determined by the land use assigned to each subcatchments, namely through buildup and washoff laws describing accumulation and washout by either a mass per unit of subcatchment area or per unit of curb length. This approach completely lack of quality algorithms within LID models that take into account of their quality performances as, for instance, reduction of efficiency due to the clogging effect. The clogging phenomenon, described as the decrease in infiltration rate of the soil due to the reduction in soil porosity and hydraulic conductivity, occurs for the majority within infiltration practices such as bioretention cells, infiltration trenches, vegetated swales and permeable pavers. Precisely these latter practices are one of the easiest to implement into urban environment, being aimed to reduce impervious areas and work as ‘link’ within BGCs networks. From these premises the research in the following thesis is developed, whose main objective is to study the implementation of 'blue and green' elements in urban areas and their effect on pollutant loads reduction. Initially, a study of common errors retrieved within a DTM (Digital Terrain Model) has been faced because, if not corrected, they will affect the overland flow network generation and the subsequent hydraulic modelling. DEMs (Digital Elevation Models) can include both terrain elevation data, which commands flow direction of floodwater, and land cover information, which dictates resistance to floodwater distribution. Very often DTMs originate from a variety of ground observations supplemented by various remote sensing techniques (aerial and satellite measurements, total stations, dGPS, aerial LiDAR, terrestrial laser scanning) thus, containing systematic or random errors to individuate and eliminate. A study were carried out to evaluate how DTM resolutions and presence of building affect overland flow network delineation in the Liguori Channel basin, situated in Cosenza (Italy). To achieve this aim, three different DEMs of the study area, generated from different sources, were used: two contour-based DTMs with contour interval respectively of 30 m (*DTM 30*) and 20 m (*DTM 20*), and one LiDAR-based DEM, with horizontal resolution of 1 m (*LIDAR DTM*). Moreover, for a more in depth analysis, *LIDAR* DTM_b (with buildings) cell size has been down sampled from 1 to 5 meters coarse resolution, in order to evaluate also, how cell size affect ponds delineation. Individuation of likely flood areas (ponds) has been carried out using Arc Hydro Tools developed at Centre for Research in Water Resources at University of Texas at Austin. Research highlighted how the correction of DEM generated from LiDAR data and other sources overlapping the buildings (i.e. retrieved from cadastral maps) help to diminish the total accumulated water volume into surface ponds, real or spurious, and also that their number does not depend by the raster cell size, but from the accuracy of the source data. Afterwards, a first attempt of best management practices implementation has been carried out within the Liguori Channel situated in Cosenza, Italy. The overland flow network of a highly urbanized sub area has been enhanced through the addition of a certain percentage of green roof and porous pavements. A series of simulations were carried out, using in input the historical annual rainfall series (between 2008 and 2011) and considering a first scenario without LIDs (reference case) and a second scenario with the new practices implemented. Moreover, the same simulation were repeated in continuous, namely considering a single time series composed by 4 years of precipitations (2008-2011) and taking into account, in addition to the two previous cases, of a third scenario where LIDs may deal with clogging phenomenon. In order to perform the EPA SWMM modelling, a 'residential' land use has been defined, characterised by build-up and wash off laws for the considered pollutant (Total Suspended Solids – TSS). As regards the green roof and porous pavement simulation parameters, currently these values has been gathered from literature. Within SWMM, the clogging phenomenon is taken into account through a parameter called '*clogging factor*' that considers the possible decay of LID performance due to the fine material carried by infiltration waters. The empirical formulation is affected by some parameters such as the number of years it takes to fully clog the system (Yclog), the annual rainfall amount over the site (Pa), the pavement's capture ratio CR (area that contributes runoff to the pavement divided by area of the pavement itself), the system's void ratio (VR), the Impervious Surface Fraction (ISF) and the pavement layer thickness (T). The yearly simulation performed show how the percentage reduction of volumes into the network is around 35% on average each year, the mass of Total Suspended Solids is around 30% on average while the relative concentration undergoes an increment around 15%. The latter result can be explained looking at the SWMM runoff quality algorithm. In fact, currently SWMM takes into account of the reduction of pollutants only in terms of reduction of overland flow, due to the lacking of quality algorithms for LIDs simulation. Consequently, the presence of BMPs increases the amount of stormwater that infiltrates, decreasing runoff, therefore the mass of pollutants reaching the sewer outlet. The lower is the volumes of water reaching the sewer, keeping constant the total mass of pollutant over the catchment, the higher is the average outlet concentrations. The results of the continuous simulation are, also, very interesting. While during the annual simulations the trend of volumes for the scenario 'LIDs with clogging' ranges always between the other two cases, without and with LIDs, when the continuous simulation is considered, the volumes of the clogged

LID are even higher than the volumes occurring without any BMP implemented. The efficiency tends to decrease during time, from 50% when simulation starts to almost 0% at the end of the second year, continuing then to swing around zero per cent for the remaining part of the simulation. In this case, in fact, during the first two simulated years the trend is similar to what it has been found during the annual simulation, while starting from the third year (January 2010), volumes generated for the case 'LIDs with clogging' are equal or even higher than those ones generated when no LIDs are used. Although EPA SWMM results are interesting and indicative of LID operation, they are not very accurate, especially concerning the qualitative simulation of the stormwater management practices. For this reason, later, the research has been focused on improving the qualitative simulation algorithms, with particular attention to porous pavements. Data collected into an experimental laboratory rig of three different and widely used permeable pavement types has been analysed. The investigated systems were: monolithic porous asphalt (PA), modular Hydrapave (HP), and monolithic Permapave (PP). The rig, made of three vertical compartments in which the three porous pavers stratigraphies has been rebuilt, has been subjected to a semi-synthetic hyetograph, made of five different rain intensities (wetting regime) plus several drying periods. From the frequency curve typical of Brisbane (AU), in correspondence of different percentile ranges four flow rates has been chosen (A, B, C, D). In addition, a 1 in 5 year storm of 5 min duration was selected; this represents the typical design storm where the porous pavers are likely to be developed. The accelerated laboratory test allowed to simulate 26 years of operation under Melbourne climate. About the water quality monitoring, an intense sampling regime has been conducted in which samples were collected from inflow and outflow and analysed for Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN). Afterwards, a correlation analysis has been performed in order to individuate the key variables affecting the porous pavement functioning. According to these results, the key variables identified to affect the pollutant concentration values were: the cumulative flow every 6, 12 and 24 hours before the sampling time, the cumulative inflow volume in each time step and the cumulative trapped mass. Initially, it has been tried to analyse the phenomenon through the 'k-C* model', that is a conceptual model used to simulate the pollutant behaviour through the system, based on a first-order kinetic decay equation. Notwithstanding the wide popularity and tested applicability on various other treatment practices such as sand filters, wetlands, ponds, infiltration systems and vegetated swales, the model did not show satisfying results when applied to porous pavements, especially about heavy metal and total nitrogen modelling. The predictive power of the model has been assessed through the calculation of the Nash–Sutcliffe model efficiency coefficient, widely adopted in the Anglo-Saxon world to evaluate behaviour and performance of the hydrologic models. Nash-Sutcliffe coefficient is an indicator of the model's ability to predict about the 1:1 line between observed and simulated data. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values < 0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. Considering this, the concentration data collected has been processed, also taking into account of the correlation analysis previously carried out, which allowed to estimate the concentrations of the main pollutants such as TSS (Total Suspended Solids), TP (Total Phosphorous) and TN (Total Nitrogen) to the output section of the porous pavements. The reliability of the new proposed formulas has been demonstrated both by high values of the Nash-Sutcliffe coefficients, always positive, and also by very low errors (between 10% and 25%) among modelled and measured concentrations.

Sommario

I cambiamenti climatici sempre più frequenti hanno accresciuto nei ricercatori l'interesse nelle cause ma, soprattutto, sulle opere strutturali e non, da offrire al problema. Lo sviluppo economico e la rapida crescita della popolazione produce una domanda sempre maggiore di beni e servizi. L'estensione dei fenomeni siccitosi e, dall'altro lato, un aumento dell'intensità e della frequenza delle piogge, anche di breve durata causano eventi che per il loro alto potere devastante, vengono indicati col termine 'eventi di pioggia estremi'. L'attuale gestione delle acque in ambiente urbano risulta dunque insostenibile, quindi diviene estremamente importante sviluppare dei nuovi ecosistemi urbani che richiedono, però, il completo ripensamento delle tecniche di sviluppo convenzionale. I sistemi di drenaggio urbano tradizionali sono pensati per favorire il rapido allontanamento delle acque di scorrimento superficiale e fognarie verso gli impianti di trattamento e i corpi idrici recettori, senza assolutamente tener conto delle loro caratteristiche qualitative. Per raggiungere l'obiettivo del controllo quali-quantitativo delle acque superficiali in ambiente urbano una possibile strada è rappresentata dalla vasta applicazione in queste aree dei cosiddetti "Blue-Green Corridors" (BGC) che forniscono un approccio olistico e integrato alla soluzione del problema. Tali sistemi sono ancora più avanzati delle classiche misure di drenaggio urbano sostenibile come LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems) o BMPs (Best Management Practices), di cui consentono di massimizzare gli effetti benefici. L'uso dei BGC come parte del sistema di drenaggio urbano rappresenta un approccio vincente, che permette la gestione e il trattamento delle acque meteoriche di dilavamento, utilizzando delle componenti blu e verdi. Le componenti verdi sono rappresentate dalla vegetazione di qualsiasi tipo presente (piante floreali, prati, siepi) mentre quelle blu da laghi, ristagni, fiumi e canali (artificiali o naturali). Queste consentono insieme di creare una rete di collegamento tra le varie misure di controllo a livello locale. Il reale comportamento di questi sistemi però, non è ancora correttamente modellato. Molti dei software correntemente utilizzati nell'idrologia urbana (EPA SWMM, eWater CRC Music, ecc…) modellano in maniera abbastanza efficace il comportamento idraulico di tali strutture di infiltrazione utilizzando un semplice bilancio di masse, mentre la generazione, l'accumulo e il trasporto degli inquinanti vengono determinati assegnando delle categorie di uso del

suolo a cui corrispondono delle leggi di build up (accumulo) e wash off (dilavamento) degli inquinanti sul bacino, senza tenere conto dei reali fenomeni fisici che si verificano. Questo approccio manca totalmente di algoritmi qualitativi all'interno dei modelli delle LID, che consentano di tener conto delle performance qualitative e della riduzione di efficienza dovuta al fenomeno di *clogging*. Tale fenomeno, caratterizzato dalla successiva riduzione della capacità filtrante e dispersiva delle pratiche LID, dovuta alla riduzione della porosità del suolo e della conduttività idraulica per effetto degli inquinanti presenti nelle acque, si verifica in misura maggiore nelle pratiche infiltranti quali celle di bioritenzione, trincee infiltranti, fasce filtro e pavimentazioni permeabili. Proprio queste ultime pratiche sono facilmente inseribili all'interno di contesti urbani esistenti col duplice scopo di diminuire le aree impermeabili e funzionare da 'rami' delle reti di BGC. Da questi presupposti si sviluppa la ricerca affrontata nella seguente tesi, il cui principale obiettivo è rappresentato dallo studio dell'implementazione degli elementi 'blu e verdi' nelle aree urbane e dell'effetto che questi hanno sulla riduzione dei carichi inquinanti. All'inizio è stato affrontato lo studio degli errori più comunemente riscontrabili all'interno dei DTM (Digital Terrain Models) che finiscono, se non corretti, per influenzare la delineazione della rete di scorrimento superficiale e la conseguente modellazione idraulica. I DEM possono includere sia i dati di elevazione, che regolano la direzione del deflusso, che le informazioni sulla copertura del suolo. Molto spesso i DTM sono generati da informazioni sul terreno provenienti da diverse tecniche di rilievo (remote sensing, LiDAR, rilievi aerofotogrammetrici e immagini satellitari) e contengono perciò degli errori (sistematici, random) che necessitano di essere individuati ed eliminati. Si è effettuato uno studio relativamente all'influenza della risoluzione del DEM sulla generazione della rete di scorrimento superficiale per il bacino del Canale Liguori, situato nella città di Cosenza. La ricerca è servita anche a valutare come la presenza degli edifici possa influenzare la delineazione dei ponds, ovvero delle potenziali aree allagabili. A tal fine sono stati considerati per l'area studio tre DTM generati da diversi dati sorgente: due basati su carta a curve di livello con equidistanza di 30m e 20m ed uno basato su dati LiDAR con risoluzione orizzontale di 1m. Inoltre, per un'analisi più approfondita, è stato effettuato il downsampling del DTM LiDAR con edifici, passando da una risoluzione di 1m ad una di 5m, al fine di valutare l'influenza della dimensione della cella del raster sulla delineazione delle depressioni (ponds). La determinazione dei ponds è stata effettuata con software Arc Hydro Tool sviluppato presso il Centre for Research in Water Resources all'Università di Austin, Texas. Dallo studio è emerso come la correzione di DEM generati da dati LiDAR e da altre fonti sovrapponendo la presenza degli edifici, ottenuti ad esempio da mappa catastale, può portare alla riduzione dei volumi accumulati nelle depressioni superficiali (*ponds*), siano esse reali oppure fittizie e che il numero di queste ultime dipende non tanto dalla dimensione delle celle del raster utilizzato, quanto dall'accuratezza del dato originale. In seguito, è stato effettuato un primo tentativo di implementazione di pratiche sostenibili sempre all'interno del bacino del Canale Liguori nella città di Cosenza. La rete di drenaggio superficiale di una sottoarea del bacino densamente urbanizzata è stata potenziata ipotizzando l'inserimento di una certa percentuale di tetti verdi e di pavimentazioni permeabili. Sono state effettuate quindi delle simulazioni, utilizzando in input la serie storica delle precipitazioni annuali (per gli anni 2008 - 2011) e considerando i due scenari dello stato attuale (senza alcun intervento) e con l'implementazione delle nuove superfici permeabili. In seguito la stessa simulazione è stata effettuata in continuo, considerando cioè un'unica serie storica di 4 anni di precipitazioni (dal 2008 al 2011) e considerando oltre ai due casi precedenti, anche lo scenario in cui le LID fossero soggette a fenomeno di clogging. Per la modellazione con software EPA SWMM è stato inizialmente necessario definire una copertura del suolo 'residenziale', caratterizzata dalle leggi di build up e wash off degli inquinanti da modellare (in questo caso TSS). Per quanto riguarda i parametri da assegnare alle due LID (tetti verdi e pavimentazioni permeabili), al momento sono stati scelti dei valori di letteratura, mentre in futuro si prevede di utilizzare dei parametri progettuali provenienti da installazioni sperimentali all'interno dell'Unical. All'interno dello SWMM, per tener conto del fenomeno di clogging, si utilizza un parametro noto col termine di '*clogging factor*', che tiene conto della possibilità di decadimento delle prestazioni di una LID, dovute all'intasamento dello strato di accumulo inferiore per opera del materiale fine trasportato dalle acque di infiltrazione. La formulazione, di natura empirica, è influenzata da alcuni parametri quali il numero di anni necessario per il completo intasamento (Yclog), la pioggia media annua sul bacino (Pa), il 'capture ratio' (CR) ovvero il rapporto tra l'area che contribuisce al runoff e l'area totale della pavimentazione, dall'indice dei vuoti (VR), dalla frazione di pavimentazione impermeabile (ISF) e dallo spessore della pavimentazione (T). Dall'analisi effettuata considerando le serie storiche di precipitazioni annuali risulta una riduzione dei volumi in rete in media del 35%, una riduzione della concentrazione del TSS (Total Suspended Solids) in media del 30% mentre risulta un incremento delle concentrazioni di TSS in media del 15%. Quest'ultimo risultato può essere spiegato poiché lo SWMM tiene conto della riduzione degli inquinanti solo in termini di riduzione della portata di scorrimento superficiale, non essendo presente nessun algoritmo di modellazione qualitativa delle BMPs. Di conseguenza, la presenza delle BMPs nel bacino aumenta l'aliquota di deflusso superficiale che si perde per infiltrazione e non raggiunge la fognatura: i minori volumi d'acqua presenti, al mantenersi costante della massa totale di inquinante sul bacino, fanno si che le concentrazioni in uscita risultino in media più elevate. I risultati della simulazione pluriennale mostrano altresì dei risultati molto interessanti. Mentre infatti nelle simulazioni annuali l'andamento dei volumi nella sezione di chiusura nel caso di scenario con presenza di clogging risulta sempre compreso tra i casi senza LID e con LID, quando si considera la simulazione pluriennale, si nota come a partire dal 2° anno simulato, i volumi nel caso di clogging tendono ad essere addirittura superiori del caso senza LID, evidenziando un intasamento in atto delle BMPs. L'efficienza tende infatti a diminuire nel tempo, da un massimo del 50% ad inizio simulazione fino ad azzerarsi quasi completamente alla fine del 2° anno, per poi continuare ad oscillare con degli scarti minimi intorno allo 0% per la restante parte della simulazione. In questo caso, infatti, per i primi due anni l'andamento qualitativo è analogo a quello che si è riscontrato per le simulazioni annuali, mentre a partire dal terzo anno (gennaio 2010), i volumi generati dal caso "LID con clogging" risultano uguali se non in alcuni casi superiori ai volumi che si generano quando tali pratiche non sono applicate, indice ciò del completo intasamento dei pori della pavimentazione e conseguente mancato fenomeno di infiltrazione che non ha più la possibilità di avvenire. I risultati forniti dallo SWMM, seppur interessanti e indicativi del funzionamento delle LID, non risultano molto precisi specie riguardo la simulazione qualitativa delle pratiche di gestione. Per tale motivo la ricerca è stata nel prosieguo orientata al miglioramento degli algoritmi di simulazione qualitativa, con particolare riguardo alle pavimentazioni drenanti. Sono stati analizzati i dati raccolti da un'installazione sperimentale di laboratorio delle tre più diffuse tipologie di pavimentazione permeabile: asfalto poroso, mattoncini porosi e calcestruzzo poroso. L'impianto, costituito da tre compartimenti nei quali è stata ricostruita la stratigrafia per le 3 tipologie di pavimentazione, è stato sottoposto ad uno ietogramma di pioggia semisintetico, costituito cinque differenti intensità (portate di tempo bagnato) ed un periodo di tempo asciutto. Dalla curva di frequenza tipica di Brisbane (AU) sono state selezionate 4 portate (denominate A,B,C,D), ognuna corrispondente ad un determinato percentile di intensità di pioggia; a queste è stata aggiunta una quinta pioggia di progetto con tempo di ritorno di 5 anni. Ogni anno simulato è stato composto da una sequenza random delle 4 portate A,B,C,D; ogni 4 anni simulati è stata intervallata la pioggia di progetto con tempo di ritorno di 5 anni. In totale, dunque, si è riusciti a simulare 26 anni di funzionamento delle tre pavimentazioni con circa 1 anno di funzionamento in laboratorio. Alcuni campioni per l'analisi qualitativa delle acque sono stati collezionati in ingresso ed in uscita alla pavimentazione al fine di analizzare le concentrazioni di Solidi Sospesi Totali (TSS), Fosforo Totale (TP) e Azoto Totale (TN). In seguito sono state effettuate delle analisi di correlazione tra le diverse variabili in gioco, al fine di comprendere quali di esse influenzassero maggiormente i valori di concentrazione in uscita per ciascun inquinante. Le grandezze maggiormente correlate con la concentrazione in uscita misurata sono state: concentrazione in ingresso, portata, portate cumulate ogni 6, 12 e 24 ore, volumi cumulati e masse cumulate. Inizialmente si è cercato di interpretare il fenomeno utilizzando il 'modello k-C^*', modello concettuale utilizzato per simulare il comportamento degli inquinanti attraverso il sistema, basato sull'equazione cinetica di decadimento del primo ordine. Nonostante la vasta popolarità e l'applicabilità testata per altre pratiche quali filtri sabbiosi, aree umide, bacini di sedimentazione, biofiltri e trincee infiltranti, il modello non ha mostrato risultati soddisfacenti quando applicato alle pavimentazioni permeabili, specialmente riguardo la modellazione dei metalli pesanti e del fosforo totale. Il potere predittivo del modello è stato misurato facendo riferimento all'Indice di Nash-Sutcliffe (NSE) largamente adottato, specie nel mondo anglosassone, per la valutazione prestazionale dei modelli idrologici. L'NSE indica quanto bene il grafico dei punti osservati verso quelli simulati interpola la bisettrice dell'angolo retto. Tale indice varia tra $-\infty$ ed 1 (incluso), dove NSE=1 rappresenta la condizione ottimale. Valori tra 0 ed 1 sono generalmente visti come accettabili, mentre valori negativi dell'indice esprimono prestazioni non ammissibili. Tenendo conto di ciò, i dati di concentrazione collezionati sono stati elaborati, anche in considerazione dell'analisi di correlazione precedentemente effettuata, riuscendo ad individuare tre nuove formulazioni capaci di predire la concentrazione di inquinante in uscita dalle tre tipologie di pavimentazione relativamente a TSS (Total Suspended Solids), TP (Total Phosphorous) e TN (Total Nitrogen). L’affidabilità delle nuove formule proposte è dimostrata sia dagli alti valori dell’Indice di Nash-Sutcliffe, sempre positivi, sia dagli errori molto contenuti sulle concentrazioni modellate (tra il 10% ed il 25%) rispetto ai valori misurati.

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Chapter 1 - Background and Thesis objective

1.1 Problem description

The Earth's climate always keeps changing, but it is the recent acceleration of this change that has caused concern to many scientists, authors and also to common people, leading to increased interest in our environment. In geological period of the Holocene (approximately the last 11000 years) has occurred in a situation of rather stable climate that has also facilitated the wide spread of our species on the planet (Jansen et al., 2007). This situation is currently changing, due to economic development together with population growth and its constantly increasing demand of goods and services like freshwater, food, electricity and much more.

Beyond that, another factor affecting climate changes is raise of global temperatures, causing an upheaval of seasons, and more generally, of climatic worldwide conditions. In this regard, it is worth considering a couple of important distinctions. The terms ‘weather’ and ‘climate’ are frequently considered to be interchangeable, but weather and climate refer to different things. Weather is the brief, rapidly changing condition of the atmosphere at a given place and time, influenced by the movement of air masses. Climate, on the other hand, should more accurately be the term applied to the average weather conditions over longer periods of years to decades. Thus, climate change refers to any long-term trends in climate over many years or decades, around which climate variability may be evident year on year. Hence, a single warmer or cooler year on its own is not sufficient evidence to assert that climate is changing (Cleugh H. et al., 2011). 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, with a significant impact on the timing of growth and maturation of crops. As for precipitation, experts of IPCC provide in Mediterranean countries radical changes with reductions from 4 to 27%. Finally, all the studies conducted up to now, despite uncertainties about climate variability, agree on an increase in extreme events: drought in the countries to the west of the Mediterranean region and throughout southern Europe.

As the same as drought, also precipitation became more intense and frequent, even with more ever short duration. These events that for its heavy impact are called ‘extreme rainfall events’ (Fig. 1. 1) 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).

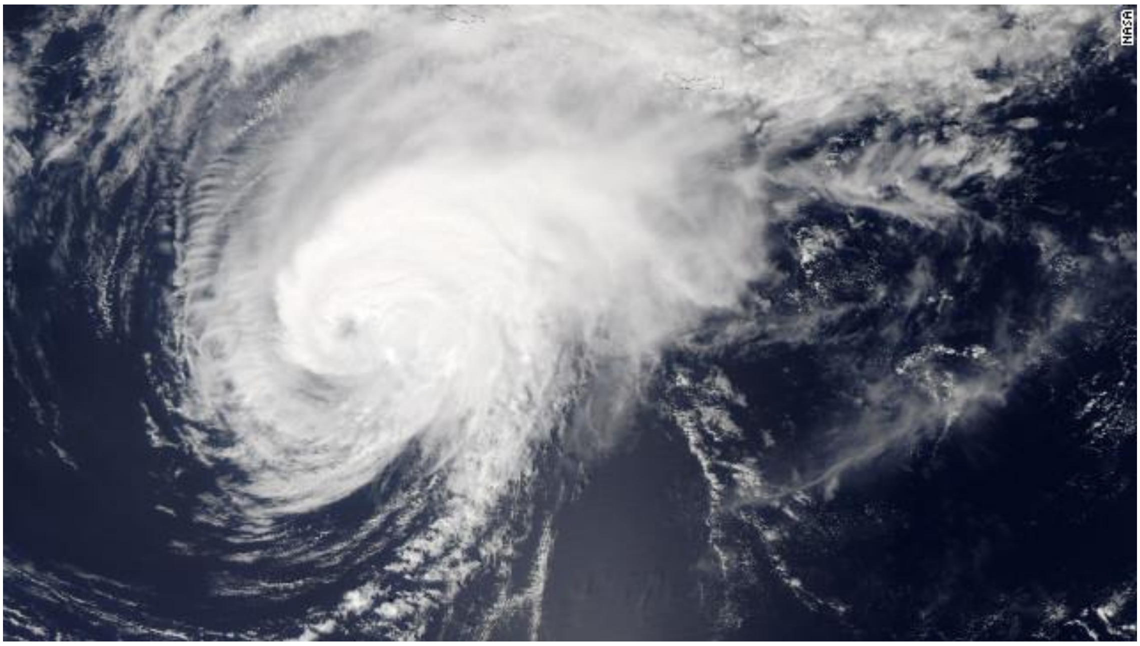


Fig. 1. 1 - Hurricane Gordon seen last 20-Aug-2012 between the Azores and mainland Europe (CNN website - http://edition.cnn.com/2012/08/20/world/europe/hurricane-gordon).

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 and Jones, 2005; Tebaldi et al., 2006; 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 actual management of urban waters is unsustainable for the world of tomorrow thus, foregoing reasons lead to an imperative need to reduce vulnerability to meteorological extremes, as essential part of the complex adaptation to climate change. Development, climate change and ecosystem sustainability issues are increasingly interlinked, requiring a rethinking of traditional development assistance in order to remain relevant to human needs (Min et al., 2011).

A possible way to reach these objectives is the widespread implementation in urban areas of 'blue-green infrastructure' that provide an holistic and integrated approach to the problem. They are one step beyond other 'classic' sustainable urban drainage measures such as LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems) or BMPs (Best Management Practices), allowing to emphasize their beneficial effects. The foregoing measures in fact, if stand-alone applied, are only partially effective (Benedict & McMahon, 2002). The Blue-Green Corridors (BGCs) concept, further discuss in Chapter 3, integrate the role of SUDS with urban planning, fluvial redevelopment and flooding management. It allows to develop spatial planning strategies to increase value of urban environments, including therein blue-green components. These elements allow impervious areas, largely present in our cities, to be converted to more permeable areas reducing stormwater runoff. The excessive runoff generated during a storm event, in fact, is responsible of urban floods because existing drainage systems are unable to handle peak flows and, moreover, they deliver contaminants to receiving waters (lakes, rivers and creeks). This aim is reached, for instance, through the utilization of porous pavements. Porous pavers are a type of SUDS made of a structure that is permeable to water, consisting on a pervious layer sits on the top of a reservoir storage layer. These systems reduce both flood peak and contaminants concentration, improving the quality of stormwater at source before it reach receiving waters. The real behaviour of these structures yet is not properly modelled. Most of the software currently used in urban hydrology (SWMM by EPA, Music by eWater CRC, etc…) model in a reasonable way the hydraulic behaviour of infiltration practices (such as bioretention cells, infiltration trenches, vegetated filter strips, porous pavement) using a simple mass balance approach. Generation, inflow and transport of pollutants are, instead, determined by the land use assigned to each subcatchments, namely through buildup and washoff laws describing accumulation and washout by either a mass per unit of subcatchment area or per unit of curb length. The presence of BMPs in the basin, increases the infiltration rate, decreasing runoff, thus the mass of pollutants. This approach completely lack of quality algorithms within LID models that allow to take into account of their quality performances as, for instance, reduction of efficiency due to the clogging effect. The clogging phenomena is described as the decrease in infiltration rate of the soil due to the reduction in soil porosity and hydraulic conductivity. Many studies shown that clogging of the porous pavements happens between 15 and 20 years after construction (Yong, 2011; Yong and Deletić, 2012). How this process works is not still clear thus, further studies are required to predict porous paver efficiency over time.

1.2 Climate changes

The rapid and continuous increase of greenhouse gases in the atmosphere, starting from the Industrial Revolution, has given rise to some of the biggest questions in the history of science. The whole scientific community tried to study if current global warming has been cause mainly by concentration rise of carbon dioxide (CO_2), chlorofluorocarbon compounds (CFC), methane (CH_4), ozone (O_3) and how this temperature raise will affect Earth's climate, humans and the environment. The Intergovernmental Panel on Climate Change (IPCC) and the National Research Council (NRC) have independently concluded that "changes observed over the last several decades are likely mostly due to human activities", but that "a causal linkage between the buildup of greenhouse gases in the atmosphere and the observed climate changes during the 20th century cannot be unequivocally established" (NRC, 2001). The fourth report of the Intergovernmental Panel on Climate Change (IPCC) in his 2007 detection studies estimated that the average temperature of the Earth's surface has increased by 0.74 ± 0.18 ° C during the twentieth century (IPPC, 2007). This slow but constant increment of temperature has lots of negative effect, such as ozone depletion (Fig. 1. 2).

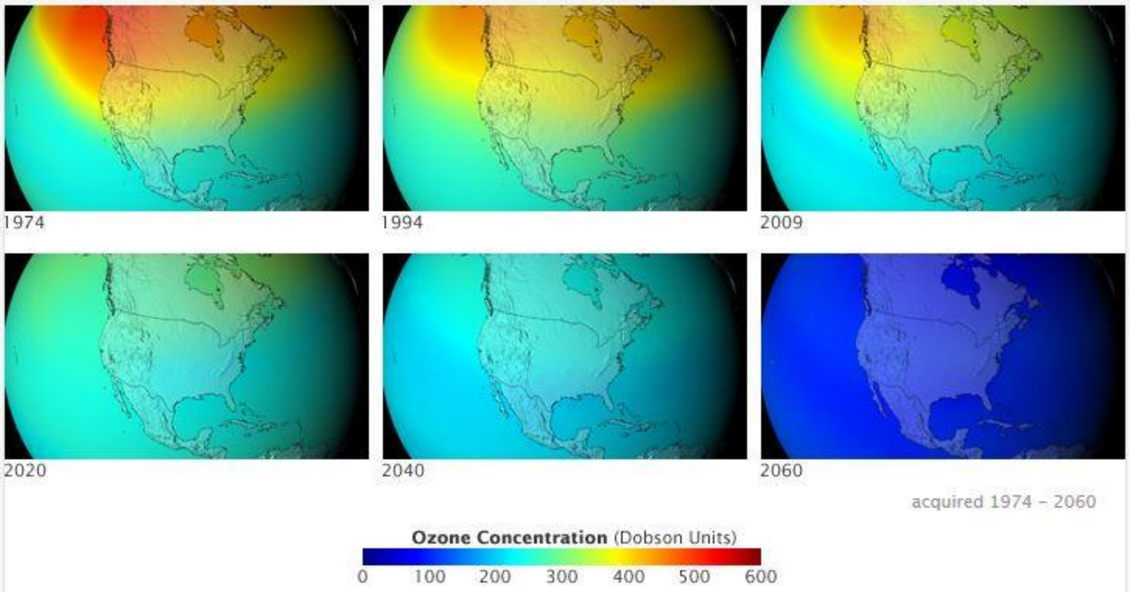


Fig. 1. 2 - Ozone concentrations over the mid-latitudes of the Western Hemisphere, based on months of calculations by the Goddard Earth Observing System Chemistry-Climate Model (NASA Earth Observatory, 2009 - http://earthobservatory.nasa.gov/IOTD/view.php?id=38685).

Ozone depletion describes two distinct but related phenomena observed since the late 1970s: a steady decline of about 4% per decade in the total volume of ozone in Earth's stratosphere (the ozone layer), and a much larger springtime decrease in stratospheric ozone over Earth's polar regions. The latter phenomenon is referred to as the **ozone hole**. In addition to these well-known stratospheric phenomena, there are also springtime polar tropospheric ozone depletion events (Wikipedia, 2012). As it can intuitively understood, hydrologic cycle play also an important role within global warming mechanism together with greenhouse gases emission. A traditional water cycle starts with precipitation flows along naturally flow paths to eventually reach the sea (or other receiving bodies) and then it returns to the atmosphere (or infiltrate into the soil) (Fig. 1. 3).

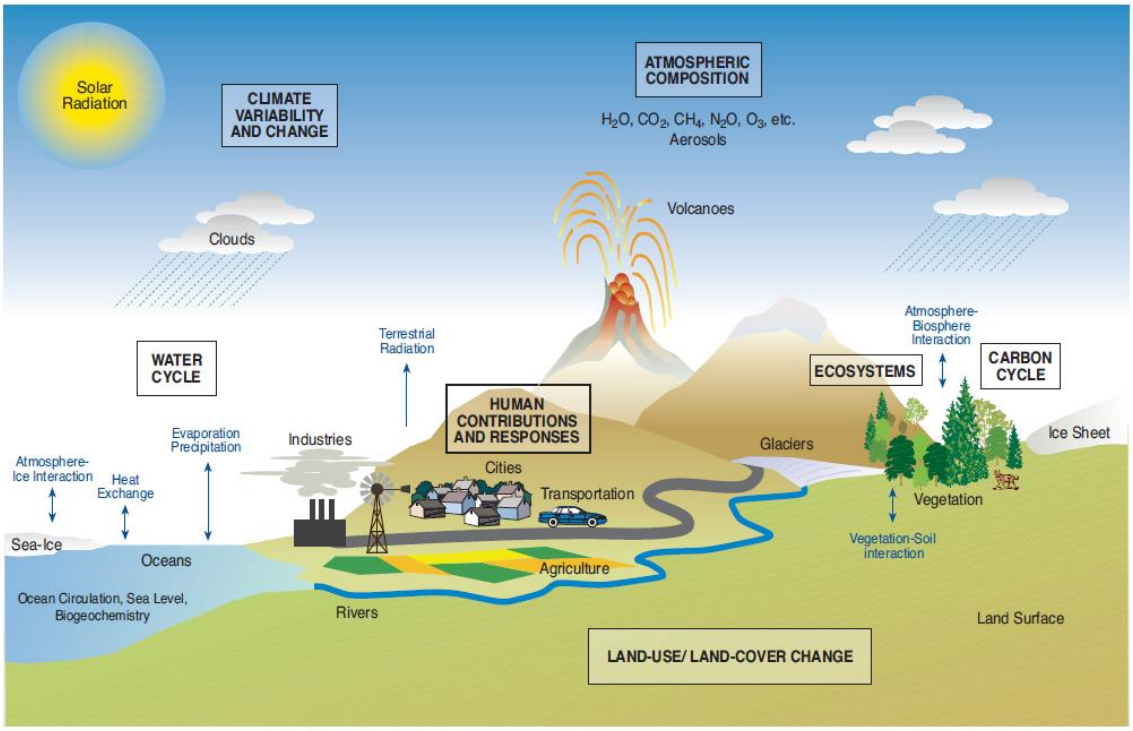


Fig. 1. 3 - Major components needed to understand the climate system and climate change (Adapted from IPCC, 2001).

Due to the recent changes in worldwide climate, traditional hydrologic cycle has been altered, because of the urbanization (that reduces availability of green spaces and lead to the overland flow network modification) and, more generally, of human activities. Alteration of the water cycle has an impact on: warming of the atmosphere, soil drying up, the process of desertification, loss of biodiversity, flora and fauna of the land, impact on the economies based on fishing fresh water, changes in the balance of marine flora and fauna. At the same time changes on the balance of ecosystem due to human intervention or natural changes due to the evolution of spontaneous ecosystem processes have an impact on the water cycle (Fig. 1. 4).

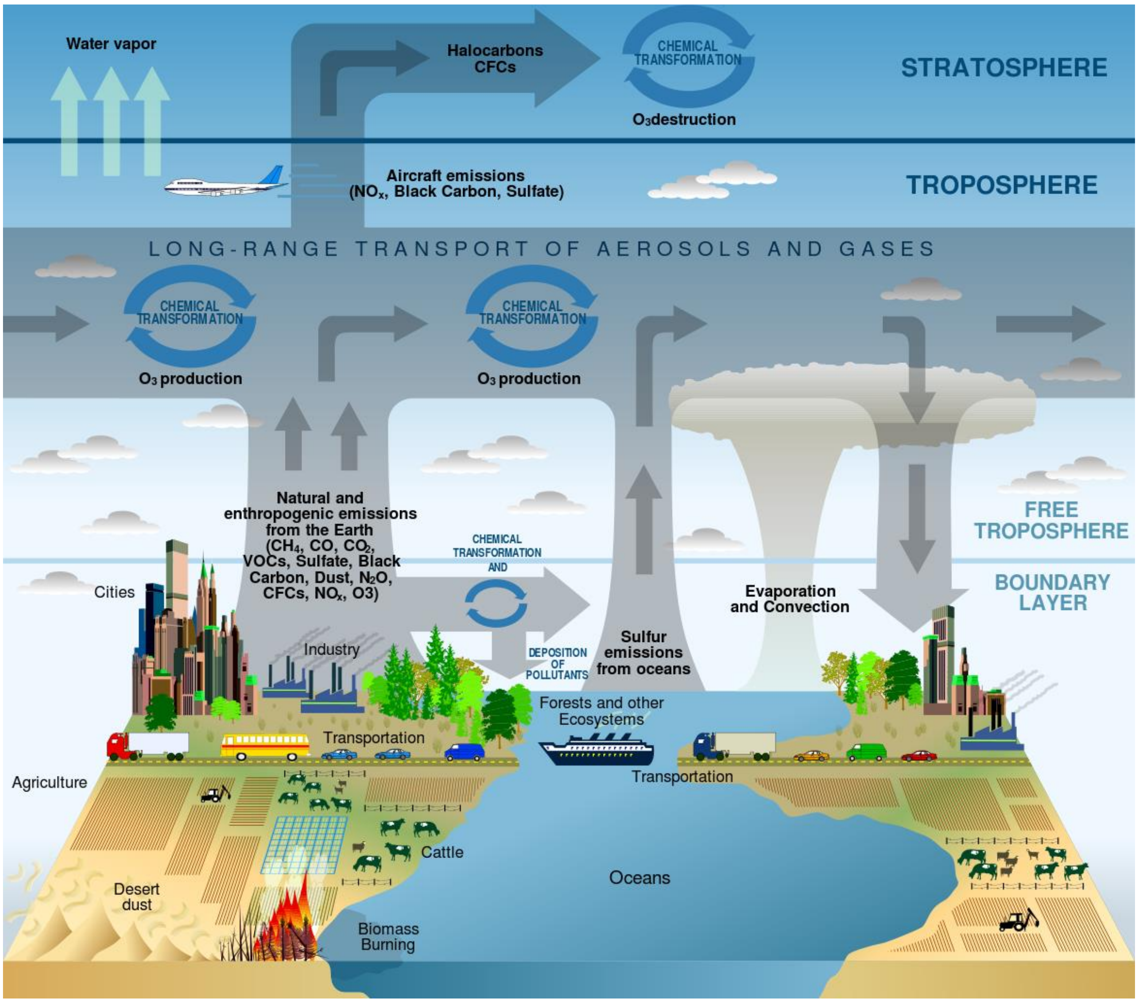
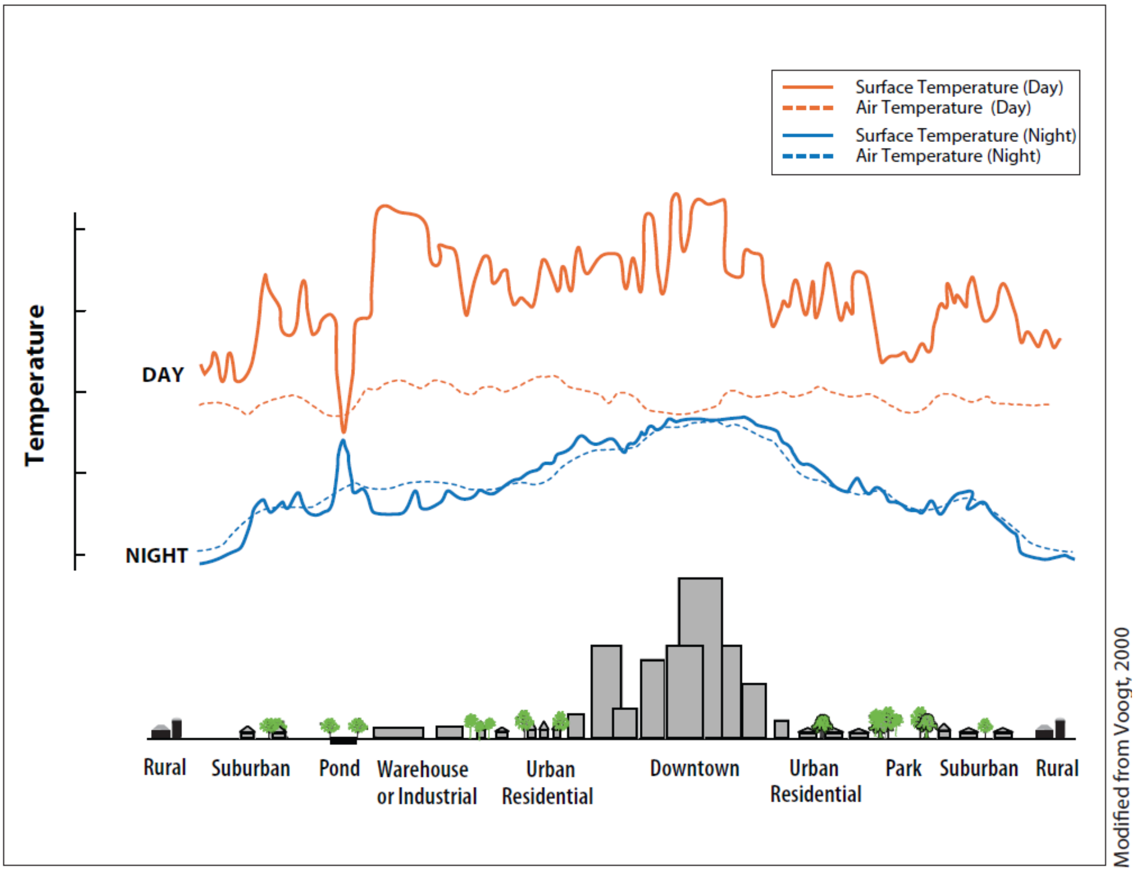


Fig. 1. 4 - Schematic of chemical and transport processes related to atmospheric composition. These processes link the atmosphere with other components of the Earth system, including the oceans, land, and terrestrial and marine plants and animals (Strategic Plan for the U.S. Climate Change Science Program, 2003).

The composition and geographical distribution of many ecosystems (forests, grasslands, deserts, mountain systems, lakes, wetlands, oceans, etc..) will tend to transform depending on how individual species respond to climate changes. Global warming will trigger desertification processes in temperate areas of the planet, threatening organisms that, even today, live nearly limit of heat tolerance. During transitional and adaptation stage, likely a lot of biological diversity that currently exists will be lost. The forest systems may undergo changes in species composition, with the disappearance of entire forest types and the establishment of new plant species associations, and hence new ecosystems. Due to change in sea level, marine-coastal ecosystems (salt marshes, mangroves, coastal wetlands, sandy beaches, cliffs reefs, atolls, and river deltas) will be seriously damaged. Certainly the most prevalent factor of natural habitat alteration it has been (and still it is) human worldwide spread. The need for human beings to live together and take advantage of basic services (water, food, etc...) has led them, from the beginning, to create cities and venues. Growth of population and expansion of cities are two effects strictly related one each other. The presence of more amenities and services all gathered together, has allowed an improvement in hygienic and sanitary conditions, and consequently, an increase of the population. But more population implies more places to live, thus more houses and buildings to realize, then city growth. Problems began when this development became fast and uncontrolled, taking no longer in account the environment that was destroyed to make space for new artefacts, therefore, the impact over nature and surrounding ecosystems. The dominance of economic issues in the development of urban form has led people forget that nature, a day, could take her revenge, as it is happening now. Although contemporary cities are on apex of their economic, social and industrial progress, they are more exposed and vulnerable to many risks than in the past such as extreme events, air and water pollution, urban flooding, heat island effect (Imhoff et al., 2010; Peng et al., 2012), drought, high energy consumption and carbon footprint.



Modified from Voogt, 2000

Fig. 1. 5 - Surface and atmospheric temperatures varying over different land use areas (EPA, 2008).

The rising trend towards urban living and the escalating costs of hazardous events has resulted in a growing awareness of the need for modern cities to adapt to their local conditions to manage environmental risks more effectively in the face of a changing climate. Where urban areas were once seen as a place of safety, cities are now the hub of modern risks and there is a recognition that urban development patterns have profound implications for managing hazards (White I., 2008).

1.3 Urbanization

It is now clear that one of driving forces causing changes in the environment at local, regional, and even global scales is the human activity. Social, economic, and cultural systems are changing in a world that is more populated, urban, and interconnected than ever. Available statistics show that more than half (51%) of the world's 7 billion people live in urban areas, value rising to 68% in Italy (Population Reference Bureau, 2012). Main effect of the urbanisation process is certainly the increasing use of virgin lands destined for urban use, making them ever more impervious (Paoletti, 1997; Cannata, 1993). The growth and spread of impervious surfaces within urbanizing watersheds pose significant threats to the quality of natural and built environments. These threats include increased stormwater runoff, reduced water quality, higher maximum summer temperatures, degraded and destroyed aquatic and terrestrial habitats, and the diminished aesthetic appeal of streams and landscapes (Barnes et al., 2002). Impervious surfaces like roads, parking lots, rooftops and sidewalks are made of asphalt, concrete or stones, and their presence change water cycle in urban areas (Fig. 1. 6). When landscapes are natural, the falling rain can easily infiltrate to the soil or be absorbed by vegetation. The latter also slow down the surface runoff, increasing watershed time of concentration. Moreover water infiltrated into soil is naturally filtered of impurities before it supplies groundwater or it reaches lakes, streams, rivers and sea. Conversely when a site is developed, it becomes less permeable and therefore less water can infiltrate back into the ground. As a consequence, rainfall is converted quickly into storm water runoff that can lead to increasing flooding events in our cities. Other negative effects of imperviousness are:

- weather alteration at local scale; parking lots and other hard surfaces (such as buildings), which often dominate urban areas, tend to absorb solar energy more easily and then release it more slowly, causing the well-known "heat island effect".

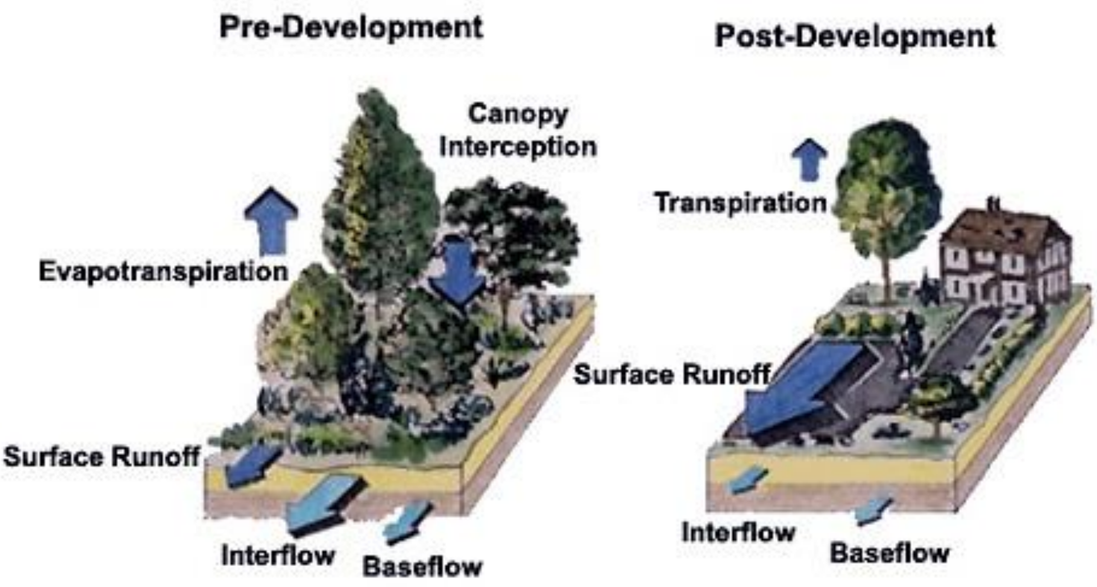


Fig. 1. 6 - Water Balance pre and post-development (Centre for Watershed Protection, 2003).

- <u>transport of pollutant emphasis</u>; impervious surfaces accumulate pollutants (fertilizers, automotive fluids, animal waste, deicers, and dirt) that are carried into surface waters by stormwater runoff. The initial half-inch of stormwater tends to carry the most pollution as it washes into the street and down the gutter. These pollutants degrade habitat for aquatic species and can also affect drinking water quality and limit recreational opportunities.
- <u>river habitat degradation</u>; high stormwater flows cause erosion. Small stream channels in particular cannot accommodate the unnaturally high flows of water that occur as impervious surface increases. As a result of flash flows, the stream bank and stream bed erode more frequently, degrading the habitat quality for aquatic organisms.

Definitively, hydrological worst effects from urbanization are increased surface runoff volumes and velocities during storms events, involving emphasis of peak flow rate in catchment hydrograph when comparing situations before and after development has occurred (Fig. 1. 7).

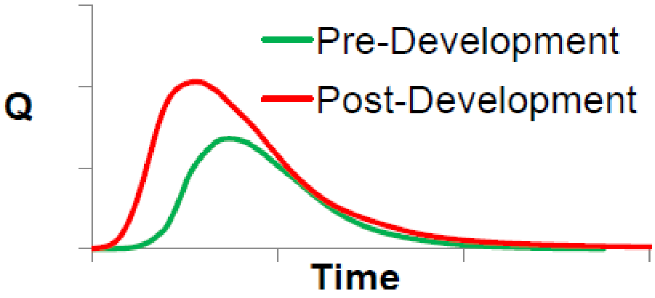


Fig. 1. 7 - Hydrologic alteration due to site development (Giacomoni et al., 2011)

1.3.1 Urban flooding

Changes in climate together with advancing of urbanization lead urban areas facing insistently new problems such as *urban flooding*. The latter, also known as "*flash flooding*", refers to intense falls of rain in a relatively short period of time. The National Weather Service defines a flash flood as "a rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within six hours of the causative event (e.g., intense rainfall, dam failure, ice jam)" (NWS Manual, 2012). Usually the spatial effect is localized and, within urban areas, can be a major cause of erosion and damages for human artefact and loss of human lives (Fig. 1. 8). While natural areas are not much affected by this phenomenon thanks to the vegetation that ensure more resilience of the overall landscape, conversely, arid, semi-arid, cultivated (where a high portion of the land is fallow), urban or steep drainage basins are much more prone to modification by flash floods because of their potential to generate the highest maximum probable rainfalls.

Fig. 1. 8 – Inundation of Cedar Creek urban area, Iowa, 2008 (Wikipedia, 2013).

Several different types of floods can occur, depending on the cause that generated them. It is possible to distinguish between:

- ✓ Coastal flooding, when the coast is flooded by the sea. This is due to a severe storm that, together with storm wind action, allow water waves to move inland on an undefended coast or overtop or breach the coastal defences.

- ✓ Fluvial flooding, maybe the most common flooding event that people associate with the term “flood”. Due to the increase in volume of water within a river channel and the overflow of water from the channel onto the adjacent floodplain.
- ✓ Pluvial flooding, occurs when the precipitation intensity exceeds the infiltration rate of the ground and soil, when the soil is saturated and cannot absorb any more water, or when extensive impermeable surfaces are present (Lancaster et al., 2004).
- ✓ Sewer flooding, occurs when surface water drains or combined sewers become overwhelmed with heavy rainfall, have inadequate capacity or are blocked (DCLG, 2010).

Each of them can happen in a urban environment but particularly latter two types are very dangerous in a city, because can lead to overwhelm of sewage system resulting in an excess of flow visible on the surface. Frequent flooding causes problems for residents and also the local authorities which has to clean up the sand deposited on the road, and also had to install the drainage pipe to move water off the roadway.

In addition to augmented flood risk, the water quality of the receiving water course is often reduced due to pollutants and sediments running off impermeable urban surfaces (Roy et al., 2008). 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. Also, drainage systems in which there is mixing of wastewater and stormwater may allow pollutants from the wastewater to enter the river (Butler & Davies, 2011).

It is evident, therefore, that current water management practices are not robust enough to cope with the increasing rainfall variability associated with climate change, thus the necessity to develop integrated approaches to surface water flood management (Bates et al., 2008).

1.4 Sustainable Solutions

In order to reduce impact that impervious surfaces have on urban catchments traditional solutions have been adopted until now (Carter & Jackson, 2007), such as storage tanks or ponds, where water can be temporarily stored during flooding event (White R., 2002). These solutions, extremely good on peak flow reduction, require lot of space to store temporary captured volume, not readily available on cities and developed landscapes. Thus, it is necessary and urgent to develop new sustainable solutions in urban planning, whose purpose is to mitigate the negative impact of the traditional drainage systems and to preserve the hydrological cycle of a site bringing it back before the urban development. In fact, it could be encouraged the use of permeable pavements for transport networks (streets, car parks, sidewalks) or recreational green space for urban squares in order to promote infiltration and limit runoff. The introduction of pervious pavements meet all requirements and principles of Water Sensitive Urban Design. Porous pavements are very popular structures for the management of both urban runoff quality and quantity. As their name implies, they promote the infiltration of rainfall and urban runoff, either to the underlying soil, or to a storage reservoir. Compared to other stormwater management measures, porous pavements are easily retrofitted in existing dense urban environments and are capable of reducing the hydraulic connectivity of the drainage system. They also trap pollutants and therefore can meet common stormwater management objectives (Yong et al., 2013). Despite of the many positive effects, use of permeable paving is often hampered by its high likelihood of failure due to clogging. Clogging is defined as the processes of reducing porosity and permeability (and hence decreasing the infiltration rate of the system) due to physical, biological and chemical processes (Bouwer, 2002). In stormwater systems, clogging occurs primarily due to the deposition of sediments. Several studies has been conducted in the past to evaluate clogging phenomena in porous pavement laboratory installation or when they are new (Fwa et al., 1999; Abbott & Comino, 2003; Kuang et al., 2007; Haselback, 2010), but only recently these studies has been extended trying to evaluate long-term performance of latters (Welker et al., 2012; Sansalone et al., 2012; Kuang & Fu, 2013; Yong et al., 2013). The key mechanisms that govern clogging in different systems are also poorly understood. A better understanding of this process would have several beneficial effects: cost reductions due to better design (choosing an optimal soil and configuration, requiring an appropriate capacity due to infiltrated volumes); policy changes to allow for “dynamic” routing of stormwater, evapotranspiration, and groundwater recharge; and increased understanding of stormwater control measure longevity.

Summarizing, literature review show as to cope with significantly increase of urbanization (thus increasing of stormwater runoff, peak flow rates, flooding and water pollution), a new way to manage stormwater in urban areas it is being implemented.

Use of WSUD, LID or BMP to adequately address the cause of urban stormwater problems seems promising, but some questions still remain unanswered especially about meet of stormwater requirements, implementation costs and long-term performances. Overcoming of this doubts will encourage a widespread implementation of this practices, actually hindered by technical, social and legislative impediments, even though the benefits lead to a more sustainable environment. Major barriers on their implementation are, in fact, defragmented local jurisdictions, extensive maintenance and uncertainty in selection, modelling and performance (Ellis et al., 2010; DCLG, 2010).

1.5 Aim of the Research

The major objective of this study can be summarised as follows:

> Qualitative and quantitative assessment of SUDS implementation in urban areas (within 'Blue Green Corridors' concept), through the overland flow network enhancement and the reduction of the relative water pollution.

By going into detail, the main aim of the research is to study how the implementation of blue-green elements (such as green roofs, porous pavements or swales) in urban areas can be a cost-effective solution to improve water management, in terms of flooding reduction as well as water pollutant decrement. At the beginning, the most common "errors" in Digital Elevation Models (DEM) (such as "pit cells" and "ponds" — see Ch. 2) were analysed as well as influence of resolution and human artefacts (such as curbs and buildings) on major system delineation. After that, a first attempt to implement Best Management Practices (BMPs) in urban area were conducted, doing a simulation by assuming presence of a certain percentage of green roofs and porous pavement in a subarea of Liguori's Catchment. This simulation, previously performed in EPA SWMM for 1-year rainfall, was repeated using 4-year rainfall in continuous. Behavioural differences were found (see Ch. 5), especially about sensibility to clogging efficiency. Because of the poor modelling of porous pavements in SWMM, particularly in regard of water quality, three new porous pavement formulations have been proposed, using the experimental data coming from the laboratory test of three different porous pavements installed at the Monash University. These data allowed to focus on understanding the main physical processes that govern physical clogging in porous pavers, and to develop three new simple models that predicts output concentration of the main pollutants, taking into account as a key variables influencing the phenomenon: pavement design, clogging ratio and climate characteristics. This new model bear in mind both quantitative and qualitative aspects, and it is able to estimate the discharge rate and the concentration of the main pollutants (TSS, TP, TN) at the outlet of the porous pavement.

Finally, the new proposed formulations have been validated with the Monash laboratory data, through the calculation of the Nash-Sutcliffe Efficiency coefficients as goodness of fit. Moreover, to further verify the reliability of the three proposed shapes, an error analysis was also carried out, performing the comparison of the percentage relative errors on the measured concentrations.

Therefore, this thesis provides a comprehensive methodology for assessing the long-term performance of porous pavement facilities which contributes to better engineering decision-making.

1.6 Thesis outline

Research begins with study of one of the main data sources currently utilised as a basis for many hydraulic analysis: terrain data coming from a Digital Elevation Model (DEM). In fact, to individuate the most likely position to site a best management practice in a basin, it is necessary to retrieve before some morphological properties of the catchment itself such as slope, aspect, depressions and overland flow network. Anyway, since this kind of data often bring with it some "errors", a pre-processing it is strongly suggested before to use it. Therefore, main "errors" and processing methods currently available to enhance Digital Terrain Model (DTM) are presented, together with the two of major software usable to retrieve depressions, ponds and overland flow network from a DEM. Also an application has been performed to the Liguori's catchment (Chapter 2).

In Chapter 3 is introduced and explained the "Blue-Green Corridor" concept and its origin from previous green technologies applications. Moreover, the major best management practices currently used are descripted, as well as barrier to its widespread implementation such as "clogging phenomenon" for infiltration practices like porous pavement and the existing clogging models. Chapter 4 contains a review on modelling software available in urban drainage like EPA SWMM. Current modelling capabilities of this and others software about BMP simulation are also provided together with its limitations. For instance, although some LID practices can also provide significant pollutant reduction benefits, at this time SWMM only models their hydrologic performance (EPA SWMM 5 Manual, 2012).

In Chapter 5 a case study on Liguori's catchment is explained and a brief description of the data used is also presented. Both annual and long-time continuous simulations (4-years) were performed to assess decay of efficiency of porous pavers in Mediterranean area. The same chapter also shows the development of the new porous pavement formulations, able to take into account about clogging formation in three different kind of porous pavements: Porous Asphalt (PA), Permapave (PP), and modular Hydrapave (HP). Finally, a summary of the conclusions is presented in Chapter 6. Future directions of research are also presented in this chapter.

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Chapter 2: DTM Processing

2.1 Introduction

The growing availability of updated and detailed land use data, largely obtained from satellite or airborne surveys, and the increasingly widespread diffusion of software tools able to manage large amounts of data and operate at high computational speed, has stimulated research to investigate the old hydrology and land management problems with new techniques and advanced models. In particular there has been a transition between an average terrain detail of 1km x 1km (available at high costs) towards a cheapest and more detailed terrain information, where cells resolution can be easily of 10m x 10m in size. The numerical 3D representation of the land is defined, in jargon, as **Digital Elevation Model** – **DEM** – containing the elevation of the terrain over a specified area, usually at a fixed grid interval over the surface of the earth. The intervals between each of the grid points will always be referenced to some geographical coordinate system. This is usually either latitude-longitude or UTM (Universal Transverse Mercator) coordinate systems. The closer together the grid points are located, the more detailed the information will be in the file.

Whereas word DEM is most of the time used as a generic term, is worthy to highlight the differences between other two most closely used and confused acronyms:

- **Digital Surface Model (DSM)** – a first-reflective-surface model that contains elevations of natural terrain features in addition to vegetation and cultural features such as buildings and roads.
- **Digital Terrain Model (DTM)** – a bare-earth model that contains elevations of natural terrain features such as barren ridge tops and river valleys. Elevations of vegetation and cultural features, such as buildings and roads, are digitally removed (Intermap solutions, 2012) (Fig. 2. 1).

DTMs are generated from DSMs using DEM filtering algorithms (Sithole and Vosselman, 2004). Each filtering method has its own advantages and drawbacks which depend on how it identifies the points that belong to the bare earth and those that not. Sithole and Vosselman (2004), after an in deep comparison of several methods, concluded that some methods produce better results than others on specific situations, but there is no filtering method better than others overall.

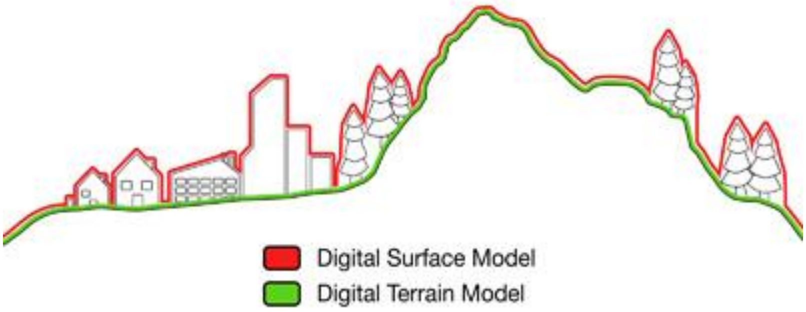


Fig. 2. 1 - Surfaces represented by a Digital Surface Model include buildings and other objects. Digital Terrain Models represent the bare ground (http://www.computamaps.com/).

Elevation data needed to produce DEMs can be obtained from various sources (Raber et al., 2002):

- Theodolite or total station
- Topographic maps
- GPS
- Interferometry from radar data
- Doppler radar
- Stereo photogrammetry from aerial surveys
- Optical satellite imagery
- LiDAR (Light Detection and Ranging)

The selection of a specific DEM creation technique will rely on the accuracy required, extent of the area of interest, budget, time frame, etc. (Smith, 2006). Moreover, each technique has its pros and cons so that, more likely, different techniques will produce different DEMs for the same area. DEMs are not only used to represent the ground elevation but, since they are a georeferred numerical matrix, can represent many others land characteristics such as land use, soil geology, lithology, pedology, permeability, or vegetation, geotechnical and agronomical characteristics.

Due to their relative ease of acquisition and relative cheap costs, especially in analysis of wide areas, this new data were immediately used for flood risk estimation and flood risk exposure, particular in urban areas (Sanders et al., 2005; Mason et al., 2007; Obermayer et al., 2010; Nielsen et al., 2011; Álvarez & Malpica, 2012; Santos et al., 2012). DEMs are essential to modelling overland flow; they can be used to generate 1D (One-Dimensional) overland flow networks, or used to describe accurately ground surface on 2D (Two-Dimensional) models (Simões et al., 2010). This terrain representation is heavily used as input for overland flow models such as dual-drainage and two-dimensional models (Cazorzi et al., 2013). Moreover, use of this kind of data, allow easy extraction of many hydrological features such as terrain slope, drainage networks, drainage divides and catchment boundary. This method, surely less time consuming than previous traditional manual techniques, it is also less error-prone, at least regarding human errors. It should be noted, however, that DEM quality and resolution affect the accuracy of derived hydrological features (Kenward et al., 2000). Therefore, DEM quality and resolution must be matched to the application of the attributes as part of planning the hydrological attributes derivation process. Moreover, due the need for using and analysing a huge volume of the spatial as well as non-spatial environmental hazards and exposure data in a fast and reasonably accurate way, Geographical Information Systems (GIS) based software applications using a variety of modelling techniques serve as powerful tools for effective environmental risk assessment and management (Raheja, 2003).

2.2 LiDAR and input data

Due to the growing environment complexity, to achieve an optimal management and representation of itself, new information from various sources at different level of detail are nowadays needed, being occasionally representable only in a three-dimensional domain (Barrile and Cotroneo, 2006). Today's availability of these information to meet these requirements, it is a problem respect to which airborne laser scanner (LiDAR) data could represent a possible solution. New data sources such as LiDAR are enabling the creation of DTMs with elevation precision in the range ± 0.5 m (Lane and Chandler, 2003). This technique, in fact, allows rapid acquisition on wide scale of high precision three-dimensional data, from which can be derived geometric attributes that define spatial manmade objects, even of a complex nature (such as buildings, sidewalks or bridges). Survey data acquired through airborne laser scanner technology can be stored on digital databases, becoming manageable and viewable by affected users.

The term LiDAR (Light Detection And Ranging) indicates a remote sensing technique similar to radar but using laser light pulses instead of radio waves. Use of high-precision laser scanner has been developed originally for study of architectural elements, thus used on the ground. Later on it was applied on helicopter and airplanes (Airborne Laser Scanner ALS) to remote sensing purposes. Hereinafter only the ALS technology will be discussed. ALS refers to a remote sensing technology that emits intense, focused beams of *light* and measures the time it takes for the reflections to be *detected* by the sensor. This information is used to compute *ranges*, or distances, to objects. In this manner, lidar is analogous to radar (radio detecting and ranging), except that it is based on discrete pulses of laser light. The three-dimensional coordinates (e.g., x,y,z or latitude, longitude, and elevation) of the target objects are computed from 1) the time difference between the laser pulse being emitted and returned, 2) the angle at which the pulse was "fired", and 3) the absolute location of the sensor on or above the surface of the Earth (Fig. 2. 2).

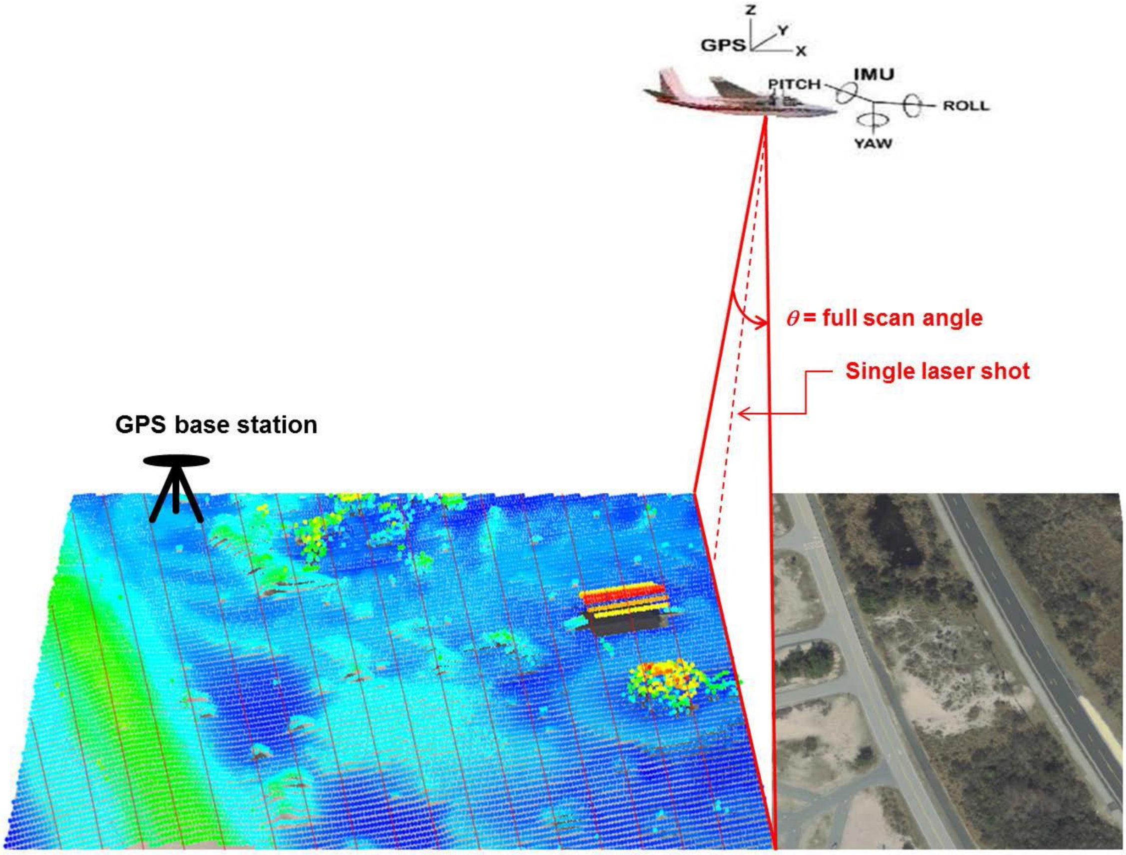


Fig. 2. 2 - Schematic diagram of airborne lidar performing line scanning resulting in parallel lines of measured points (NOAA, 2012).

In reality, to achieve a high level of accuracy, this process is a bit more complicated since it is important to know, within a centimeter or so, where the plane is as it flies at 100 to 200 miles per hour, bumping up and down, while keeping track of hundreds of thousands of lidar pulses per second. Fortunately, several technologies—especially the Global Positioning System (GPS) and precision gyroscopes—came together to make it possible (NOAA, 2012).

Major advancements in Inertial Measuring Units (IMU) or Inertial Navigation Systems (INS) have been instrumental in making the exact positioning of the plane possible.

These systems are capable of measuring movement in all directions and parlaying these measurements into a position. They are, however, not perfect, and lose precision after a short time (e.g., 1 second). A very highly sophisticated GPS unit, which records several types of signals from the GPS satellites, is used to "update or reset" the INS or IMU every second or so. The GPS positions are recorded by the plane and also at a ground station with a known position. The ground station provides a "correction" factor to the GPS position recorded by the plane (NOAA, 2012).

Likewise, lidar systems have advanced considerably. Early commercial units were capable of 10,000 points per second (10 kilohertz) and were large and bulky. Newer systems are more compact, lighter, have higher angular precision, and can process multiple laser returns in the air (i.e., a second laser shot is emitted before returns from the previous laser shot are received), allowing for pulse rates of over 300,000 per second (300 kilohertz). Multiple return systems, which are common, can capture up to five returns per pulse (Fig. 2. 3). This can increase the amount of data by 30% or more (100,000 pulses/second ≈ 130,000 returns/second) and increases the ability to look at the three-dimensional structure of the "features above the ground surface," such as the forest canopy and understory (NOAA, 2012).

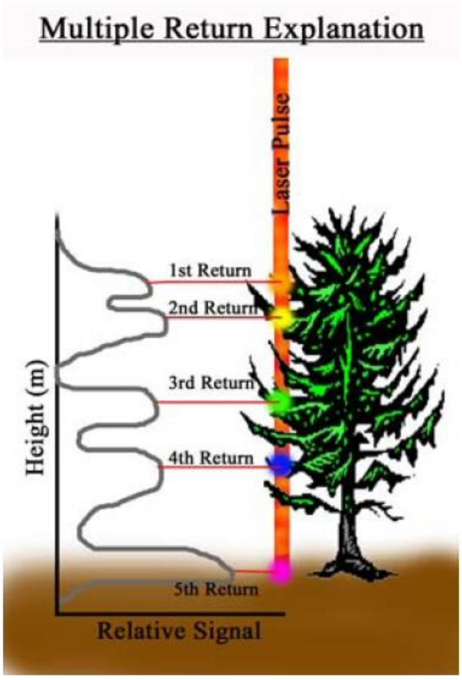


Fig. 2. 3 - Multiple returns from single pulse (NOAA, 2012).

Multiple reflections greatly increase likelihood that, even in forest areas, part of beams will reach the soil, allowing determination of ground points. Multiple reflections are recorded by the receiver in different times, with different pulse intensity, making possible to distinguish, already being recorded, belonging class of each return echo: first return echo (first pulse) allow detection of upper part of objects (e.g. forest canopy or roofs) while the latter (last pulse) identify bare earth elevation (ground points).

It is therefore important to underline that from last pulse is derived the Digital Terrain Model (DTM) composed by ground points only; DSM (Digital Surface Model) is made by first plus others returns, properly filtered. In nearly all LiDAR applications, ground filtering is a necessary step to determine which LiDAR returns are from the ground surface and which are from non-ground surface features. Distinguishing ground from non-ground can be a significant challenge in regions with high surface variability. Nevertheless, accurate DEMs can only be obtained if non-ground points are removed prior to interpolation to a raster DEM (Shan J. & Sampath A., 2005; Zhang K. & Whitman D., 2005). Many filtering algorithms have been proposed in the last decade. Meng et al. (2010) present a comprehensive reviews on LiDAR ground filtering algorithms used to create Digital Elevation Models, discussing critical issues for their development and application. A first classification approach establishes a structure element which describes admissible height differences that depend on horizontal difference. This is achieved mostly by applying morphological filters. Another group of approaches use seed points to establish triangulation and detect the points in the triangulation based on height difference. Further, surface-based filters assign different weights for each point and interpolate the terrain trend. Since all of the above approaches only cover the local neighbourhood without topological and geometric consideration, on the other hand, a segment-based filter algorithm are developed, because they can provide more reliable result since geometric and topological information are considered in the step of point clouds classification (Yang et al., 2012). The latest frontier of innovation is aimed to the automatic extraction of digital elevation models in urban areas through a simple scan-line-based algorithm that detects local lowest points first and treats them as the seeds to grow into ground segments by using slope and elevation. The scan line segmentation algorithm is also naturally accelerated by parallel computing, taking advantage of modern graphics processing units (GPUs), due to the independent processing of each line (Hu et al., 2013).

2.3 Importance of input data quality

As stated before, DEMs can include both terrain elevation data, which commands flow direction of floodwater, and land cover information, which dictates resistance to floodwater distribution. The source data of ground information are a compilation of variety of ground observations, supplemented by various remote sensing techniques, which are aerial and satellite measurements. Total stations (Fuller et al., 2005), dGPS (Brasington et al., 2003; Wheaton et al., 2009), aerial LiDAR (Devereux and Amable, 2009), and terrestrial laser scanning (Heritage and Milan, 2009; Hodge et al., 2009) are valid instruments to obtain an high-quality DEM from a spatially distributed and morphologically based survey. Since there are many data sources, each of them has its own error so that notable importance has the correct calibration of these instruments before the survey. These systematic errors (due to the accuracy of survey equipment) greatly influence the resulting DEM, together with random error (such as pole tilt when survey with a total station, or triangulation when surveying with a dGPS) that are probably the most difficult to individuate and then to eliminate. It is necessary to point out that density and spatial distributions across the surface relative to the morphology are also very important; factors that may vary between surveys. Quite often, survey error are uneven across a surface, with low error across uniform surfaces and increased error associated with breaks of slope such as banks and bar edges (Milan et al., 2011). Another error source for DEM derives from interpolation procedures (Mingfeng et al., 2008; Mei et al., 2011) of data retrieved by topographic, contour-based or spot height maps. Interpolation techniques, now ubiquitous in every Geographic Information Systems (GISs), are the easiest way to get a quick and affordable DTM, but even more error prone, due to the chance to obtain “artificial” or spurious depressions (Zhu et al., 2013), also called *pits* or *sinks*. Other typical error often obtained by an oversimplified interpolation method are *flat areas* (Fig. 2. 4) that, even if generally present in DTM, are considered as errors to remove (Nardi et al., 2008). The practice of removing every depression from DEMs has been justified in the past in three main ways: (1) the scale and accuracy of a DEM is inadequate to represent actual depressions, which are generally small landforms; (2) depressions rarely occur in natural landscapes and artefact digital depressions are abundant, and (3) actual depressions have minimal impact on hydrogeomorphic processes since they either fill with water and overflow or find sub-surface pathways that are closely approximated by surface topography.

However, the development of high-resolution DEMs has meant that the assumption that all depressions are artefacts is now more questionable. In fact, modern DEMs that are created from digital photogrammetry, laser altimetry, and satellite imagery are often capable of representing actual depressions in the landscape because of their fine scale and high level of precision. Therefore, it is no longer justifiable to assume that all digital depressions are artefacts on the basis of DEM quality alone (Lindsay & Creed, 2006).

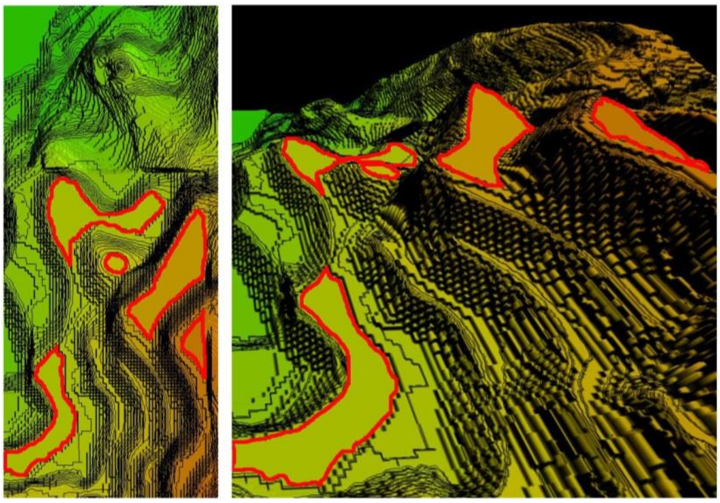


Fig. 2. 4 – "*Flat areas*" due to bad contour line interpolation (2D view on left; 3D view on right).

However, DEM errors are likely generated even when data is coming from LiDAR survey, so that the accuracy of this data is still subjected to debate.

Although the positional accuracy and precision of LIDAR data far exceeds those afforded by traditional remotely sensed imagery, laser return coordinates do contain random and systematic errors. Both error types originate in one or more of the laser system's components. Random errors relate to noise in the computed location of the aircraft, in the recording of aircraft attitude and scanning angles, or in the recording of time between pulse emission and backscatter reception, which ultimately determines the distance (range) to the target. Regardless of the exact methodology used, also the assessment of relative accuracy in LIDAR data is susceptible to artifacts or errors introduced during the creation of the derived products, such as raster surfaces or object (i.e., individual tree) segmentations. Often the algorithms used to produce these derivatives are complex and highly sensitive to the input parameters. Lack of continuity or scanning uniformity in a LIDAR data acquisition can be sources of artifacts and local variability in data derivatives, thus precluding data analysis. Even sporadic discontinuities in the laser data could, for example, prevent a successful delineation of the drainage network or the computation of landform and vegetation structure metrics.

Aircraft attitude, such as variability in aircraft pitch or the combined effect of roll and pitch changes, can also affects laser scanning and local pulse density. Last but not least important, portion of returns that are removed by post-processing prior to the data delivery can generate errors in the derivative products. Although the elimination of returns in the latter case is theoretically legitimate, the procedure used to identify them can contain flaws, at least in certain circumstances. Ideally, a report with quantitative estimates of data quality measures (return coordinate accuracy and precision, compliance with acquisition specifications, and data spatial consistency) would be part of every laser data delivery. Unfortunately, such reports are rare, and when they are produced, the information included is frequently selective or incomplete, because, as discussed above, the procedures involved in evaluating data quality are costly and time consuming (Gatziolis & Andersen, 2008).

2.4 DEM errors and enhancement methods

Decrease in the cost of acquisition and increase in the density and accuracy of Light Detection and Ranging (LiDAR) data, encouraged whole scientific community to widespread adoption and use of DEM for hydrological and hydraulic purposes. High quality DEMs can be used, in fact, to retrieve both spatially derived hydrologic parameters (such as watershed area, curve number, gridded precipitation, flow length in each watershed, slope) for input into more powerful hydrologic models and extraction of topographically correct cross-section data that can be used to determine river stage and floodplain extent (Deshpande, 2013) as calculated in hydraulic modelling software packages. Although increasingly available, efficient processing and extraction of useful information using LiDAR data remains a big challenge in several fields (Chen, 2007), because of loss of accuracy and true elevation values due to interpolation of original random points to create DEM. As discussed earlier, in fact, DEMs obtained by topographic surveys, LiDAR or any other source are primarily affected by systematic and random errors owned by acquisition equipment, then by pre-processing operations performed by acquisition companies with their proprietary algorithms to distinguish between *"ground"* and *"non-ground"* points and lastly by the interpolation method (deterministic methods such as inverse distance weighted – IDW – assume that each input point has a local influence that diminishes with distance, spline-based methods that fit a minimum-curvature surface through the sample points, and geostatistical methods such as Kriging that takes into account both the distance and the degree of autocorrelation) used to generate two-dimensional surface (Chaplot et al., 2006). Although calibration of instruments and supervised classification of laser return are carried out to minimise number of errors, very often final data comes to the end user with (desirable) few errors remaining that tend to be increased again by erroneous interpolation procedures. The main categories of errors that can be found in a DEM are:

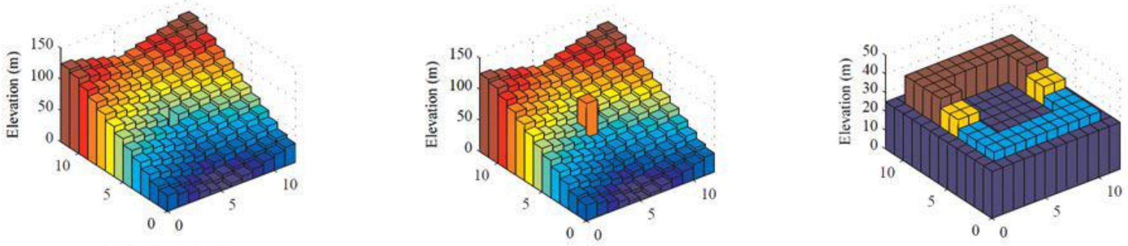
- *sinks* or *pit cells*, when a cell is surrounded by other cells with higher elevation – no lower adjacent cells;
- *peak cells,* when a cell is surrounded by other cells with lower elevation;
- *flat areas,* when a cell is surrounded by other cells with its same elevation.

Since the DEM is an approximation to terrain characteristics, the accuracy of the topography and the related hydrological applications will depend on the quality of the DEMs, especially the characteristics such as slope analysis, river network density, flow path and the topographic index. DEMs have to be made "hydrologically correct" before being used in hydrological models (Zhu et a., 2013).

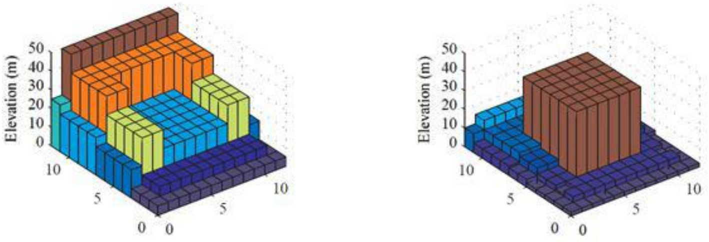
Whereas sinks or peak cells are likely more easy to individuate (and to correct), especially if they are isolated and uneven from surrounded topography in a particular area of the DEM, it is not the same regarding depressions and flat areas. The latter often create difficulty in determining flow directions as the flow cannot continue downstream until the depressions are filled (Jenson and Domingue, 1988).

In the past, particularly when DEM accuracies and resolutions were not so high and precise like today, the main approach was to treat all digital depressions as artefacts to be removed (e.g., O'Callaghan and Mark, 1984; Band, 1986; Jenson and Domingue, 1988; Hutchinson, 1989; Fairfield and Leymarie, 1991). Conversely, current high resolution LiDAR-derived DEMs often contain a very large number of (mostly small) depressions because of greater surface roughness and finer resolutions (MacMillan et al., 2003). This arises the problem to understand if depressions and others DEM's artefacts are real or spurious, so, to be removed in latter case and, moreover, to comprehend which algorithm use to achieve these objectives. Unconditional and thoughtless use of available methods, neglecting knowledge of real topography, can lead immediately to wrong results, compromising original terrain features and DEM's accuracy.

As demonstrated by Leitão (2009) that performed a sensitivity analysis on five common error case that may be occur in a DEM (Fig. 2. 5), often commercial software (CatchmentSIM Filling method, ArcGIS Fill method, IDRISI Pit removal method) operate only changes to solve pit cells caused by under- or over-estimation of the real terrain height, and large terrain depressions cases. Besides these methods do not resolve flat area problems and, in some cases, terrain features are altered or destroyed by them.



(a) Sink (case 1) (b) Peak (case 2) (a) Flat area in depression (case 3)



(b) Intermediate plateau (case 4) (c) Plateau (case 5)

Fig. 2. 5 - Typical range of errors that may be found in a DEM (Leitão, 2009).

Beyond that, these algorithm are very time consuming and computationally demanding, especially for DEM with big number of cells. Hence the need to maximize the grid size, while maintaining adequate resolution for the specific purpose. A general remote sensing sampling rule is that the cell size of the lidar-derived DEM should be at least equal to or greater than the nominal post-spacing. Using a smaller cell size would result in no improvement in detail or overall accuracy. However, the relationship between the modelled surface (e. g. elevation and slope accuracy) and the covariation of DEM cell size and/or lidar post-spacing is not well understood (Chow and Hodgson, 2009). Obviously, the DEM resolution progressively affects its first (e.g. slope and aspect), second (e.g. profile and plan curvature) and compound derivatives (e.g. wetness index) besides all others hydrologic features extracted such as drainage network, catchment delineation, watershed longest flow path, floodplain determination, erosion and sedimentation and river analysis (Liu, 2012; Deshpande, 2013). A sensitivity analysis of sink removal operation and influence of DEM resolution on overland flow network delineation has been performed in Liguori catchment (Cosenza, Italy) and described in the next section (§2.6).

2.5 Overland flow network delineation

Urban drainage studies were classically focused solely on modelling of sewer network in urban catchments. The hydraulic processes of the sewer networks, in fact, are simulated in more detail rather than catchment processes, because the sewer geometry is or should be completely known and the hydraulic phenomena occurring, although abundant and complex, are undoubtedly less numerous. This means that overland surface runoff is usually simulated by conceptual models, whereas the routing of the sewer flow is commonly analysed by physical-based approaches, i.e. by using the mass and momentum conservative equations (Tomei, 2012). The traditional approach was to evaluate the *minor system* (sewer network) without inclusion of the *major system* (overland flow network) and when the latter was evaluated, it was generally done as a separate model.

This methodology has one of the major deficiency in its inability to model the flooding process, i.e. the situation when the underground system becomes surcharged, water flowing out of the system interferes with the water that flows superficially because there was no more capacity to enter the sewer system. The concept of *dual drainage* is to enable flooding in urban environment to be modelled more realistically by taking into account all features of terrain and manmade structures that affect surface runoff (Maksimović & Prodanović, 2001).

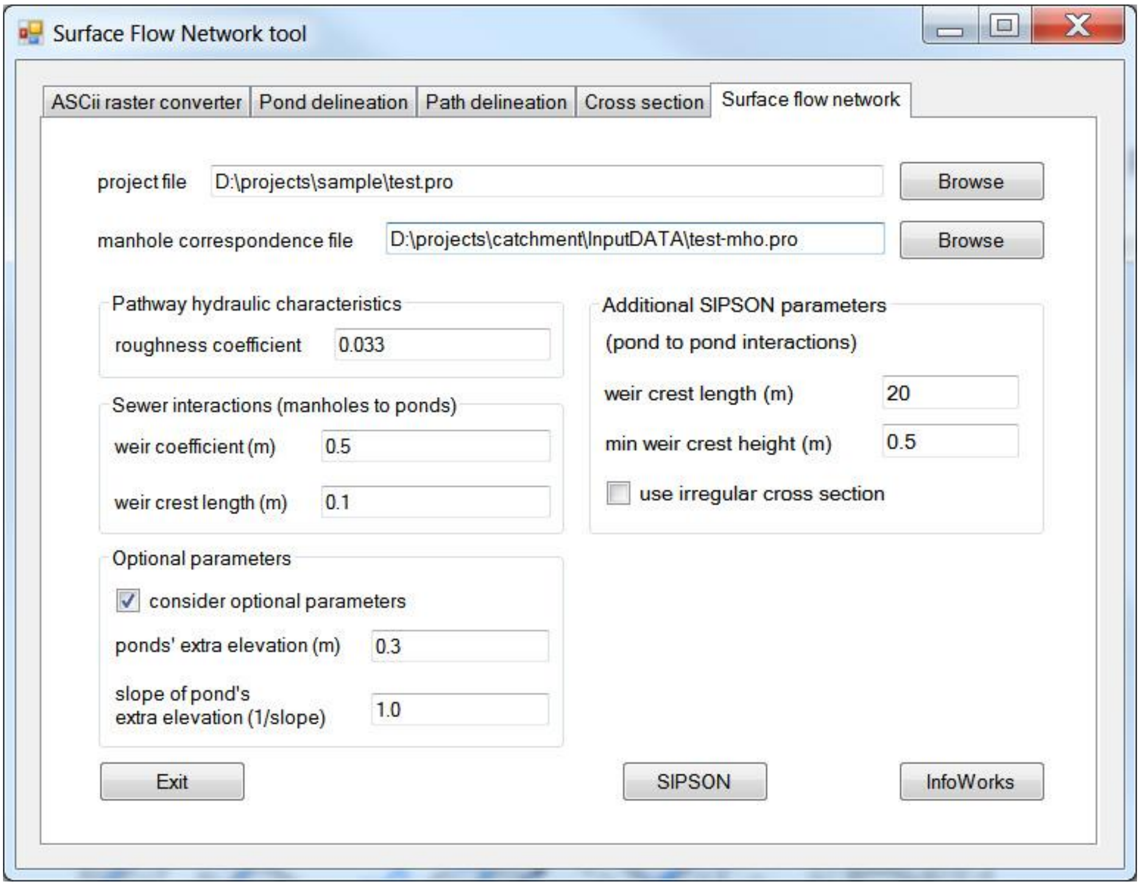
Regardless of the final purpose, development of major system model can be significantly speeded up by semi-automated processes using spatially based queries within a GIS database and a 2-dimensional surface for evaluation of overland flows. This implies that *overland flow network* generation is influenced by obstacles (i.e. buildings, roads, sidewalks) existing over the surface so, ultimately, by accuracy and resolution of DTM used (Song et al., 2012; Zhu et al., 2013).

Except for slope, other topographic characteristics can be calculated solely after determination of flow direction. However, before being able to do this, depressions and flat areas within a DEM must be rectified. This problem is always present in hydrologic modelling, because theoretically all DTMs contains flat areas and sinks (real or spurious) that if leaved there, can alter or prevent flow paths delineation. Several algorithms have been developed for rectifying flat and sink pixels in DEM data; these have typically been implemented in conjunction with the D8 flow-routing approach and range from simple DEM smoothing to arbitrary flow direction assignment. A thorough review of these methods and their possible improvement can be found in Leitão (2009). Hence to cope with the requirement to have an "hydrologically corrected" DTM for hydraulic purposes, different tools for terrain processing can be found online. Hereinafter two of them will be analysed, one based on ESRI ArcGIS (at least ArcView license – Editor license is recommended) with Spatial Analyst extension enabled and another one working standalone. Either advantages and drawbacks will be analysed and discussed.

2.5.1 AOFD

AOFD is the acronym of Automatic Overland Flow network Delineation and it is a tool that automatically analyses, quantifies and generates 1D overland flow network, developed by the Urban Water Research Group (UWRG) of Imperial College London. The tool consists of several GIS routines that analyse and quantify surface overland flow network on urban catchment based on input data e.g. master map, elevations, sewer network. The outputs were designed to give additional surface pathways' network in order to improve the accuracy of simulation model of urban flooding. The analysis can be divided in four main steps: (i) ponds' delineation; (ii) pathways delineation; (iii) pathways geometry; and (iv) generation of input files for urban drainage models (Simões et al., 2010) (Fig. 2. 6).

The methodology, originally developed and described in Maksimović (2009), scans the entire DTM matrix looking for local low points. For each local point, boundary and natural exit point are determined. After, pond filtering is performed, and user can define, at the beginning of procedure as a filtering criteria, volume and depth of ponds to be discarded. Studies conducted by Leitao (2009) suggest a value of ± 5m^3 for volume and pond depth between 0 – 0.2m, but a preliminary analysis on distributions of volume and depth of ponds is strongly suggested. Following step consists on overland flow path delineation. The tool allows delineation of paths starting from ponds (from their outlets) or from sewer manholes and inlets (in both directions, from and to manholes/inlets) therefore the final overland flow network is influenced by their number and position.



project file D:\projects\sample\test.pro

manhole correspondence file D:\projects\catchment\InputDATA\test-mho.pro

Pathway hydraulic characteristics

roughness coefficient 0.033

Sewer interactions (manholes to ponds)

weir coefficient (m) 0.5

weir crest length (m) 0.1

Optional parameters

☑ consider optional parameters

ponds' extra elevation (m) 0.3

slope of pond's extra elevation (1/slope) 1.0

Additional SIPSON parameters (pond to pond interactions)

weir crest length (m) 20

min weir crest height (m) 0.5

☐ use irregular cross section

Fig. 2. 6 – AOFD user interface; tabs show functionality and analysis performed by the tool.

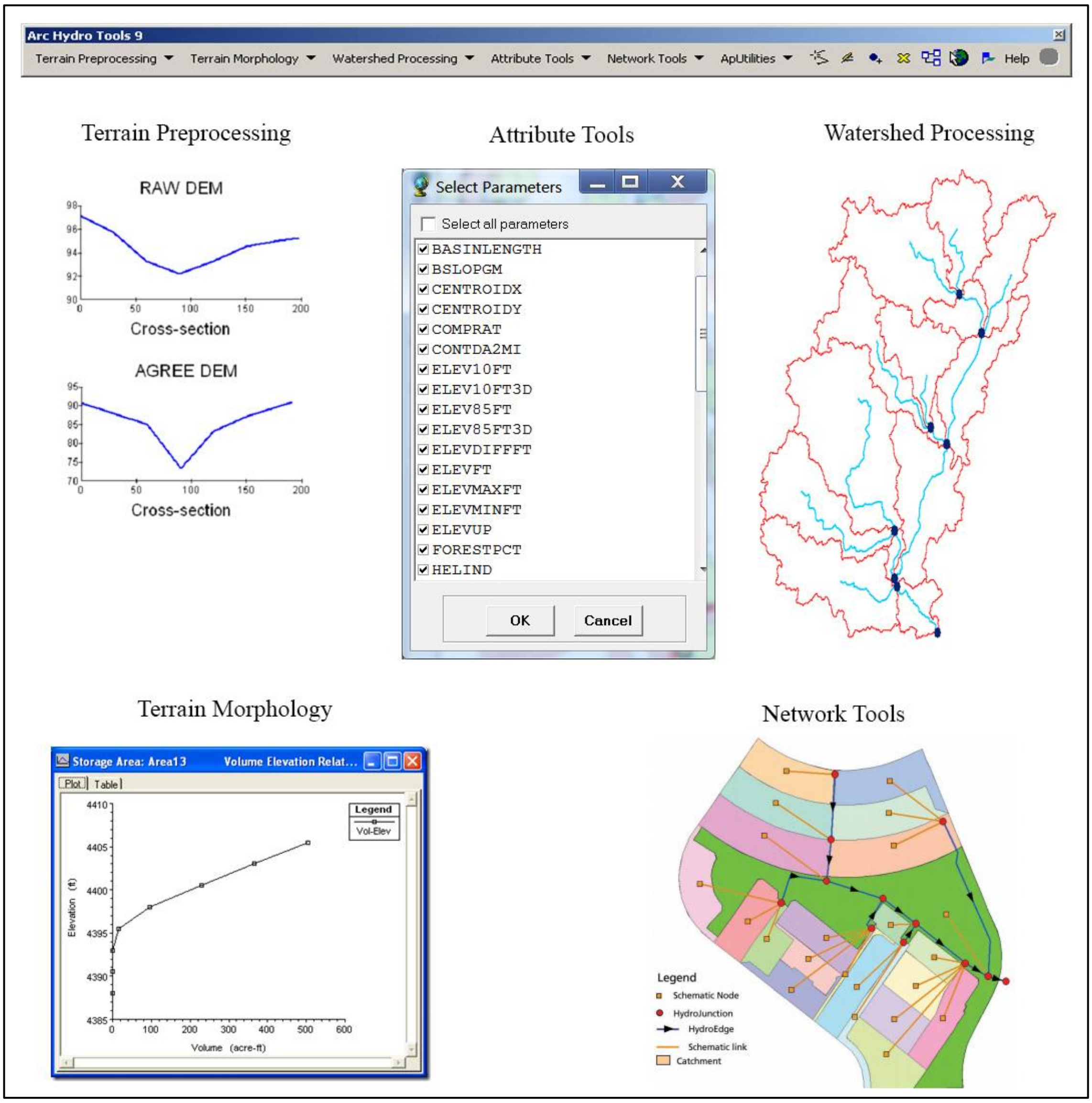
The tool is able also to take into account the presence of buildings, avoiding pathways fall down within them. Last two steps are generation of channel cross section (trapezoidal or rectangular) and output files of the network, ready to be imported in two hydraulic modelling software: Infoworks or SIPSON (Djordjević et al., 2005).

AOFD is a good software, but it needs more improvements. Indisputable advantages are: detailed ponds delineation and filtering, pathways delineation taking into account for presence of buildings and sewer network and cross section calculation (the latter two not available in any other similar software). Conversely, use of the software is slightly difficult. Many of the input file need to be prepared before, externally of the tool. The tool itself does not allow any other kind of DEM data preprocessing (such as DEM reconditioning) and there are also some limitations about size of DEM used and its cell size (in order to not prolong too much calculation time). Moreover, there are no functions able to provide topographic features (i.e. slope, aspect, catchment boundary) or other watershed characteristics (i.e. perimeter, area, storage-area curve). In conclusion, the tool is very specialized and it provides some unique results such as the quick possibility to easy couple overland and sewer networks (even if the subsequent simulation must run into another software) as well as the extraction of geometric channel characteristics from the DEM. This extreme specialization represents, however, one of its main drawbacks, together with the not so friendly user-interface and the dataset limitations, that make the tool unusable for analysis of large areas.

2.5.2 Arc Hydro

Arc Hydro is a powerful GIS data schema and toolbox developed at Centre for Research in Water Resources at University of Texas at Austin. The toolbox is open source freeware and is available online (Center for Research in Water Resources – CRWR). Arc Hydro is an additional toolbox for ArcGIS capable to manage data, spatially and temporary distributed, for water resources. In particular, set of tools provided allow to estimate many hydraulic features such as area, slope trend, drainage network of river basins, that are essential for both urban and natural hydrological modeling. These tools can be grouped into five categories, based on their functionality (Fig. 2. 7):

- *Terrain Preprocessing*. Tools on this menu allow the development of hydrologically-correct DEM (HydroDEM) and its derivatives, primarily the flow direction and flow accumulation grids as well as identification of preferential flow path patterns in the vector environment.
- *Terrain Morphology*. Provides a global view of the tags assigned by the functions to the selected inputs and outputs in the active Map/Data Frame. The function also allows determining some important basin characteristic such as Drainage Area Characterization, Drainage Boundary Definition, Drainage Boundary Characterization, Drainage Connectivity.
- *Watershed Processing*. This menu provides access to several functions that allow fast watershed delineation and topographic characteristics extraction. Some of the available functions are: delineation of watershed and subwatershed, delineation of multiple inlet and outlet points, longest flow path for watershed, flow path parameters and basin length (perimeter).
- *Attribute Tools*. This menu provides access to several functions that allows reading and writing attributes (retrieved catchment characteristics such as average elevation and area) in specified tables.
- *Network Tools*. Provides access to several functions that allows processing (generation) of the hydrologic network, retrieving its geometric properties.



☐ Select all parameters

☑ BASINLENGTH
☑ BSLOPGM
☑ CENTROIDX
☑ CENTROIDY
☑ COMPRAT
☑ CONTDA2MI
☑ ELEV10FT
☑ ELEV10FT3D
☑ ELEV85FT
☑ ELEV85FT3D
☑ ELEVDIFFFT
☑ ELEVFT
☑ ELEVMAXFT
☑ ELEVMINFT
☑ ELEVUP
☑ FORESTPCT
☑ HELIND

Fig. 2. 7 – Arc Hydro Tools Functionalities.

The first step, using the software, is to perform the DEM preprocessing, to take away any misleading elevation values along the main river channel and remove any spurious depression (pits and sinks). After that, watershed and streamflow delineation is performed following this sequence: Flow Direction, Flow Accumulation, Stream Definition, Stream Segmentation, Catchment Grid Delineation, Catchment Polygon Processing, Drainage Line Processing, and Adjoining Catchment Processing. The final step of the delineation process is using the earlier defined design points to delineate the sub-watershed assigned with each design point, using the Drainage Point Processing function in Arc Hydro.

Some studies (Zhang J. et al, 2010; Baumann & Halaseh, 2011), including application in Liguori's Channel (§2.6), showed that, automatically extracting watershed features based on Arc Hydro tools is feasible and effective.

The tool is very powerful and it allows full delineation of watershed and drainage line delineation both in urban and natural areas. Obviously precision of the results depends from input data (DTM) used, even if the software allows little improvements such as fill of sinks and creation of reconditioned DEM (AGREE method adjusts the surface elevation of the DEM to be consistent with a vector coverage; the vector coverage can be a stream or ridge line coverage). The software allows, also, to analyse DTM looking for depressions, determining their characteristics (i.e. volume, area, storage-area curve). In each case, user must decide which one is real and which spurious, but the tool offer a series of filtering instruments (by area, by depth, mixed) to do it. Conversely to AOFD, the software does not give any option about pond and path delineation as well as overland flow path cross section evaluation.

2.6 Ponds delineation in Liguori Channel basin

In this section a case study is presented to evaluate the influence of DEM resolution on overland flow network delineation. For this purpose, six different DTMs generated from different sources (thus with different resolutions) are used, in order to compare achieved results.

The catchment examined for the application is the Liguori Channel (LC), situated in Cosenza (Italy) that it is been subjected for several years to an accurate and extensive research by the Department of Civil Engineering (ex. Department of Soil Conservation) of University of Calabria (Calomino et al ., 2000). Within the catchment, in fact, there is a measuring station equipped with an ultrasonic sensor for measurement of water levels in the sewer channel and a tipping bucket. In addition, since 2004, it is ongoing an experimental campaign aimed to characterize the conditions of wastewater quality during dry and wet weather periods (Piro, 2007).

This watershed is characterized from a total area of 414 hectares, 51.4% of which is natural (grassland and olive groves) and the remaining part urbanized. It is a combined sewer system that collects sanitary sewage and stormwater runoff in a single pipe system, conveying the whole water volume directly to the waste water plant in Montalto Uffugo, Cosenza (Italy) (Fig. 2. 8).

Fig. 2. 8 – Experimental Liguori's catchment located in Cosenza, Italy.

Further details about physical characteristics and drainage system of the watershed, can be found in Piro & Sole (2001).

As stated before, the research were carried out to evaluate how DTM resolutions and presence of buildings affect the delineation of ponds, namely potential flooded areas. To achieve this aim, three different DEMs of the study area, generated from different sources, were used: two contour-based DTMs with contour interval respectively of 30 m (*DTM 30*) and 20 m (*DTM 20*), and one LiDAR-based DEM, with horizontal resolution of 1 m (*LIDAR DTM*).

These three DTMs, showing only information of bare earth, were later modified overlapping the building layer, thus increasing the height of surface by 10 m in correspondence of buildings, to take into account their presence ($DTM\ 30_b$, $DTM\ 20_b$, $LIDAR\ DTM_b$) (Fig. 2. 9).

Moreover, for a more in depth analysis, $LIDAR\ DTM_b$ cell size has been down sampled from 1 to 5 meters coarse resolution, in order to evaluate also, how cell size affect ponds delineation.

The legitimacy of the performed operations has been validated through the use of the Shannon theory, or information theory (Shannon, 1948). The Shannon–Weaver Information statistic has been proposed as a useful measure of the quality of a Digital Elevation Model (Wise, 2012). This statistic is usually based on the concept of entropy, that represents a measure of the degree of organization in a system. Entropy gives an indication on the quantity of information incorporated into a system: the lower is the entropy, the lower is the number of information contained in it.

From a geographical point of view, entropy is a measure of how many categories are present in a parameter map at a given sampling interval or grid cell resolution. If the resolution is too large, categories will drop out of the ensemble, affecting model results (Kemp, 2003). With the DEM grid size increasing, entropy becomes smaller. This means DEM with coarser resolution has less information (Hao et al., 2005).

Entropy of an interpolated DEM (*H*) can be calculated using the equation (Sharma, 2011):

$$H = -\sum_{i=1}^{m} (P_i \cdot \log P_i)$$

where P_i is the probability of a cell being classified as class type '*i*' and *m* is the number of classes. Any base can be used for logarithm; when logarithms to base 10 is used, the units for entropy are called Hartleys.

Further information on DEM quality can be retrieved from the Spatial Variability Measure – SVM (Farajalla and Vieux, 1995) which measures the difference between the entropy and the maximum elevation value, where N is the total number of bins (or classes) in the elevation histogram:

$$SVM = 1 - \left(\frac{H}{\log(N)} \right)$$

The spatial variability gives an indication on how much the DEM elevation distribution differs from a uniform distribution (Wise, 2012).

Bearing in mind the concept of entropy, the two previous indices has been calculated for DEMs used in the study, both for original data and the enhanced data, when the presence of overlapped buildings has been considered (Tab. 2. 1).

	H [Hartleys]	*SVM*
DTM 30	2.208	0.049
DTM 30$_b$	2.215	0.048
DTM 20	2.116	0.093
DTM 20$_b$	2.125	0.089
LIDAR 1 M	2.200	0.063
LIDAR 1 M$_b$	2.203	0.061
Resampled data		
LIDAR 1 RCL5	2.200	0.061
LIDAR 1 RCL5$_b$	2.204	0.061
DTM 20 RCL1	2.116	0.093
DTM 20 RCL1$_b$	2.125	0.089

Tab. 2. 1 - Entropy (*H*) and Spatial Variability Measure (*SVM*) for DEM used in the study; subscript 'b' indicates DEMs with overlapped buildings and code '*RCL*' the reclassified data.

As it is possible to notice, when buildings are overimposed entropy slightly increases, meaning that the operation produces an increment of the DEM quality. Together, spatial variability slightly decreases or, in some cases, does not change at all. Inclusion of buildings produces the same trend for LiDAR downsampled to 5 meter in cell size and DTM20 upsampled to 1 meter in cell resolution. However, in this latter case, it is worth to notice how the resampling operation does not change the entropy value if compared with the original data, confirming that the process does not improve the original data accuracy.

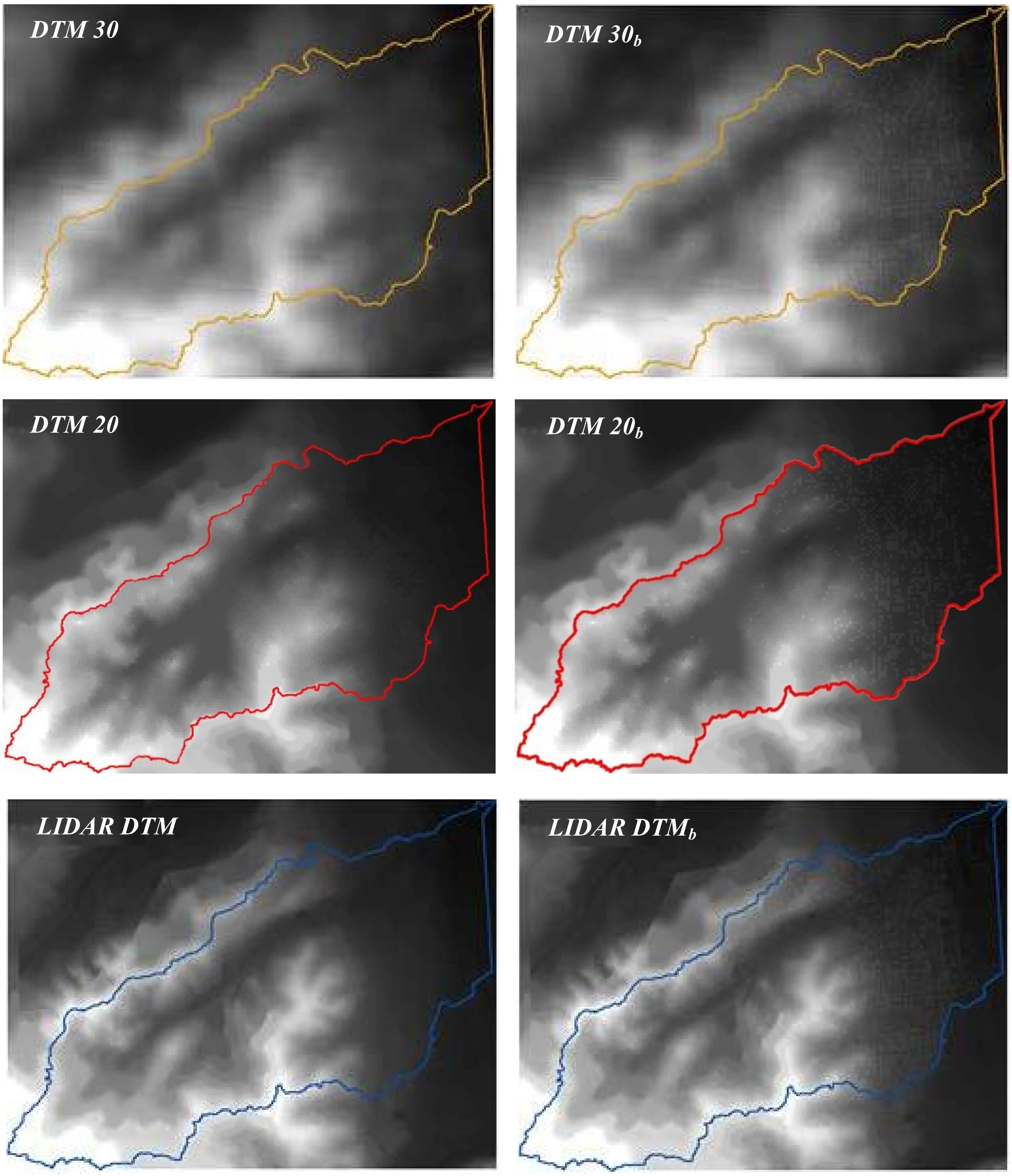


Fig. 2. 9 - DEMs used in the case study.

Afterwards, individuation of likely flooded areas has been carried out using Arc Hydro Tools, within GIS environment (§2.5.2). Even AOFD has been used in this task but its primary application is related to overland flow paths delineation, because of the great number of option that it is possible to specify and its precision on performing this task (§2.5.1).

2.6.1 Influence of DEM's resolution and buildings on the major system

At a first look, the thing that immediately stands out is that, the coarser is the resolution, the lower is the number of cells needed to represent the same area. Conversely, it is even more true that, the finer is the resolution, the better are the details, but the higher will be the computational time to analyse the matrix (Tab. 2. 2 & Tab. 2. 3).
As revealed by Arc Hydro Tool processing, DEM's resolution has a very strong impact on ponds delineation, in terms of numbers of depressions identified, their area and storage volume (Tab. 2. 4).

	DTM 30	***DTM 20***	***LIDAR DTM***
Horizontal resolution	30 m	20 m	1 m
N° of rows	8941	125	3125
N° of columns	4894	166	4255

Tab. 2. 2 - Characteristics of bare earth DEMs.

	DTM 30$_b$	***DTM 20$_b$***	***LIDAR DTM$_b$***
Horizontal resolution	30 m	20 m	1 m
N° of rows	84	125	2508
N° of columns	111	166	3321

Tab. 2. 3. - Characteristics of DEMs with overimposed buildings.

	Number of ponds	***Area occupied by depressions [m^2]***	***% of catchment area occupied***	***Storage volume of depressions [m^3]***
DTM 30	5	110045.46	2.46%	306280.37
DTM 20	24	20400	0.46%	27200
LiDAR DTM	23615	193802	4.34%	91209.52

Tab. 2. 4 - Ponds delineation and their characteristics.

It is possible to notice that the higher is the resolution, the lower is the storage volume of ponds, except for the LiDAR case.

A similar trend is shown for modified DEMs with superimposed buildings (Tab. 2. 5), where it is possible to see a slightly increase of accumulated volume when comparing with the previous case. This behaviour can be partially explained with the presence of buildings that create new small ponds whilst filling the larger ones, thus reducing the total accumulated volume (Fig. 2. 10).

	Number of ponds	***Area occupied by depressions [m^2]***	***% of catchment area occupied***	***Storage volume of depressions [m^3]***
DTM 30$_b$	14	158400	3.55%	437400
DTM 20$_b$	44	32800	0.73%	51200
LiDAR DTM$_b$	25310	200706	4.50%	89501.84

Tab. 2. 5 - Ponds delineation in DEMs with superimposed buildings and their characteristics.

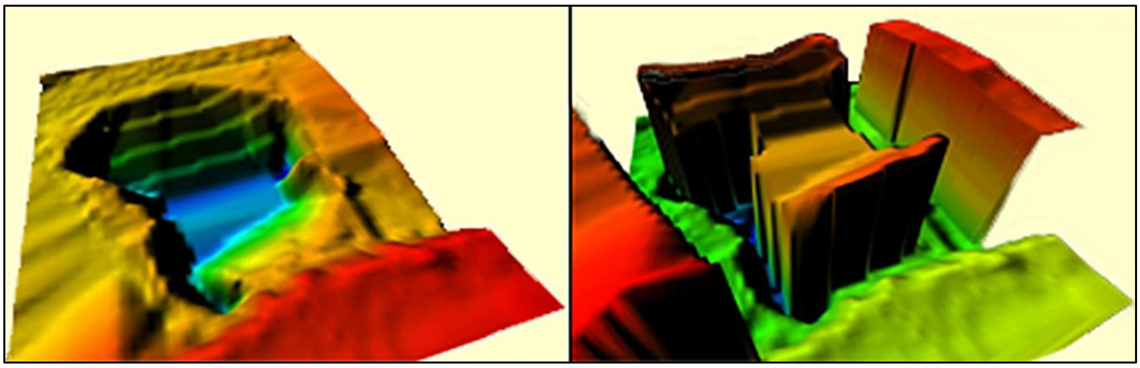


Fig. 2. 10 - Overimposed buildings fill larger ponds while create new little ones around them; this help to minimise the total accumulated volume, even increasing number of delineated ponds.

However, presence of buildings is also useful to correct a common problem of any kind of flow path delineation algorithm: generation of ponds and overland flow path falling within them. Correction of this problem is important both to avoid erroneous estimation of trapped volume in ponds and subsequent influence on hydraulic simulations (Fig. 2. 11).

Fig. 2. 11 - Use of DEMs without superimposed buildings can lead to common errors like delineation of ponds and overland flow path within them.

Comparison of previous results can lead to some notable remarks: number of depressions generated is higher when using high quality data and when buildings are considered. Conversely, storage volume of depressions is lower when using high quality, except for LiDAR data; moreover it is higher in presence of buildings, except for LiDAR data where behaviour is opposite (Fig. 2. 12).

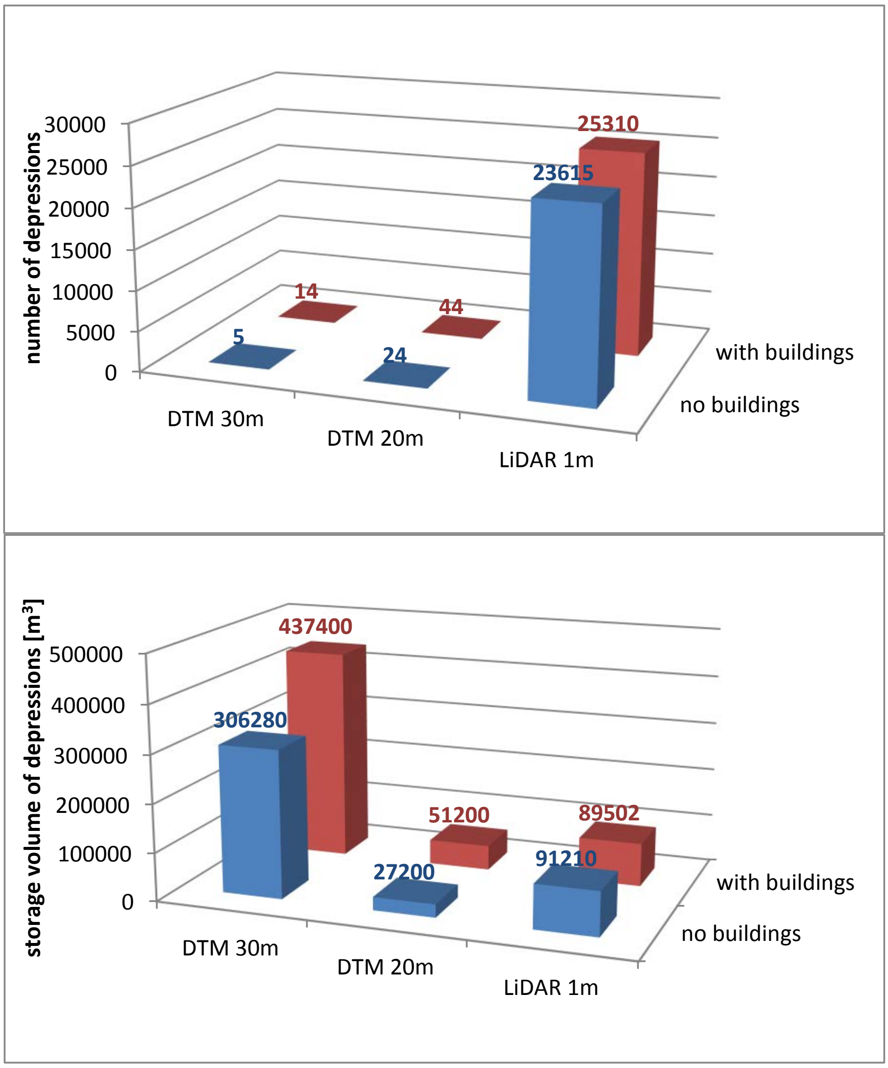
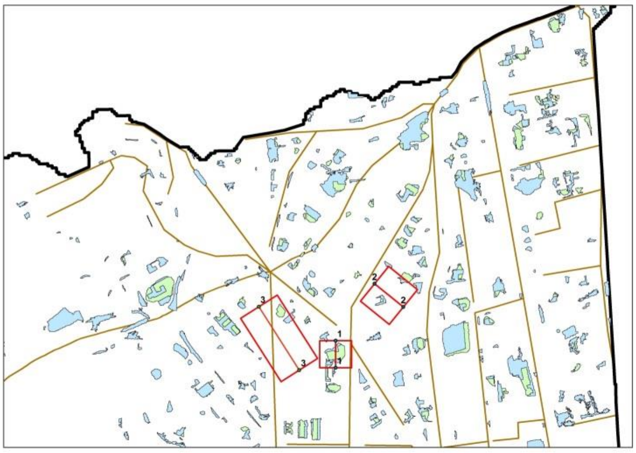
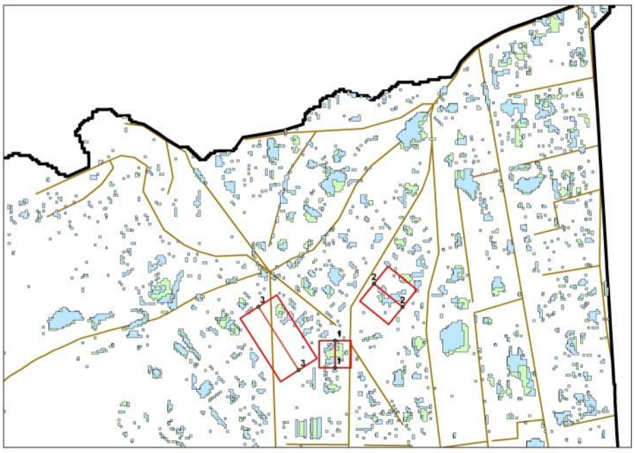
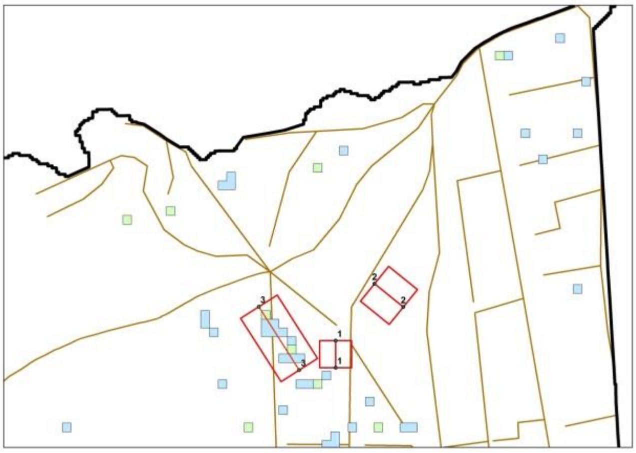


Fig. 2. 12 - Comparison between number of depressions in DEMs and their storage volume with and without overlapped buildings.

In order to investigate the unusual behaviour of LiDAR data regarding number of depressions and accumulated volume, further examinations have been conducted. In particular, after a visual inspection of previously delineated ponds, three section were chosen and analysed. These sections were located in three different points of the catchment, based on pond’s positions and DEM resolution. Indeed it is interesting to notice how the presence of ponds in correspondence of these section varies according to cell resolution, resulting in shape, location and volume modifications (Tab. 2. 6).

Delineated ponds for LiDAR 1m	
Delineated ponds for LiDAR downsampled 5m	
Delineated ponds for DEM 20m upsampled 1m	

Tab. 2. 6 - Ponds delineation for different source data and different sections analysed.

2.6.2 Section 1

First section was analysed using the original LiDAR data (1 meter resolution) and a downsampled version, where cell size has been enlarged to 5 meters. A look at the picture below shows very interesting details (Fig. 2. 13).

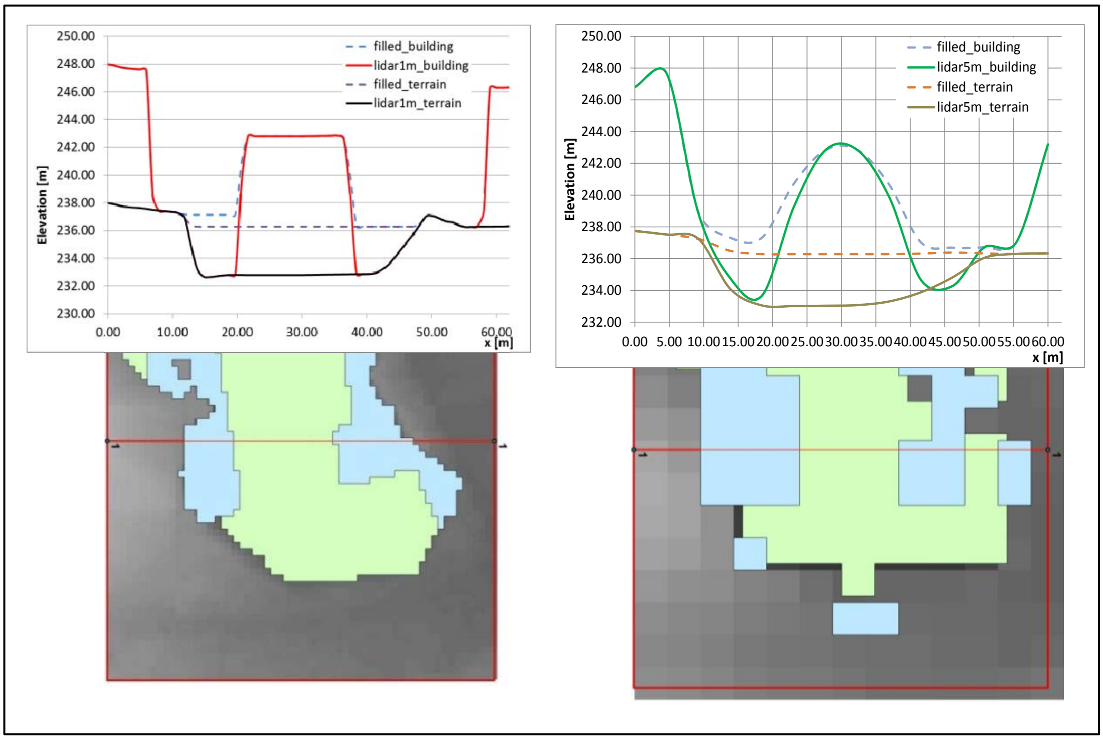


Fig. 2. 13 - Comparison of LiDAR data (left) and downsampled 5m data (right), with and without overimposed building; section 1.

The first image on the left shows the original LiDAR data before (black and red lines) and after (dashed violet and blue lines) the filling operation (performed by many software to remove ponds in DEM). Due to the great quality and precision of data, overimposing of building and subsequent filling, effectively reduce area and volume of present pond without displaying strong alteration of terrain itself or of building layout. The image on the right, after data resampling, shows instead an evident alteration of the pond (yellow line) that results bigger than in reality (more volume accumulated). Anyway, the subsequent filling operation (dashed orange line) seems to solve the problem. Conversely, when building layer is overimposed, it is evident a loss of form of the building erroneously interpreted as terrain from the software: next filling operation goes to fill space between them, whilst this space should remain because it is really existent.

2.6.3 Section 2

The second section analysed shows a trend similar to section 1, both when original LiDAR data and downsampled data is used (Fig. 2. 14). When original data is used, a correct representation of terrain and building layer is shown, without any ponds detected (left image).

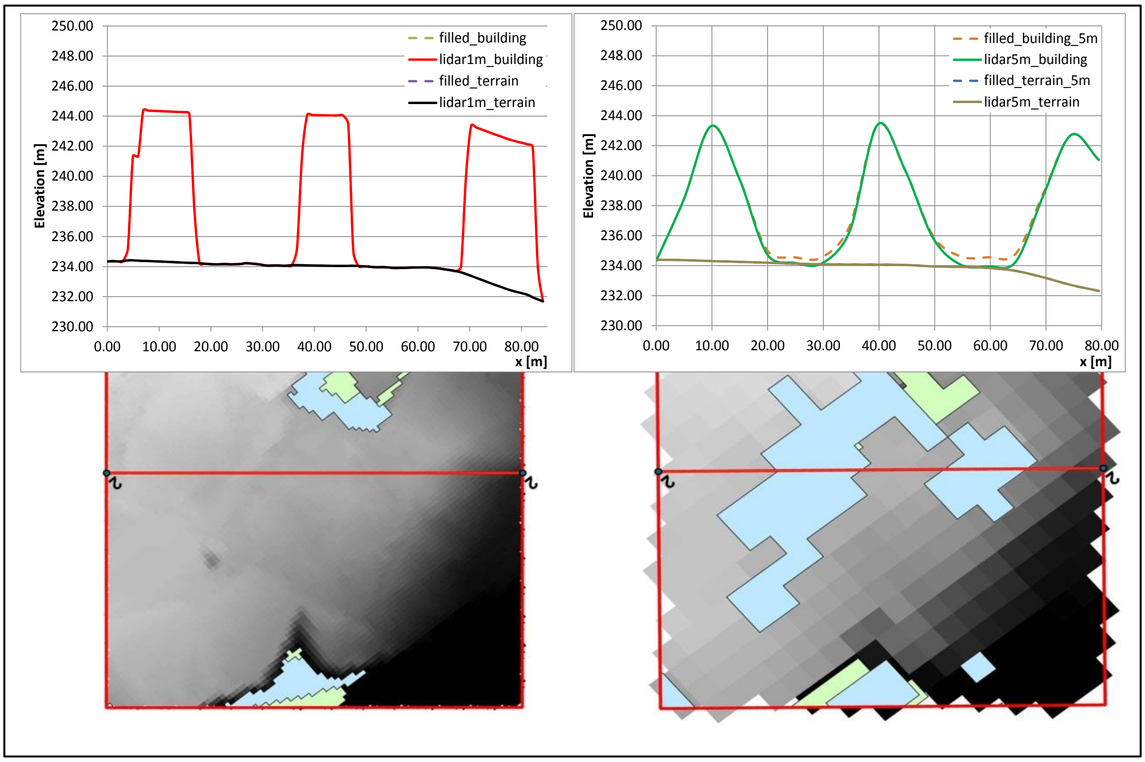


Fig. 2. 14 - Comparison of LiDAR data (left) and downsampled 5m data (right), with and without overimposed building; section 2.

In contrast resampling of data to 5 meters cell size (right picture), even if seems to correct represent bare earth (dark yellow line) without ponds recognition (dashed dark blue line), produces some mistake when building layer is added. It is possible to notice how, again, presence of building is badly interpreted as ground by the software (green line) thus, erroneously filled up during filling operation (dashed orange line). Furthermore, loss of shape of buildings that make them similar to “little mountains”, magnifies distance between building in the upper part, increasing spaces where water can accumulate, leading to bad results after hydraulic simulations. This case has been analysed because AOFD software requires use of 5m data for elaborations. Therefore downsampling of LiDAR data and subsequent use with AOFD algorithm could lead to a greater number of recognised depressions and bigger accumulated volume estimation.

2.6.4 Section 3

In the last example a DTM with 20 meters cell size has been analysed before and after addition of buildings layout and, afterwards performing an upsample of data to 1 m cell resolution (Fig. 2. 15).

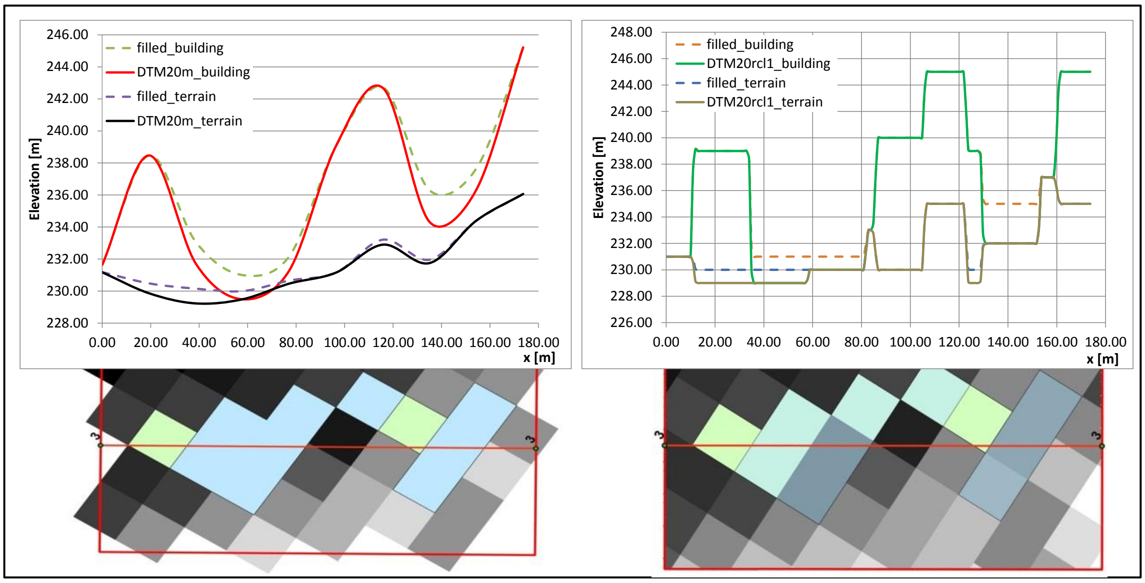


Fig. 2. 15 - Comparison of DEM 20m data (left) and upsampled 1m data (right), with and without overimposed building; section 3.

When the original 20 m data is used (left image), it is possible to notice that identified ponds in the bare ground (black line) are filled up by filling algorithm (dashed violet line), that also wrongly emphasises peaks. Furthermore, over imposition of buildings fills superficial sinks (red line) but, at the same time, it creates a spurious (not real) depressions, because of the misinterpretation of the space between buildings. These voids are filled up by the next filling operation but, anyway, residuals ponds are larger than the original real ones and they will lead to an higher accumulated water volume estimation in case of hydraulic simulations.

The situation has not too much improvements when data is upsampled to 1 meter cell resolution (right image). Without buildings (brown line) only real depressions are filled up (dashed blue line), resulting in a data enhancement. Conversely, the added building layer (green line) partially fills up real depressions but again it leads to a misinterpretation of the space between buildings as ponds, subsequently filled up by the filling algorithm (dashed orange line). Even if depressions are filled up, space between buildings still remains larger than the beginning, leading to a worsening estimation of accumulated water volumes in case of hydraulic simulations.

2.7 Results

Major advances in survey technologies give today to researchers and professional engineers new tools to improve their researches and working activities. An example of this is given by topographic maps that, even always been used in the past, now can be obtained from high quality data (such as aerial surveys, optical satellite imagery, LiDAR), at relative cheap price. Often though, use of this data can hidden some pitfalls that it is worth to know and avoid. For hydrological and hydraulic purposes, in fact, high quality DEMs can be used to retrieve spatially derived hydrologic parameters, correct cross-section data, floodplain extent and many other features. The entire analysis process of this data is normally performed using a GIS (Geographic Information System) that consists in a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes (Burrough & McDonnel,1988). Along with developing of GIS software, many universities and research centres start to develop standalone tools or GIS plugins based on the goal they were trying to achieve. Regarding DEM quality enhancement and error removal, two software are actually at the state of the art: Arc Hydro Tool and AOFD, both described above, showing their advantages and disadvantages.

These two software were used in order to investigate the latest algorithm available for delineation of ponds, namely potential flooded areas. A sensitivity analysis about DEM resolutions and presence of building were also carried out, considering six different DTMs obtained by various data source. Elaborations carried out bring to the conclusion that reliability of major system strongly depends by quality of data used with particular attention to DEM’s resolution, because overland flow paths are influenced by urban characteristics. The most interesting result does not regard the different number of surface depressions identified (as expected) depending on the DTM used, instead the storage capacity associated with these, since it is precisely this characteristic that determine the main effects on the subsequent hydraulic modeling. An underestimation of this variable, in fact, lead to an overestimation of the volume of water actually outflowing on the surface.

A first main achieved result was that presence of building generally improves delineation of ponds, diminishing total accumulated water volume, even if number of depressions tend to increase with higher resolutions (lower cell size). In fact, overimposed buildings fill larger ponds while create new little ones around them; this physically explains the trend. Besides, presence of buildings avoid physical inaccuracies as, for instance, overland flow paths and ponds falling within them.

The second main achieved result shows that both downsampling (in case of high-resolution data such as LiDAR) and upsampling (in case of low-resolution data) of original data unarguably led to an increment of errors within DEM. When this happens, the next filling operation (normally executed to reduce errors in DEM) bring to an emphasizing of these errors, without solve it.

When high-resolution data is downsampled (cell size increment), space between buildings are increased and, consequently, new spurious ponds are created as result of an erroneous misinterpretation of these voids. Similarly, when low-resolution data is upsampled (cell size decrement), peaks and valley of terrain are emphasized, so that not even presence of buildings can later help to minimise or remove them.

This means that DEM's filling operation is only partially influenced by cell size, instead primarily depends on the accuracy of the original dataset used.

Concluding, based on the performed analysis, the data source used for the generation of the overland flow network were the LiDAR data with overlapped buildings. This choice was justified both from entropy analysis, demonstrating that there is no loss in accuracy of the data and also by the ponds analysis that argues how the over imposition of buildings helps to diminish the storage volume of depressions, notwithstanding their number is higher compared with other low-resolution DEMs.

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Chapter 3: Blue-Green Corridors

3.1 Introduction

Environmental sustainability theme has become ever more pressing and crucial in recent years. Designing for resilience to the impacts of climate change, and in particular ensuring secure water supplies and the protection of water environments, is an emerging challenge as growing urban communities seek to minimise their impact on already stressed water resources (Wong et al., 2012).

Sustainability represents a progression from previous environmental protection endeavours that incorporates the consolidated "urban drainage" concept, expanding it. Urban drainage comprises gathering and conveyance of water produced in urban areas, towards a final outlet (Fanizzi and Misceo, 2010). It is more than 20 years that commonly the acronym Integrated Urban Water Management (IUWM) is used, meant as the whole knowledge relating the collection, distribution, and treatment of water in urban environments. This concepts has been expressed also within the Italian Legislative Decree No 152/2006 – part III – section III where has been defined as *"the complex of major infrastructures needed to supply, collect, convey, store and distribute water for civil and sewerage use, and wastewater treatment"*.

Across time, many laws have been issued about this topic in Italy. The first one was the Law 10 May 1976 No 319 (known as Legge Merli), which was designed to manage all kinds of wastewater discharge, public or private, direct or indirect, of all kinds of waters, overland or underground waters, sewage water and within sea. After this, it follow the Recovery plan for Water of Calabria Region (Piano di Risanamento delle Acque della Regione Calabria) of 1982, the European Community Directive 271/91, the law of Lombardia Region 1986/1991, the regional law 10/97 of Calabria Region, the Legislative Decree 258/2000 and the last one, Legislative Decree 152/2006.

Despite the existing huge legislation, water treatment and its mitigation is a problem that still affects not only Italian territory, but also all countries in the world. As a matter of fact stormwater run-off in urban areas, heavily contaminated and with high volumes, can determine a significant negative impact on the quality of the receiving water bodies, conversely on what was incorrectly thought in the past, when the design criteria of conventional sewage systems were based, instead, on the assumption that meteoric waters had a negligible level of contamination (Bornatici et al., 2004). Consequently one of the main purposes of water management in urban drainage is the reduction of suspended solids concentration in stormwater before that their discharge into receiving waters (Piro et al. 2009). Numerous studies have been demonstrate that stormwater flows, conveyed to combined sewer overflows designed according conventional criteria, are too high to effectively reduce pollutant loads discharged into water bodies (Papiri, 2000; Bornatici et al., 2004) and, in most cases, the existing wastewater treatment plants are not adequate to treat the material remaining inside them, because they result undersized. The crucial issue therefore is not only the poor water quality but also the increasing amount of surface water flow on the street (quantity). The main cause can be sought in a widespread urbanization growth and a consequent excessive imperviousness, without an adequate development of flood attenuation control systems. Stormwater infrastructures in urban environments has traditionally been built to convey urban stormwater rapidly to receiving waters (e.g. waterways, bays and estuaries, groundwater, sea and oceans), without properly take into account qualitative aspects that, instead, have become most important and cannot be longer neglected (Ciaponi et al., 2006). It has been widely demonstrated in various researches (Ciaponi et al., 2006; Fanizzi L. & Misceo S., 2010) that urban rainwater are heavily contaminated, containing significant concentration of Total Suspended Solids (TSS), heavy metals (iron, arsenic, copper, zinc, lead) and dissolved nutrients (ammonia, nitrogen, phosphorous). A measure of the amount of organic and inorganic compounds in water is obtained through measurement of Chemical Oxygen Demand (COD) and also by Biochemical Oxygen Demand (BOD_5), that represents just an index of biologically active organic matter. Urban stormwater treatment, involving different competences such as hydraulic engineering, sanitary engineering, hydrology and hydraulic construction, it is therefore one of the aspects faced by Best Management Practices (BMPs) utilization, together with many other provided advantages with quantity.

In contrast to conventional stormwater management systems, water-sensitive urban design (WSUD) technologies manage rainfall where it falls, through enhancement of infiltration capacity of impervious areas and rerouting runoff across pervious areas. WSUD aims to better incorporate several urban water sources, including stormwater, into the local hydrological cycle so as to reduce demand on potable water, minimize pollutant loading to surface waters, and restore or maintain predevelopment hydrological processes. Urban stormwater treatment and harvesting represents a significant opportunity to provide a major new water source for use by cities, while simultaneously helping to protect valuable waterways from excessive pollution and ecosystem degradation. The opportunities to realise this potential varies from cities to cities and are dependent on the seasonal variability of rainfall and corresponding demands for alternative water supply, and the availability of cost-effective storages (Wong et al., 2012).

Fig. 3. 1 - Water Sensitive City is a place with an integrated urban water system with appropriate uses for rainwater, groundwater, surface water, wastewater, stormwater and potable water. It is a place where ecosystems, communities, organisations and infrastructure are resilient to future change (Allan et al., 2009).

3.2 SUDS, WSUD, BMP, LID practices

In order to minimize impacts of urban nonpoint source pollution and associated costs of control (storage and treatment) associated with wet-weather flows (WWFs), stormwater runoff volumes and pollutant loads must be reduced. A number of control strategies and so-called “Best Management Practices” (BMPs) are being used to mitigate runoff volumes and associated nonpoint source (diffuse) pollution due to WWFs and include ponds, bioretention facilities, infiltration trenches, grass swales, filter strips, dry wells, and cisterns. Another control option is popularly termed “Low Impact Development” (LID) – or hydrologic source control – and strives to retain a site’s pre-development hydrologic regime, reducing WWF and the associated nonpoint source pollution and treatment needs (USEPA, 2006).

In-situ runoff treatment devices mimic natural water cycle, favouring retention of surface runoff, pollutants removal and underground infiltration. However, it is worthy to bear in mind that this practices alter natural overland flow paths, therefore it is necessary to develop environmentally sustainable solutions.

Despite the initial implementation stage, many cities recognize undoubted advantages of these practices, including them in future development projects. Certainly urban development of cities has a profound influence on local hydrological cycle, both in terms of quality and quantity. In fact, hydrological regime of a site change both during the initial levelling stage and the subsequent developing stage. Trees, grasslands and plants intercepting and absorbing rain for a long time are removed and natural depression where water were temporary stored are filled up, in order to achieve the same slope. Once development has ended, situation worsen. Streets, roofs, parking lots, driveways and many other impervious surfaces block water underground infiltration. Therefore the most rainfall are immediately converted to surface runoff, incrementing the runoff coefficient. Moreover, impervious surfaces build up pollutants deposited from atmosphere, leaching from vehicles or moved by wind from adjacent areas. During rainfall events, these pollutants (such as suspended solids, hydrocarbons, pesticides) are washed off from surfaces and rapidly moved towards receiving water bodies. Even redevelopment/requalification of urban environments can have the same negative effect on water quantity and quality, if not adequately monitored (City of Griffin – Stormwater Design Manual, 2007).

Therefore, the integration of site design and planning techniques that preserve natural systems and hydrologic functions on a site, can be achieved through the use of Structural as well as Non-Structural BMPs (Pennsylvania Stormwater BMP Manual, 2006). These represent a diverse range of source control procedures, which integrate stormwater quality and quantity control as well as enabling social and amenity perspectives to be incorporated into stormwater management approaches (Scholes et al., 2008).

Below it is provided a description of the most common BMPs, structural and non-structural, for use in both existing urban contexts and in those of new construction.

3.3 Non-structural practices

Non-structural BMPs are practices able to reduce rainfall water pollution, without development of any new treatment facility. These methods aim only to reduce impact on rain water, by enhancing its quality through the reduction of potential pollutant sources or limiting runoff surface washout (Linee guida per la predisposizione dei Piani di Adeguamento ex L. 192/2004). Non-structural BMPs implementation is not based on regulated standards, laws or mandatory prescriptions, but is mostly related to a combination of that practices that bring a variety of environmental and financial benefits. The use of these technologies encourages treatment, infiltration, evapotranspiration of rainfalls down in the close proximity, thus helping to keep a much better and natural landscape functionality.

Key concept of LID is preventing stormwater runoff by integrating site design and planning techniques that preserve natural systems and hydrologic functions, protect open spaces, as well as conserve wetlands and stream corridors on a site (SEMCOG, 2008).

BMPs realization involves many stakeholders:

- Land's owners;
- Local authority responsible for runoff water quality management;
- National and Regional basin's authorities;
- Population.

Even though they are not structural practices, they allowed to reach, in such cases, also important pollutant removal rates. The most representative cases are related to pollution source control, such as the case of lead banning from fuels, which in some countries has led to a reduction of 70-75% of the pollutant loads released into the environment through rainwater. Non-structural BMPs are usually a remarkable tool for rainwater quality control, because aim to reduce impacts on environment, even if often are not sufficient to reach required water quality standard (Hvitved-Jacobsen et al., 2010).

Potential benefits from using non-structural BMPs for city-wide urban stormwater quality management include (Taylor A. & Wong T., 2002):

- **Cost:** Some non-structural BMPs are inexpensive for stormwater management agencies to run, particularly when compared with structural alternatives. For example, where major educational and enforcement campaigns aimed at erosion and sediment control have been conducted in Australia, the revenue gained from enforcement has often resourced the campaign's total operational expenses;
- **Coverage:** Some non-structural BMPs cover broad areas compared with structural alternatives (e.g. city-wide stormwater awareness campaigns or town planning controls);

- Can target **specific pollutants** of concern: For example, in big residential areas, nutrients from lawns and gardens on sandy soils threaten the quality of stormwater and shallow groundwater. Such pollution is best managed through non-structural means (e.g. slow-release fertiliser, improved fertilisation regimes and/or soil amendment);
- The high **potential effectiveness** of some measures: For example, the use of mandatory town planning controls to promote the widespread adoption of WSUD in new developments;
- **Community participation:** Interactive programs such as the successful Master Gardener training programs in the USA can encourage the community to accept responsibility for urban stormwater pollution and participate in a solution;
- **Flexibility:** Unlike structural BMPs, most non-structural BMPs can be quickly modified to take advantage of new opportunities or to respond to new priorities (e.g. targeting problem areas that have been identified through annual compliance auditing);
- **Secondary benefits:** A strong argument for using some non-structural BMPs in a balanced city-wide stormwater quality management program is their secondary benefits, such as helping build a mandate for increased political support, funding and bolder initiatives.

Among non-structural BMPs can be included (Linee guida per la predisposizione dei Piani di Adeguamento ex L. 192/2004):

- **Site planning:** designers must try to keep hydrological characteristic of the area as much intact as they can, maximizing storage volumes and infiltration into soil, keeping original terrain slopes and features;
- **Irrigation control:** excessive amounts of water represent one of the main causes of diffuse pollution not directly related to rainfall in urban areas;
- **Selection of building materials**: alternative materials must be selected, able to ensure the functional requirements, reducing the potential release of pollutants (application of these principles during development of new buildings complex in Stockholm has led to pollutants load reduction within the sewage system – Wickman et al., 2009);

- **Population engagement and information:** effectiveness of interventions is greater if it is accompanied by participation, support and involvement of various groups working towards the same goal;
- **Manholes reporting:** reporting has become a popular method to rise population risk awareness about the consequences that pollutants discharge into the drainage network may have on the environment;
- **Street sweeping:** the cleanup frequency, variable with location and land use, does not occur, however, more than once a week and the street sweepers play an important role in waste and debris removal, even though are less effective against fine dust (Lau et al., 2005);
- **Cleaning of drainage network:** regular cleaning of the sewer system reduce the amount of pollutants and debris both in the network and in the receiving water body.

Thus, in most cases it is easier and less costly to prevent the pollutants from entering the drainage system than trying to control pollutants with structural BMPs (City of Griffin - Design Manual, 2007).

Below it is provided a synthetic description of the most common non-structural BMPs.

3.3.1 Cluster Development

Cluster development or open space development concentrates the whole development in small lots or portions of a much bigger area. This clustering technique allows designers to avoid constrained or sensitive areas, such as steep slopes or aquatic zones including buffer strips, wetlands and floodplains, without limiting urban development.

Clustering reduce amount of infrastructures required as well as costs for their realization. This method well suit development of residential areas, especially for those municipality with great large-lot residential zones available. Clustering can reduce total impervious area and total disturbed areas at development sites, thereby reducing stormwater peak rates of runoff, reducing total volume of runoff, and reducing nonpoint source pollutant loads (SEMCOG, 2008).

Fig. 3. 2 – Aerial view of cluster development in Ann Arbor, MI. Source: Atwell Hicks.

3.3.2 Minimize Soil Compaction

Minimization of soil compaction is a practice consisting in protection and damage reduction of soil quality caused by urban development process. This practice tries to reduce the total soil disturbance, therefore soil flattening or movement activities. The final purpose is to cut down costs and sizes of related engineered stormwater management systems as well as installation costs of new plants, vegetation and landscape maintenance. Fencing off an area can help minimize unnecessary soil compaction (SEMCOG, 2008).

Fig. 3. 3 - Minimizing disturbance of soil to protect wooded area Source: City of Andover, Minnesota.

3.3.3 Minimize Total Disturbed Area

A key component of LID systems regards the reduction of impacts during development activities such as soil flattening, vegetation removal or land cover alteration. This aim can be achieved through developing a plan to contain disturbed areas. Minimization of total environment disturbance requires multiple BMPs consideration, such as cluster development and sensitive areas identification and protection. These BMPs act as a defence for natural resources available in the area, reducing the long-term maintenance operations required (SEMCOG, 2008).

Fig. 3. 4 - Minimizing disturbance to existing trees during residential construction. Source: Insite Design Studio, Inc.

3.3.4 Protect Natural Flow Pathways

One of the main LID purposes is the identification, protection and use of natural pathways, such as vegetated filter strips, ponds and watercourses to preserve their quality. Designers can use natural overland flow paths to remove or reduce use of manmade drainage channels. As the opposite of the artificial systems, in fact, naturally vegetated drainage features tend to slow runoff and thereby reduce peak discharges, improve water quality through filtration, and allow some infiltration and evapotranspiration to occur. Protection of natural flow pathways can help to improve natural habitat, aesthetic and value of properties, reducing creation of surface runoff. If protected and used properly, natural drainage features generally require very little maintenance and can function effectively for many years (SEMCOG, 2008).

Fig. 3. 5 - Natural flow pathway in residential development. Source: Brandywine Conservancy, Environmental Management Center, 1998.

3.3.5 Protect Riparian Buffer Areas

Riparian buffer areas constitute important green infrastructures elements of local communities. These areas are crucial as regard the biological, chemical and physical integrity of our waterways. Riparian buffer areas preserve water quality from overwarming, stabilizing banks, mitigating velocities and providing pollutants and sediments removal by filtering overland sheet runoff before it enters the water. The Environmental Protection Agency defines buffer areas as “areas of planted or preserved vegetation between developed land and surface water, which are effective at reducing sediment and nutrient loads”. This practice provides utility theoretically for any kind of soil and urbanization level. This LID well suits huge areas, therefore, although riparian buffer programs should be advocated in the densest of settings, their application is likely to be limited in high density contexts. Creative design can maximize the potential of riparian buffers. Clustering and density bonuses are design methods available to increase the amount and connectedness of open space areas such as riparian buffers (SEMCOG, 2008).

Fig. 3. 6 - Maintaining a riparian buffer. Source: JFNew.

3.3.6 Protect Sensitive Areas

Protection of sensitive areas and special value features is the process concerning avoid of certain particular areas during the development process. This allows utilization of these areas for many purposes, including reduction of surface runoff. Protection of sensitive areas can be implemented at both local and community level. To cope with priority aims, natural resources should be evaluated accordingly to their functional value. These areas should be kept intact as much as possible, avoiding placement of any BMPs therein. Conservation of sensitive areas represents a challenge for natural planners to inventory and then, to the greatest extent possible, avoid resource sensitive areas at a site, including riparian buffers, wetlands, hydric soils, floodplains, steep slopes, woodlands, valuable habitat zones, and other sensitive resource areas.

Fig. 3. 7 - Protection of existing native woodlands and wetlands, Kalamazoo, MI. Source: Fishbeck, Thompson, Carr & Huber, Inc.

3.3.7 Reduce Impervious Surfaces

Reduction of impervious surfaces include the minimization of areas such as streets, parking lot and driveways. By decreasing the amount of impervious surfaces, surface runoff tends to decrease while infiltration and evapotranspiration increase. Reducing street imperviousness performs valuable stormwater functions in contrast to conventional development in the following ways:

- Increases infiltration
- Decreases runoff volumes
- Increases stormwater time of concentration
- Improves water quality by decreasing nonpoint source pollutant loading, and
- Decreases the concentration and energy of stormwater.

Imperviousness greatly influences stormwater runoff volume and quality by increasing the rapid transport of stormwater and collecting pollutants from atmospheric deposition, automobile leaks, and additional sources (SEMCOG, 2008).

Fig. 3. 8 - Use of permeable pavers for roadway shoulders.

3.3.8 Stormwater Disconnection

Reduction of runoff volumes is obtained by disconnect downpipes from roof, impervious street and driveways, deviating surface runoff towards BMPs with vegetated areas that allow in-situ infiltration to occur. Roofs, streets and driveways are mainly responsible for the high percentage of impervious area in post-urbanized environments. These surfaces affect rainwater quality and surface runoff volumes. Disconnection of downpipes from roof and conveyance of waters to traditional stormwater collection systems, allows runoff to be treated and managed onsite. Runoff can be conveyed towards vegetated areas for the accumulation in situ, to allow treatment and control of rain volumes. Besides direct conveyance of waters to vegetated areas, runoff can also be discharged into non-vegetated BMPs such as dry wells, rain barrels, and cisterns for stormwater retention and volume reduction (SEMCOG, 2008).

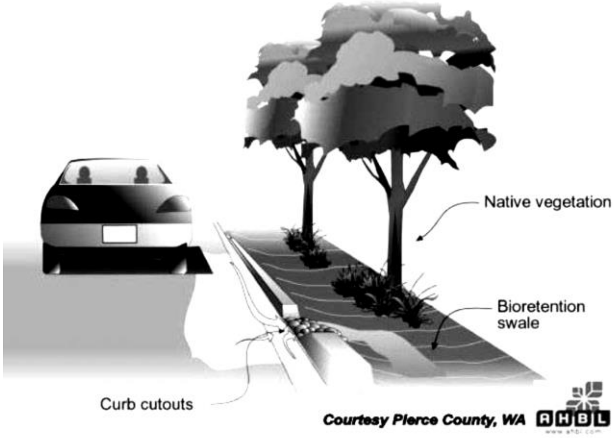


Fig. 3. 9 - Curb cut-outs allow stormwater runoff from a parking lot to flow into a bioretention swale. Source – Pierce County, WA and RHBL.

3.4 Structural practices

An high density of residences, industries and urban infrastructures, as described before, has led to an increment of problem related to urban drainage that mainly produced two kind of alterations:

- replacement of previously pervious areas with impervious surfaces and drainage channel modifications that invariably result in changes to the characteristics of the surface runoff hydrograph and, consequently, to the hydrologic behaviour of catchments; land use modifications associated with urbanisation has led to common changes such as increased runoff peak, runoff volume and reduced time to peak (Goonetilleke et al., 2005).
- introduction of pollutants of physical, chemical and biological origin in stormwater runoff.

By issuing the European Directive 2000/60/EC that established a community framework for the implementation of water policy, European Union wanted to help in management of surface, continental, coastal and underground waters, in order to prevent and reduce their contamination, promote their sustainable use, improve situation of aquatic ecosystems and mitigate negative effects of inundations and droughts.

The main objective of structural BMPs is the reduction of negative effects of rainwaters onto a site, *after* these already happened. Thus, it differs from aim of non-structural BMPs, that directly try avoiding surface runoff creation.

Structural rainwater management devices are meant to allow qualitative treatment for surface runoff. Even though each single BMP already has its own pollutant removal ability, its efficiency vary between different practices based on the desired pollutant to treat. Removal efficiency of pollutants depends on a great number of factors in each device, including physical, chemical and biological processes occurring inside it and also by unit size. Moreover, pollutant removal efficiencies for the same structural control type and facility design can vary widely depending on the tributary land use and area, incoming pollutant concentration, rainfall pattern, time of year, maintenance frequency and numerous other factors (City of Griffin - Design Manual, 2007).

Possible innovative structural solutions may include gross pollutant traps, green roofs, permeable paving, filter strips, detention ponds, constructed wetlands, infiltration basins, infiltration trenches and many others. These measures are currently identified in Anglo-Saxon literature with the term SUDS (Sustainable Urban Drainage System), in American literature with BMPs (Best Management Practices) and LID (Low Impact Development) while in Australian bibliography as WSUD (Water Sensitive Urban Design). 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 (USEPA, 2000a). The utility score is assessed by SUDS degree of performance, determined by its physical and biochemical functions, primary removal (adsorption, sedimentation, filtration, microbial degradation, solubility, volatilization, photolysis and plant uptake). The highest TSS removal efficiency is given, for instance, to infiltration and phytoremediation basins, whilst filter strips and tanks have much lower potentialities (Ellis et al., 2011).

Therefore, new development approaches have been studied and identified, aiming to abandon the traditional *“end-of-pipe”* approach, introducing more *"natural"* 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. Reduction of vegetated spaces reduces, in first instance, natural plant interception and evapotranspiration. Increasing in imperviousness causes an infiltration reduction. Consequently, more overland flow volumes are generated, accelerating the catchment response time and increasing inundation risks (Van Liew et al., 2005).

SUDS objectives can be summarised as follows (Fresno et al., 2005):

- protect natural hydrological cycle within urban areas;
- integrate stormwater treatment;
- protect water quality of receiving water bodies;
- reduce overland flow volumes through use of retention devices in order to decrease amount of impervious areas;
- minimize costs: reduction due to smaller volumes spilled into water bodies and conservation of purification filter characteristic as it has been designed.

From this perspective, use of 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. For instance, it is possible to cite SUDS implementation in city of Nijmegen (Holland), where the main principle was to disconnect impervious areas from sewage network, using particular SUDS such as green roofs, porous pavements and water harvesting tanks (Perales Momparler S., Andrés-Doménech I., 2008). Summarising, philosophy of SUDS focuses on mimic natural hydrological cycle. They aim to minimise the impact of urban development on the surrounding environment, emphasizing the interaction between landscaping, environmental and social values (Woods-Ballard B. et al., 2007).

Indeed, each BMP should not be thought as a “standalone” practice, but as a part of a much bigger stormwater management system, aiming to reduce, generally, runoff volumes, peaks of flow and pollutant concentration. This vision has led to the improved concept known as “Blue-Green Corridor” (BGC) that integrate the role of sustainable urban drainage systems (SUDS) with urban planning, river restoration and water management, in order to develop a network of blue-green elements through the catchment, linking together the existing green spaces with the main river and their tributaries.

It is worthwhile to underline the extreme value that manholes continue to keep during each storm event, ensuring to convey water from streets, car parks, sidewalks and other impervious open spaces to the sewage system. A deficit of manholes or their mismanagement, in fact, can lead to an uncontrolled increment of urban runoff causing the next raising of hydraulic parameters such as water depth and velocity, that have a great influence on urban floods and their associated risk (Gómez et al., 2005).

Core principles to take into account during design of these practices regard:

- stormwater harvesting and reuse;
- water spill out within surface water bodies;
- runoff reduction and stormwater treatment
- stormwater infiltration.

3.4.1 Vegetated swales

This practice regards open channels or depressions with high dense vegetation, used to decrease and treat surface runoff (Bregulla et al., 2010). Then, grassed swales (Fig. 3. 10) are long open drainage channel, integrated within the surrounded landscape, affected by grass growth or other kind of dense vegetation, resistant to drought during time. Widely used in residential and commercial areas, along kerbsides alternatively to the classic drainage systems, they allow pollutant abatement through infiltration processes. In addition, they decrease overland flow rate, reducing peak flows and increasing time of concentration. Depurative efficiency is good, even though it varies significantly accordingly to the design criteria locally adopted (Linee guida per la predisposizione dei Piani di Adeguamento ex L. 192/2004).

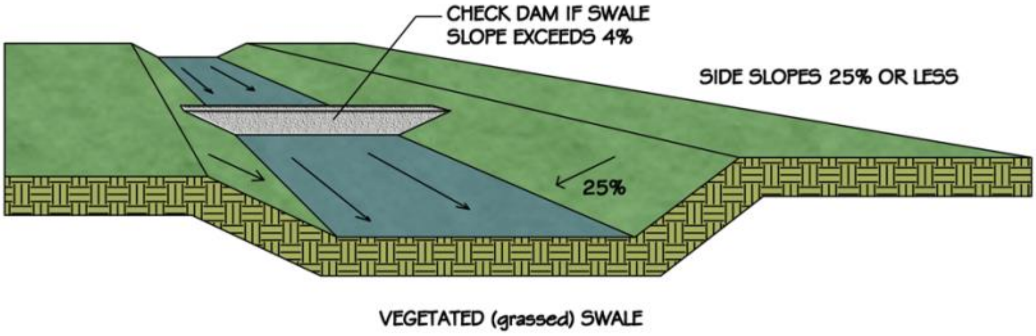


Fig. 3. 10 - Grassed swale (http://www.abbey-associates.com/).

Designed to move water towards bioretention basins, however they can be used in different climatic region, independently with gentle or steep slopes. Usually, they have a triangular or trapezoidal shape (Fig. 3. 11), with lateral steep designed to convey runoff slowly. Berms or check dams may be incorporated into grass swales to reduce velocities and encourage settling and infiltration (USDCM, 2010).

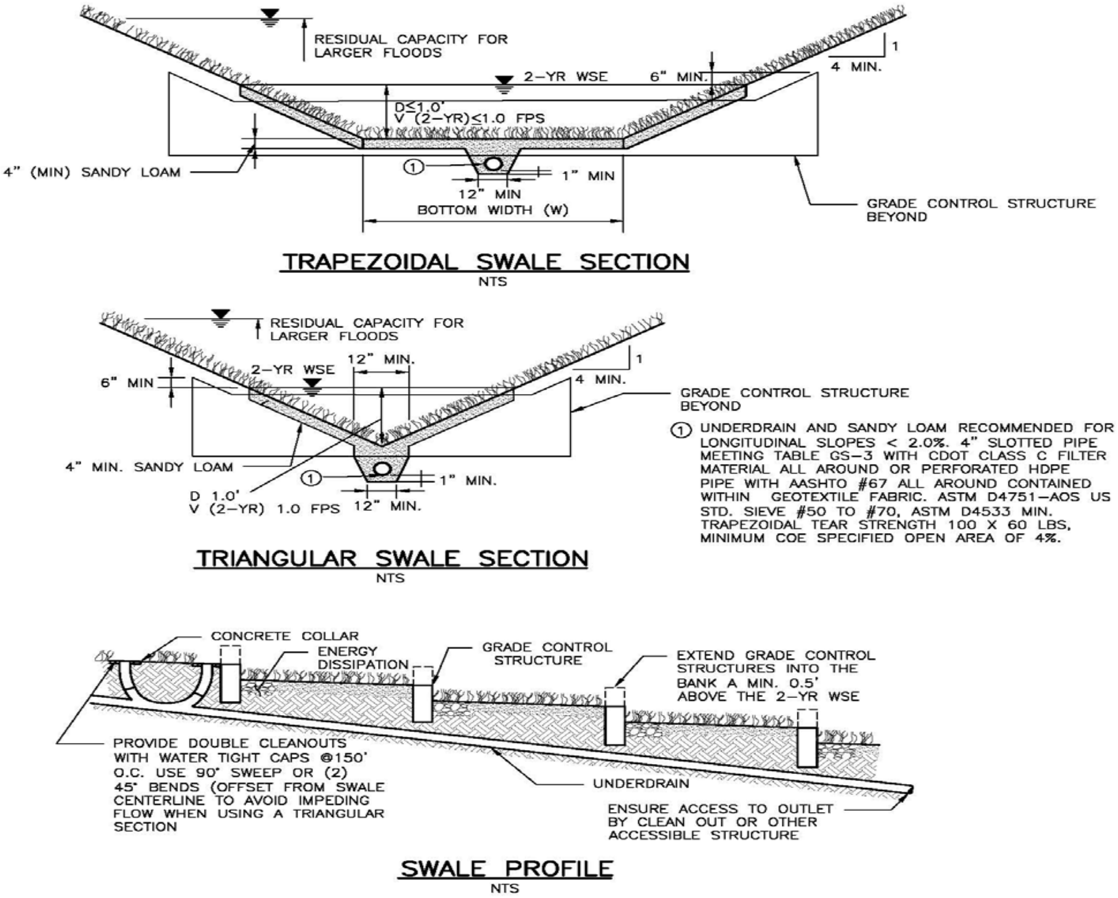


Fig. 3. 11 - Profiles and sections of a swale (USDCM, 2010).

When possible, maximize length of swale is preferred however, if some local constrains occur, slope reduction or cross-sectional area enlargement can be applied. A correct drainage is reached with a 2% of minimum slope, otherwise an underdrain system should be provided. Maximum runoff rate should not exceed 0.3 m/s. In addition, grassed swales should be provided with an irrigation system (temporary or permanent) to make available appropriate water for the selected vegetation. A poor irrigation may reduce soil permeability, affecting infiltration and surface flow (USDCM, 2010). Regarding flow reduction, overland flow volume attenuation and pollutant removal, grassed swale efficiency depends on its dimensions together with other factors such as catchment land use, soil permeability, channel cross-section slope and vegetation density.

To achieve a good result, during works execution, particular attention must be paid to (Linee guida per la predisposizione dei Piani di Adeguamento ex L. 192/2004):

- soil compaction;
- carry out the sowing after the soil has been stabilized;

- provide an irrigation system suitable for the type of vegetation selected;
- remove "weeds" manually before inserting of vegetation;
- protect vegetated swales from other surrounding buildings.

3.4.2 Vegetated filter strips

Vegetated filter strips are flat ground areas designed to encourage laminar water flow (Fig. 3. 12). Using vegetation roots to remove pollutants from stormwater, are suitable for low density developed areas and low rainwater intensity. Originally designed to use in rural areas, are always more applied in urban catchment, where can yield good depurative efficiency if properly designed and maintained.

Fig. 3. 12 - Vegetated filter strips (CASQA, 2003).

To increase their performances, vegetated filter strips are often used along riparian strips where they entrap and filter contaminants, favouring infiltration, slowing overland flow and enhancing stability of riversides. Thus, they can be used in series as pre-treatment facilities with other BMPs downstream (Linee guida per la predisposizione dei Piani di Adeguamento ex L. 192/2004).

Any vegetated area such as grassland or a small grove can act as vegetated filter strip. Many kind of plants can be used for this purpose, even though vegetation with lot of foliage and consistent root apparatus is preferred. In addition, vegetated filter strips allow disconnection of impervious surfaces from sewage systems, contributing to abate stormwater flows and prolong its transit time as well as pollutant removal originating by highways, roofs, car parks and residential areas. In order to avoid problems and keep a proper vegetated filter strips functioning, overland flow rate and water depths must be kept low.

3.4.3 Bioretention areas

The term ‘bioretention’ refers to the process used to describe a particular BMP that provides biological absorption and retention of pollutants in stormwater runoff. These BMPs, represented by depressed vegetated areas with eventual presence of floral plants, often refer to a porous landscape detention area (PDA) or ‘rain garden’, typically installed in a parking lot (Fig. 3. 13).

Fig. 3. 13 - Bioretention area or ‘rain garden’ installed in a car park (USDCM, 2010).

Horizontal surface of these practices are often flat thus, it is really difficult to find it in a steeply sloping terrain. Bioretention technique allows water accumulation, its infiltration and evaporation as well as pollutant removal such as suspended solids, heavy metals, nutrients and pathogens (NCDENR, 2007). Realization of this system within high permeable terrains allows overland runoff limitation and groundwater recharge.

The whole drainage process should last no more than 12 hours, and to achieve a good pollutant removal rate, it should realize a drain of 60 cm in maximum 48 hours (USEPA, 2000b). According to USDCM (2005), to allow a good growth of vegetation, at least 30 cm in depth are needed, but depending on vegetation type part of the depth may be used to hold water generated from events of longer duration and minor intensity (more frequent). In addition, being the filtering surface to block sediments, this must be

properly designed to ensure a total efficiency maintenance. Plants constitute integral part of these systems and their roots favour chemical and physical pollutant removal processes, enhancing soil texture and increasing infiltration capacity. Studies indicate that vegetated soils are capable of more effective degradation, removal, and mineralization of total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), pesticides, chlorinated solvents, and surfactants than are non-vegetated soils (USEPA, 2000b). When these BMPs are installed close to paved areas, protective measures must be present to avoid negative effects (such as water infiltrating inside rocks causing earth hummock and movements of terrain underneath structures).
Additional requirements are:

- use of an underdrain system in case of low permeable soils
- when potentially expansive soils or bedrock exist, BMPs adjacent to structures must include an underdrain designed to divert water away from them.

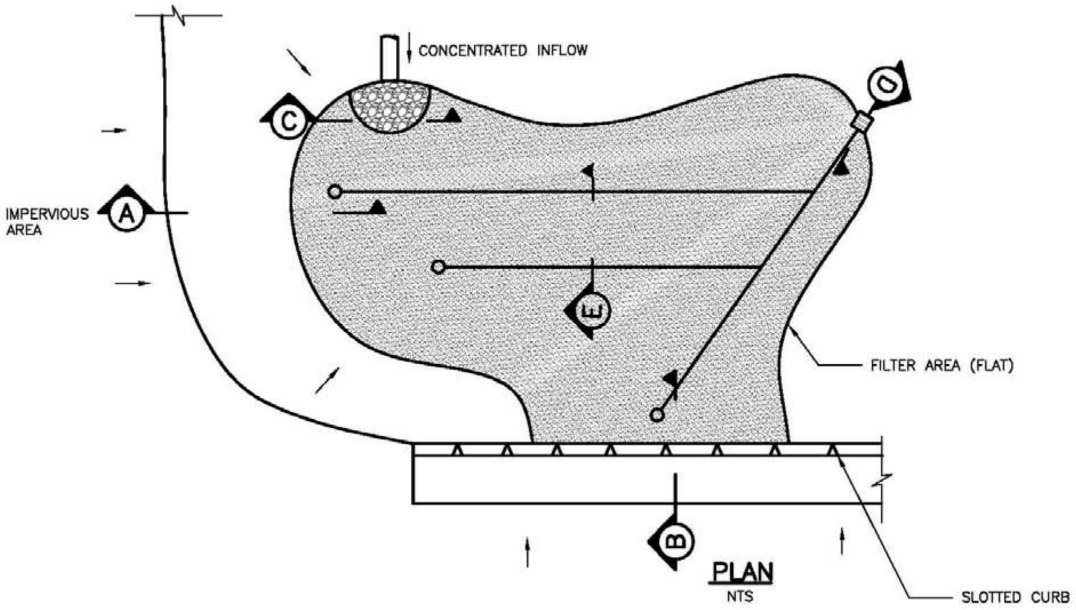


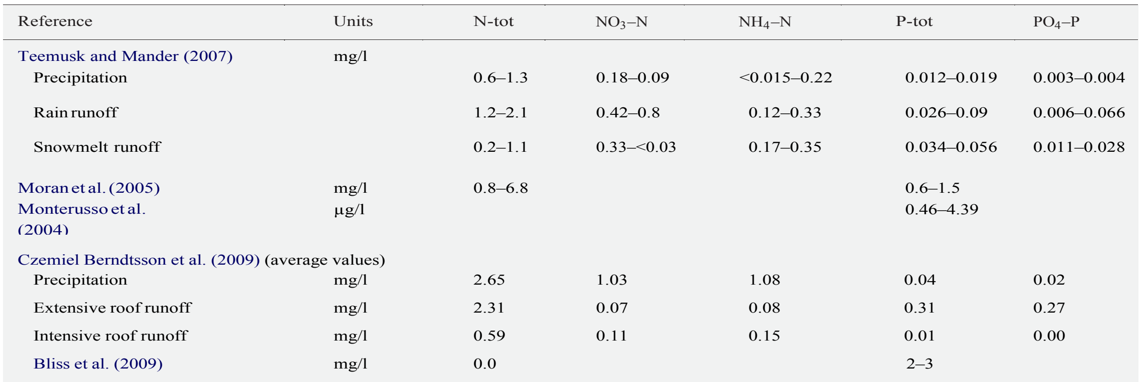
Fig. 3. 14 - Typical Rain Garden Plan and Sections (USDCM, 2010).

3.4.4 Green Roofs

Green roofs can be used as a cover for commercial, industrial and residential buildings in order to reduce stormwater runoff and limiting pollutants intakes (Tab. 3. 1; Tab. 3. 2). Conversely to the traditional impervious covers, green roofs absorb and remove (through sequential evapotranspiration processes) the initial precipitation fraction, acting as a decentralized stormwater management system and reducing flow peaks within drainage network (Linee guida per la predisposizione dei Piani di Adeguamento ex L. 192/2004).

	Extensive green roof	Semi-intensive green roof	Intensive green roof
Costs	Low	Middle	High
Irrigation	No	Periodically	Regularly
Maintenance	Low	Periodically	High
Plant	Moss, sedum, herbs and grasses	Grass, herbs, and shrubs	Lawn or perennials, shrubs and trees
System build-up height	0.06–0.2 m	0.12–0.250 m	0.15–0.4 m Underground garages >1 m
Use	Ecological protection layer	Designed green roof	Park-like garden
Weight	60–150 kg/m^2	120–200 kg/m^2	180–500 kg/m^2

Tab. 3. 1 - General criteria requirement for different types of green roofs (Bregulla et al., 2010).



Reference	Units	N-tot	NO_3–N	NH_4–N	P-tot	PO_4–P
Teemusk and Mander (2007)	mg/l					
Precipitation		0.6–1.3	0.18–0.09	<0.015–0.22	0.012–0.019	0.003–0.004
Rain runoff		1.2–2.1	0.42–0.8	0.12–0.33	0.026–0.09	0.006–0.066
Snowmelt runoff		0.2–1.1	0.33–<0.03	0.17–0.35	0.034–0.056	0.011–0.028
Moran et al. (2005)	mg/l	0.8–6.8			0.6–1.5	
Monterusso et al. (2004)	µg/l				0.46–4.39	
Czemiel Berndtsson et al. (2009) (average values)						
Precipitation	mg/l	2.65	1.03	1.08	0.04	0.02
Extensive roof runoff	mg/l	2.31	0.07	0.08	0.31	0.27
Intensive roof runoff	mg/l	0.59	0.11	0.15	0.01	0.00
Bliss et al. (2009)	mg/l	0.0			2–3	

Tab. 3. 2 - Nutrients concentration in runoff from green roofs (Czemiel Berndtsson J., 2010).

Green roofs, moreover, contribute to reduce loads of numerous micro-pollutants (such as lead, zinc, pyrene and chrysene), released by certain types of traditional roofs (Van Metre & Mahler, 2003). These practices provide different benefits such as lag and runoff reduction particularly during intense storms, supply of filtered water suitable for wildlife, reduction in the urban heat island effect through evaporative cooling, capturing of airborne pollutants and noise reduction (Graham et al., 2013).

The stormwater runoff management from rooftops involves the use of vegetation cover for both roofs and roof gardens as well as use of areas allowing storage of volumes in order to promote evapotranspiration. Green roofs are generally concentrated point sources typical of urban areas, and their management is able to provide significant benefits in high density urban areas where there is not enough space for other BMPs types. Green roofs design is affected by many factors such as aspect, ground clearance, wind exposure and shadows generated from surrounding buildings. This practice allows to control stormwater runoff, promote evapotranspiration and increasing time of concentration in urban areas that will react more slowly to rain loads.

Green roofs provide multiple environmental, social, economic, and aesthetic benefits that extend beyond stormwater management objectives. For existing buildings, the structural integrity of the building must be verified prior to consideration of retrofitting the building with a green roof. For both existing and new construction, it is essential that the design team be multi-disciplinary. This team may include a structural engineer, stormwater engineer, architect, landscape architect, and horticulturist. It is recommended that all members of the design team be involved early in the process to ensure the building and site conditions are appropriate for green roof installation (USDCM, 2010).

Green roofs are also referred to as eco-roofs or roof gardens. A green roof consists of a multilayer system that includes vegetation top layer, soil or a suitable substrate, drainage, protection, waterproofing, and insulation layers (Fig. 3. 15).

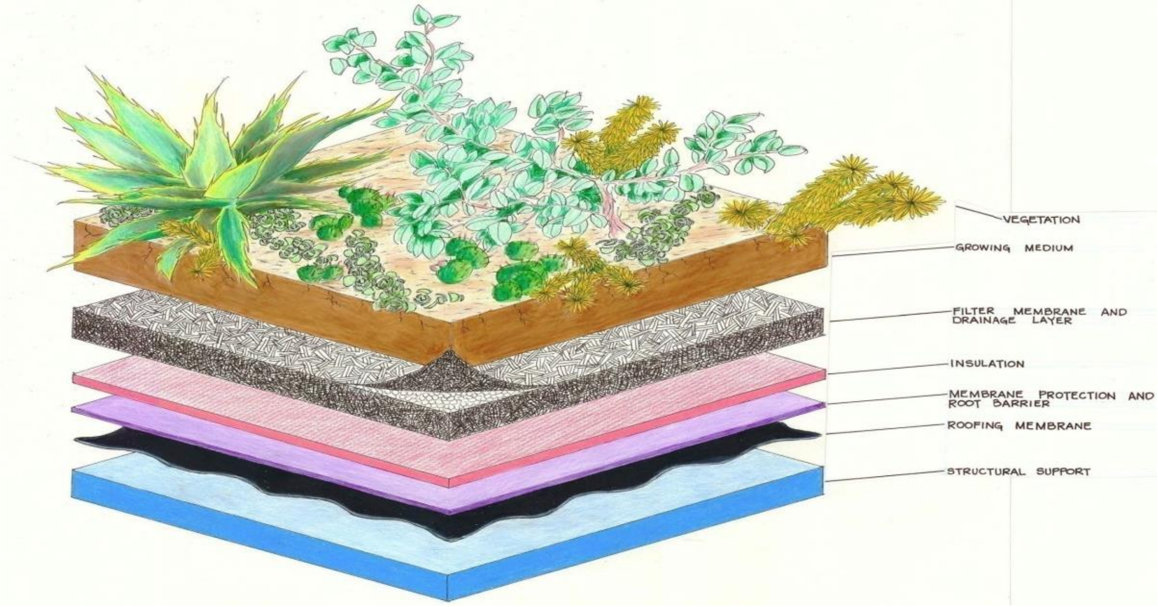


Fig. 3. 15 – Typical green roof cross section (USDCM, 2010).

There are two types of green roofs, extensive and intensive, although some buildings have a combination of both in the roofing system. cover the entire roof area with low growing, low maintenance plants. They typically comprise 25 to 125 mm thick soil layer supporting a variety of drought-tolerant, low and hardy plants. Intensive green roofs include landscaped gardens that have soil deep enough to support trees, plantains, and shrubs. Sometimes water features and rainwater storage or water harvesting systems are included. Intensive roofs impose heavy loading on the roofing structure and require on-going maintenance of the plants and water system (Bregulla et al., 2010).

Fig. 3. 16 - Green roofs implementation together with other LIDs (Green City Clean Waters, 2009).

3.4.5 Detention Basins

A detention basin is a facility designed to accumulate and detain rainwater for many hours after ending of rainfall event. It is recommended to remove a significant portion of total suspended solids (TSS) and often soluble pollutant removal is enhanced by providing a small wetland marsh or "micropool" at the outlet to promote biological uptake (USDCM, 2010).

Detention basins can be classified in two categories: dry and wet detention basins. Dry ponds are generally able to retain stormwater runoff for short time periods comprised between 24 and 48 hours. Conversely, a wet detention basin is a stormwater management facility that includes a permanent pool of water to remove pollutants, therefore having an additional capacity to face and mitigate inundations (Fig. 3. 17). To ensure the longest duration of these practices, some recommendations are:

- always provide a small wetland marsh or "micropool" at the outlet;
- maximum bed slope of 3%;
- provide adequate initial volume to cope with possible flood events.

It should be maintained a length-to-width ratio of 2:1. This avoid short-circuit creation and favors TSS removal process. Basin must have stable banks with a ratio of 4:1 and never steeper than 3:1. The inlet cross-section must be able to reduce speed and facilitate particles sedimentation. Outlet section must have a small wetland marsh (micropool) to avoid clogging as well as to avoid water stagnation that may attract annoying insects, such as mosquitoes (USDCM, 2010).

Bottom and banks of the basin must be covered with vegetation (peat) in order to allow erosion control and sediments interception. Obviously it should be also esthetically pleasurable, especially inside urban contexts where it represents a real architectural as well as naturalistic work.

Fig. 3. 17 - An example of wet detention basin in urban area (USDCM, 2010).

Based on the available space, a 'bigger' variant of these basins is constituted by dry extended detention basin. A dry extended detention basin temporarily stores incoming stormwater, trapping suspended pollutants, and reducing the peak discharge from the site (Fig. 3. 18). These practices are parts of those known as "regional control" practices because are able to convey the excessive runoff volume out of the development itself into public open space, providing a great potential to maximise both wildlife and amenity benefits (Graham et al., 2013).

Extended detention basins may be used at sites where significant increases in runoff are expected from site development. In addition, standard detention basins may be retrofitted or converted to extended detention by increasing the time over which the basin releases the stormwater quality design storm runoff volume, provided that erosion and flood control volumes and outflow rates are not adversely altered (NJDEP, 2004).

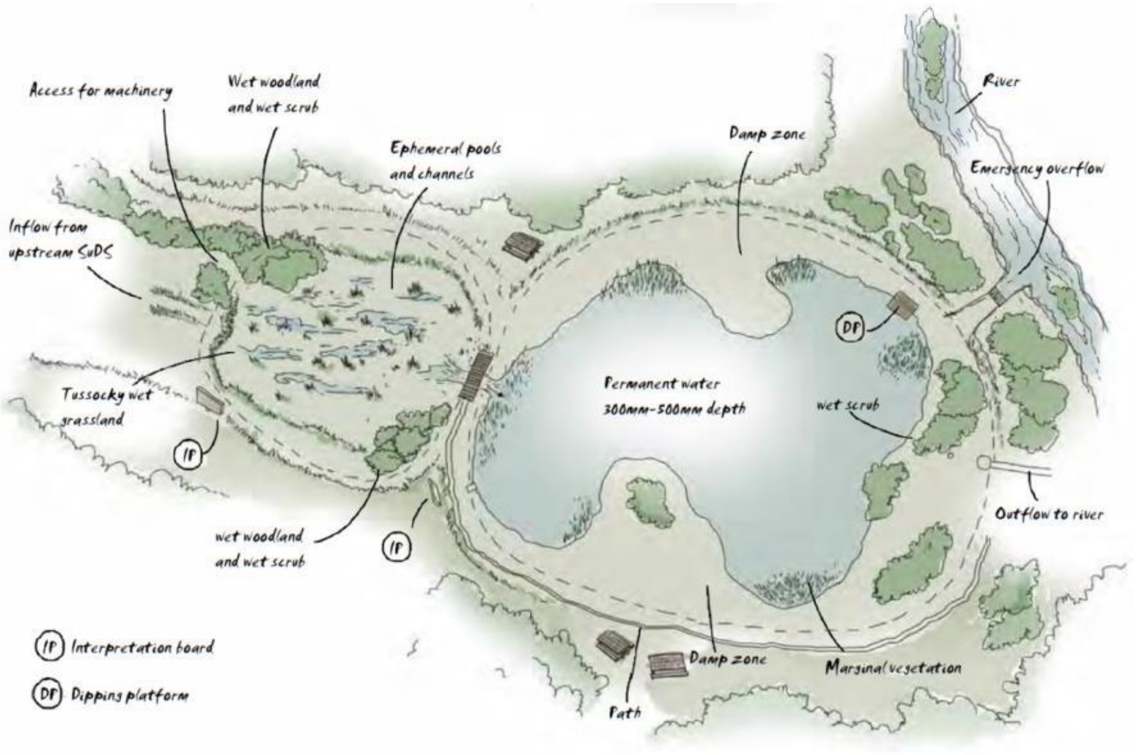


Fig. 3. 18 - Plan view of SUDS storage wetlands at end of management train with wildlife habitats and amenity features (Graham et al., 2013).

3.4.6 Infiltration systems

Infiltration systems are designed to catch and retain stormwater runoff, allowing its slowly infiltration into the ground over a period of time between few hours and few days, depending on the infiltration device installed. Within the LID practices, the term ‘infiltration system’ refers to the percolation process of rainwaters through the ground. These systems, including soakaways, infiltration basins and infiltration trenches (Fig. 3. 19), take runoff from a development and allow the surface wastewater to percolate into the ground, thereby recharging the groundwater, maintaining the water levels in local watercourses, and reducing the volume of water to be disposed of through sewers. Compared with others SUDS techniques, infiltration systems are more able to alter hydrological site conditions, helping to drain localized surface runoff into the soil. Thus, their installation is recommended adjacent to parking lot and other localized impervious areas.

Infiltration structures are constructed to temporarily store stormwater and let it percolate into the underlying soil. These structures are used for small drainage areas. They are feasible only where the soil has adequate permeability and the maximum water table (and/or bedrock) elevation is sufficiently low. They can be used to control the quantity as well as quality of stormwater runoff (Akan A.O., 2002).

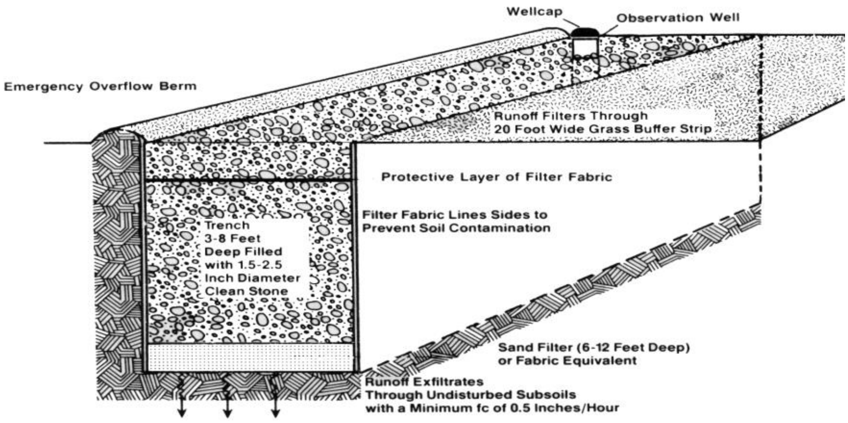


Fig. 3. 19 – Common infiltration trench representation (NCDENR, 2007).

The filling process starts when runoff reaches the trench. During the first stage a vertical infiltration through the bottom occurs, until saturated. Secondly, lateral infiltration through the walls of the trench takes place, neglecting in this case the hydraulic gradient in vertical direction. A stormwater pre-treatment is required prior water reaches the trench in order to obtain the highest TSS removal thus, these devices can be used to receive and release water from other SUDS techniques (i.e. pervious paving, swales, or basins). Therefore, infiltration trenches reduce surface runoff as well as pollutant loads such as fine sediments, heavy metals, nutrients, bacteria and it can be used in small spaces due to their lesser dimensions. Their applicability varies with number of factors such as soil type, slope, groundwater table depth and land use.

Infiltration basins are ground depressions, normally dry, where stormwater can accumulate and it is only allowed to infiltrate into the soils and eventually to the groundwater, rather than flow out into a receiving stream (Fig. 3. 20). The size and shape can vary from one large basin to multiple, smaller basins throughout a site. Ideally, the basin may avoid existing vegetation, from meadow to wooded areas. If disturbance is unavoidable, re-planting and landscaping may be necessary and should integrate the existing landscape as subtly as possible and compaction of the soil must be prevented (Pennsylvania Stormwater BMP Manual, 2006). Basins remove some pollution from rainwater runoff but still require source control up stream to operate most effectively. The key to promoting infiltration is to provide enough surface area for the volume of runoff to be absorbed within a given time (48 hours or less). An overflow must be provided for the larger storms.

Fig. 3. 20 - Infiltration basin during rainfall in a housing development (Wilson et al., 2009).

3.4.7 Constructed Wetlands

Main objective of this kind of LID is to remove water pollution from surface runoff through different mechanisms such as microbial degradation of pollutants, collection system, retention, settling and adsorption. Construction wetlands enhance growth of microbes population that is able to diminish carbon, nutrients, COD and fecal coliform concentrations. In addition, these SUDS are built to control stormwater runoff volumes and quality thus, they can act as micropools with other BMPs. Use of this LID is limited by certain conditions such as soil type, groundwater table depth, extension of contributing drainage area. Type of soil, impermeable layer depth and groundwater table depth should be investigated before design and place the wetland (Fig. 3. 21).

A constructed wetlands is designed to permit the growth of wetland plants such as rushes, willows, and cattails. They differ from "natural" wetlands, as they are artificial and are built to slow runoff and enhance stormwater quality, allowing time for sedimentation, filtering, and biological uptake (USDCM, 2010).

Wetlands functions are similar to those of a detention pond and factors that increase sedimentation rate of suspended particles are:

- laminar settling in areas with null velocity near plant stems;
- sediments attachment to the roots;
- biological activities development and dissolved nutrients removal;
- flocculation.

Fig. 3. 21 – A constructed wetland pond, located downstream of an extended detention basin (USDCM, 2010).

Constructed wetlands mimic the natural water cycle, promoting groundwater recharge, pollutant removal, erosion reduction and the creation of natural habitats. However, they present also some limitations such as unfeasibly in arid climate and, due to their sizes, in densely urbanized areas. Common pollutants removed by these practices are TSS, nitrogen, phosphorus, heavy metals, and toxic compounds in oil.

Wetlands are suitable for terrain belonging to class C and D of NRCS classification (Natural Resources Conservation Service, 1986). Ground composition analysis should be performed within the area to ensure they are adapt to growth of the vegetation and can ensure an adequate infiltration rate. Vegetated cover can have a great impact on pollutant removal efficiency. An important factor regards plants growth rate that, when higher, ensure a dense vegetation cover creation, able to overcome the coldest winters.

3.4.8 Permeable pavements

The term ‘permeable pavement’ generally refers to any of several pavements that allow movement of water into the layers underneath the pavement surface. It is a load bearing pavement structure, permeable to water, that consists of a pervious layer sitting on the top of a reservoir storage layer. Pervious pavements reduce the flood peak as well as improve the quality of stormwater at source before it is transported to receiving waters or reused productively.

Pervious surfaces are often used for pavements, walk paths, driveways, car parks, cycle routes, and sports grounds. Pervious surfaces can be either porous or permeable involving the following materials and techniques (Bregulla et al., 2010):

- porous surfacing infiltrates water across the entire surface of the material forming the paving/car parking areas, e.g. grass and gravel surfaces, porous asphalt and porous concrete;
- permeable surfacing consists of impervious material to water. However, voids are built-in to these materials that allow infiltration of water through the minute void channels, e.g. concrete paving blocks.

Use of porous pavements is not limited to new developments, but it can also be adopted in existing urban contexts. In case of requalification, maintenance or expansion, indeed, these practices help to enhance soil perviousness, replacing waterproof coatings such as asphalt, asphalt sealed concrete with permeable paving (Fig. 3. 22).

Permeable pavements offer many benefits, both aesthetic and practical. These include (CRWA, 2008):

- Reduces stormwater runoff, total water volume, and flow rate;
- Treats water runoff, including reduction of temperature;
- Increases groundwater infiltration and recharge;
- Provides local flood control;
- Improves the quality of local surface waterways;
- Reduces soil erosion;
- Reduces the need for traditional stormwater infrastructure, which may reduce the overall project cost;
- Increases traction when wet;
- Reduces splash-up in trafficked areas;
- Extends the life of paved area in cold climates due to less cracking and buckling from the freeze-thaw cycle;
- Reduces the need for salt and sand use during the winter, due to little or no black ice;
- Requires less snow-plowing;
- Reduces groundwater pollution;
- Creates green space (grass groundcover, shade from tree canopies, etc.);
- Offers evaporative cooling;

- Porous pavements reduce the volume of stormwater, increase the recharge, control the peak rate, and offer a high outflowing water quality;
- Pollutants are removed: total suspended solids are reduced by 85%, NO_3 by 30%, and total phosphorous by 85% (Pennsylvania Stormwater BMP Manual, 2006).

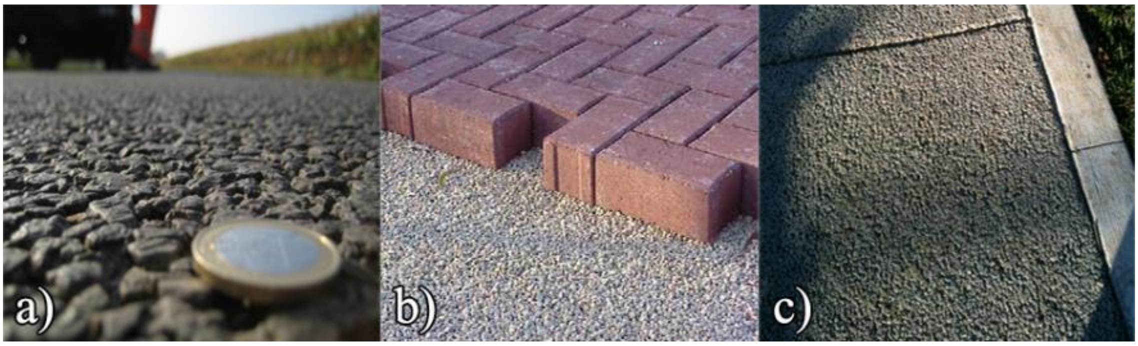


Fig. 3. 22 - Examples of porous pavements: a) porous asphalt, b) concrete paving blocks, c) porous concrete.

Porous Bituminous Pavement was first pioneered by researchers at the Franklin Institute in Philadelphia in the early 1970’s. It is a bituminous (asphalt) paving mixture which has all of the structural properties of conventional asphalt, but which is constructed of an aggregate (gravel) mix in which fine particles have been kept to a minimum. Eliminating the fine particles allows rainfall to drain through the pavement, rather than running off the surface. These pavers, having an high resistance, are mainly used in suburban areas (e.g. Highways, Expressways, State roads) and they have the function to quickly remove water from the rolling surface, avoiding problems of aquaplaning, and transferring it into the underlying impermeable binder layer that convey water to the traditional drainage system. Porous asphalt pavements have an high strength however they require an high maintenance/management costs due to the clogging of the pores by deposits and grime. Pervious asphalt is suitable for use in any climate where standard asphalt is appropriate (Pennsylvania Stormwater BMP Manual, 2006).

Pervious concrete pavement, indeed, is a mixture of coarse aggregate, Portland cement, water and little to no sand. Developed by *Florida Concrete Association* (FCPA, 1990), often with an underlying stone reservoir, they capture rainfall and stores runoff before it infiltrates into the subsoil. A typical pervious concrete pavement has a 15-25% void structure and allows 1-3 litres of water per minute to pass through each square meter (3-8 gallons per square foot).

Porous concrete systems are typically used in low-traffic areas, such as parking pads in parking lots, residential street parking lanes, recreational trails, golf cart and pedestrian paths and emergency vehicle and fire access lanes. Heavy vehicle traffic use must be limited to ensure ravelling or structural failure does not occur in the porous pavement surface, which may fail under constant exposure to heavy vehicle traffic (Stormwater Management Academy, 2007).

Properly constructed pervious paving installations treat the surface water using the following mechanisms (Bregulla et al., 2010):

- filtration;
- biodegradation of organic pollutants such as fuels from motor vehicles;
- adsorption (this will depend on the materials of the pervious paving);
- retention and settlement of solids;
- impermeable bases provide a means to control the direct flow to groundwater;
- adsorption of the subsoil within the pervious paving system can be further enhanced by adding an adsorbent substrate material, e.g. sawdust, peat, clay, granular activated carbon;
- biodegradation of organic pollutants and other hydrocarbons.

3.4.8.1 Porous pavers drawbacks

When properly realised, pervious pavements have a removal efficiency comparable to other infiltration systems. Although filtering capacity is initially quite high, the filtration process causes clogging of the pavement and, consequently, reduces the ability of filtration. Fine materials such as clay, silt or other materials derived from tire wear and pavers can cause clogging of the pores which happen, generally, between 12 and 20 years after pavement construction (Yong et al., 2013; Shackel, 2010; Pezzaniti et al., 2009; Abbott & Comino, 2003).

Decreasing in filtration capacity, also decreases pollutants retention. In general, permeable pavements require high maintenance in order to avoid potential clogging to occur; attention must be paid to ensure that all adjacent areas are stabilized, in order to prevent transport of materials and the consequent early clogging of the pavement. It is evident, therefore, that clogging determines the design lifespan of infiltration systems, then quantitative understanding of the clogging process must be carried out.

Another contentious aspect of porous paving is its damage. Causes may be vary such as use of incorrect sub-base materials, misplaced paver blocks disposition, excessive traffic load. When a damage occurs, an expedited reparation must be undertaken in order to keep the system working as designed.

Finally, an important peculiarity is the cost. The majority of added cost of a pervious pavement/infiltration system lies in the underlying stone bed, which is generally deeper than a conventional sub-base and wrapped in geotextile. However, these additional costs are often offset by the significant reduction in the required number of inlets and pipes (SEMCOG, 2008) as well as the countless benefits provided during time.

3.5 Blue-Green infrastructures: BGC

Measures previously mentioned, when individually applied, are only partially effective (Benedict and McMahon, 2002). Stormwater management, therefore, should be aimed to a more comprehensive and holistic approach.

The Blue-Green Corridors (BGC) concept integrates surface water flooding, fluvial flooding and green space planning, and provides a much needed tool for relating flood risk management and green space provision planning policies with spatial plans at catchment levels (Skilton D., 2010). Use of BGC as a part of sustainable drainage system concept is a winning approach, that allow managing and treatment of stormwater runoff within urban areas, using practices made of green and blue components. Generally the green component is indicated with the term *"Green Infrastructures"*, that may indicate different elements depending on the context in which it is used: for some it refers to trees which provide ecological benefits in urban areas; for others it refers to the engineering structures (e.g. stormwater management systems) that are designed to be environmentally sustainable. Benedict & McMahon (2006) give a definition of these most noble and wide referring to them as "an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife". Green infrastructures challenge the common green space perspective and its protection. Many people consider green spaces simply like portions of territory not yet developed, such as isolated parks, recreational sites or other natural areas. Green infrastructure are viewed as something additional, while they represent a very useful and essential part of modern urban development. Moreover, open spaces are often considered "self-sustaining", whilst they need to be actively managed, protect and sometimes restored (Benedict & McMahon, 2006).

Green infrastructure can be explained at a variety of scales—the regional scale, municipal or community scales, street level, and site level. At the regional scale, green infrastructure is a network of natural areas and open space such as forests, trails, and parks that help sustain clean air and water and provide many other benefits for people and wildlife. At the municipal or community scale, there is a set of principles used for development in general. At the street and site level, green infrastructure relates to more specific hydrological techniques and projects (Sexton G. & Smith J., 2011).

The blue component is represented by waterways, overland flow paths, drainage networks and storage areas (e.g. lakes, ponds, wetlands) existing within urban areas. These elements, when interconnected one another, create a network defined *"Urban Blue Corridor"*, that facilitate hydrological processes whilst providing benefits including reduced urban flood risk, improved water quality, enhanced biodiversity, improved access to recreation, multifunctional green space and adaptation to climate change (Scott W., 2011). Urban Blue Corridors can be applied at a variety of scales, from individual sites to the creation of authentic "linear" corridors composed of natural, semi-natural or artificial drainage paths. This may be a single overland flow path along a street or network of corridors linking one another the existing blue infrastructures inside urban area (Fig. 3. 23).

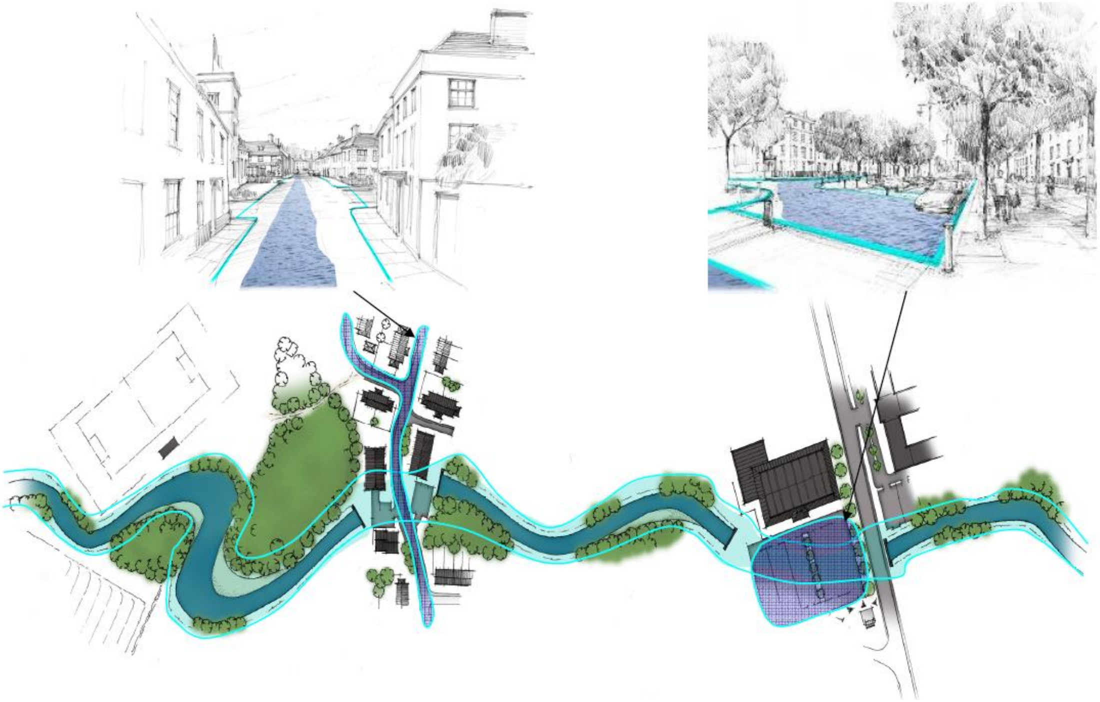


Fig. 3. 23 - Blue-Green Infrastructures inside urban area (Defra Environment Agency, 2011).

"Urban Blue Corridors" is the collective name (and linking mechanism) for a number of interconnecting features, which could include, but are not limited to, the following (Scott W., 2011):

- Overland Flow Paths
- Ponding Areas
- Rivers and Canals
- Wetlands
- Flood Storage Areas
- Historic River Channels
- Floodplains
- Multiuse Parks

Development of Blue-Green Corridors gives many benefits in terms of water quality and flood management, but even social and aesthetic advantages, including three concepts: linking parks and other green spaces for the benefit of people, preserving and linking natural areas to benefit biodiversity and counter habitat fragmentation, and using watercourses to mitigate fluvial floods (Benedict & McMahon, 2002).

By linking with Green Corridors and Infrastructure, Urban Blue Corridors offer the opportunity to help align with national environmental aspirations. For example, 'Natural England', in their Position Statement on Urban Areas, states that:

- The natural environment in towns and cities is fundamental to sustaining urban life and should be integral to the way in which urban areas are planned and managed;
- The distinctive fabric of the natural environment in towns and cities makes a major contribution to urban landscape and sense of place and should be valued, conserved and enhanced;
- The natural environment in towns and cities should underpin their adaptation to a rapidly changing climate and provide environmental security for communities; and
- People should have opportunities to readily access high quality natural environment in urban areas in order to enjoy the broad range of environmental and social benefits it offers.

The concept may be look similar to the *"stormwater treatment train"* (series of SUDS), representing a linkage between local, in-situ and regional pollutant control measures. The Stormwater Treatment Train (STT) represents an ecological approach to stormwater management and has proven effective and versatile in its various applications. Stormwater Treatment Train system is designed with sequential components that contribute to the treatment of stormwater before it leaves the site (City of Lincoln, Nebraska, 2006).

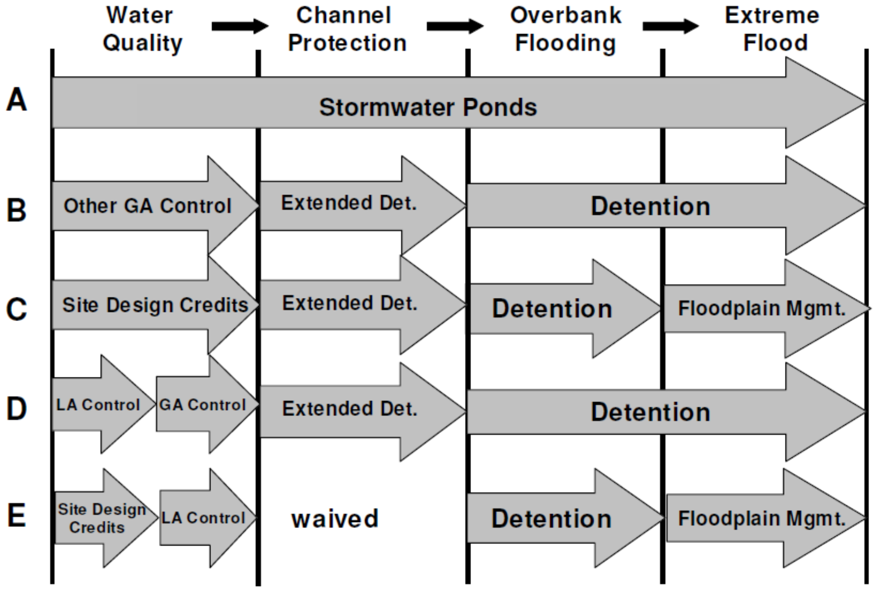


Fig. 3. 24 - Examples of Structural BMPs Used in Series (Knox County, 2008).

Compared to this latest technique, BGC appear to be a step forward, because they are not only able to treat surface water quality and reduce runoff volume, but representing almost a standalone "urban planning tool", as it actively involves also citizens and communities on protection and enhancement of green and blue resources on their territory (Fig. 3. 25).

Fig. 3. 25 - China Basin Park Concept Rendering (San Francisco, Blue Greenway Planning and Design Guideline, 2011)

However, their use is highly dependent on regulatory and legislative framework, as well as the ability to prove their usefulness and efficiency compared to conventional systems.

3.6 Barriers to BGC implementation

Despite countless benefits of WSUD, LID, SUDS and BMPs practices, their implementation still find many impediments. First of all, in some countries these practices are still unknown or their knowledge is at an early stage. For instance, only recently some laboratory studies have started in Italy (Garuti, 2000; Palla et al., 2008; Piro et al., 2012) on some of these devices, while still there is a general lack of real scale implementations. In such cases, there is also a lack of awareness on benefits provided, especially by main potential stakeholders like municipalities, councils and state governments that should promote a widespread implementation in long term planning of cities and communities. In addition, even though known, initial installation costs represent another limit, because sustainable solutions are particularly costly at the beginning than conventional techniques, although these costs are subsequently saved in the long-term period. Another limiting factor is the scarce involvement of population that may set up those kind of LID adapt for renovation/requalification sites, such as permeable pavers, green roofs or rainwater harvesting. On the other hand, institution should encourage resident to implement these sustainable practices, using monetary or other kind of incentives: for instance, the Municipality of Faenza (Italy) has implemented a bio-neighbourhood incentive programme for developers, allowing them to extend the cubature of buildings in bio-neighbourhoods in excess of approved standards, if the buildings meet certain criteria of environmental sustainability. These include green roofs, green walls and water retention systems, and also the creation of continuous public green spaces by developers (Kazmierczak A. et al., 2010).

Furthermore, an undoubted barrier is represented by the lack of national specific legislation about Blue-Green Corridors implementation or strength in planning policy to better encourage investment in these sustainable practices. Finally, among others (Fig. 3. 26), two important obstacles are the extreme difficulty to quantify in monetary terms to developers and local residents the observed positive environmental impacts (Duffy et al., 2008) and, due to the transcend boundaries of BGCs, the difficulty to allocate maintenance responsibilities in broad shared areas (Scottish Water, 2009).

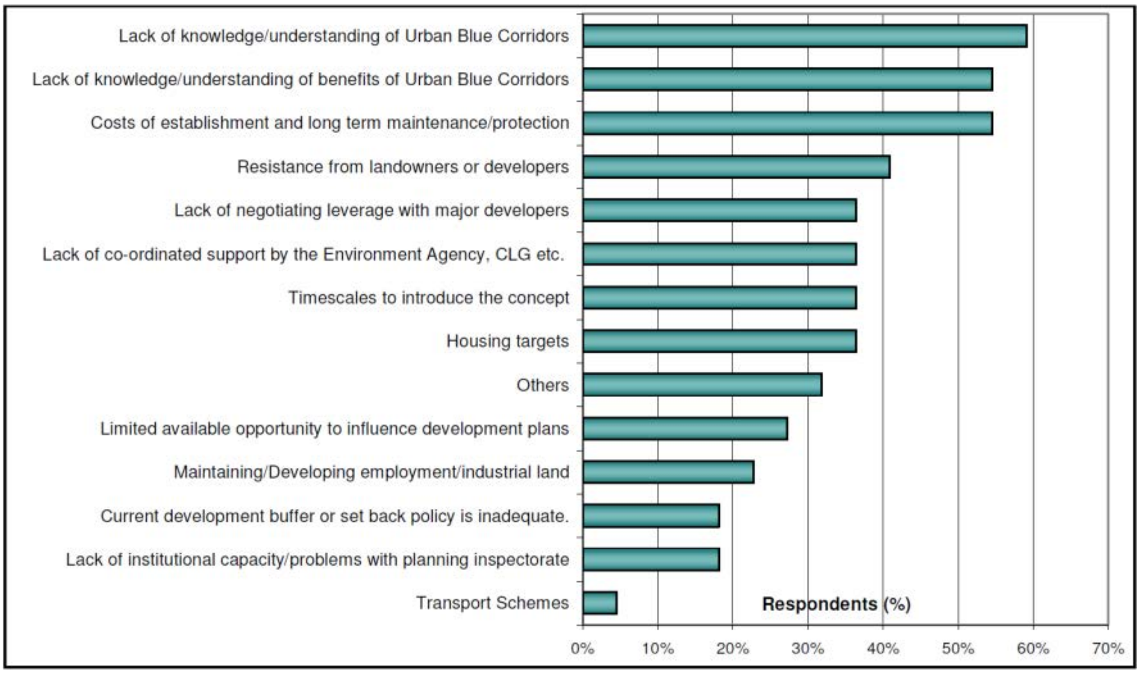


Fig. 3. 26 - Perceived Barriers to Developing Urban Blue Corridors (Scott W., 2011).

3.7 Clogging in porous pavements

As it has been previously mentioned (§3.4.8.1), porous pavements are very susceptible to clogging. When this happens, likewise other infiltration facilities, permeability, porosity and pollution treatment efficiency tend to rapidly decrease over time. If the final outcome is to encourage a widespread adoption of this practice within urban environment, decrease in infiltration capacity due to the clogging is an aspect that cannot be neglected. In reality, final aim is to prevent this phenomenon to occur, preserving permanently good performances.

During the granular filtration process, particles are first transported from suspension to a nearby media grain, come into contact with grain, finally attaching to it. The transport step, which is physical–hydrodynamic in nature, involves three main mechanisms (WHO, 2004):

- *interception* — particles following the streamline of fluid flow come into contact with a media grain (this mechanism is affected by the size of the particle);
- *sedimentation* — particles with density greater than that of water deviate from the streamline of fluid flow by gravity and come into contact with a media grain;
- *diffusion* — particles subjected to random motion by their thermal energy come into contact with a media grain.

Single collector efficiencies (defined as the ratio of the number of successful collisions between particles and a filter media grain to the total number of potential collisions in the projected cross-sectional area of the media grain) have been well developed to describe these transport mechanisms.

As stated by Li and Davis (2008), mathematical filtration expressions initially has been derived by Iwasaki (1937), using a first-order kinetic formulation:

$$\frac{\partial C}{\partial Z} = -\lambda C$$

where λ is the filter bed coefficient [L^{-1}], C is the suspension concentration (of TSS) and Z is the media depth. This equation, describing the removal of suspended particles within the filter depth of a granular sand bed, has been widely accepted as the foundation for modern filtration theory, including both slow and rapid sand filtration (Hendricks, 2005). The filter bed coefficient presented in the equation above refers to the "clean bed" condition, and describes the behaviour of the filter during early stages of filtration. This law shows an exponentially decaying profile of particle concentration through the filter depth, as demonstrated by different authors (Metcalf and Eddy, 2003; Hendricks, 2005; Tien and Ramarao, 2007).

As a results of its simplicity and reliability, from this equation have evolved two of the most used stormwater infiltration model: the first-order *k*-*C** model (Kadlec & Knight, 1996) and the Yao model (Yao et al., 1971).

The *k*-*C model** is a simple conceptual pollutant removal model, based on the first-order kinetic decay theory that assumes steady-state conditions (Siriwardene et al., 2007):

$$\frac{\left(C_{out} - C^*\right)}{\left(C_{in} - C^*\right)} = e^{-kL/q} \quad \Rightarrow \quad \frac{C_{out}}{C_{in}} = Ae^{-kL/q}$$

where C_{out} is the output sediment concentration (mg/L), C_{in} is the input sediment concentration (mg/L), *q* is the hydraulic loading (m/year), *L* is the water depth in the filter (m), *C** is the background sediment concentration (mg/L), *k* is the decay rate constant (L/year) and, in the second formulation, *A* is a parameter that replaces *C**. The model has been widely used in predicting the performance of wastewater treatment, as well as stormwater wetlands, ponds, and gravel filters. However, the two model parameters (*k* and *C**) may vary with the pollutant concentration and hydraulic conditions even for the very same system for which they are calibrated (Siriwardene et al., 2007).

Yao et al. (1971) developed a conceptual model of granular filtration and indicated that particle transport during filtration is analogous to transport in the flocculation process (diffusion, interception, and sedimentation). The Yao filtration equation, generally used to calculate a steady-state concentration profile under "clean bed" conditions, is based on a simple mass balance approach to predict particle removal efficiency:

$$\frac{C_{out}}{C_{in}} = \exp\left[-\frac{3}{2}\frac{(1-\varepsilon)}{d_M}\alpha\eta Z\right]$$

where C_{out} is the particle concentration [M/V] at depth Z [L]; C_{in} is the influent particle concentration (M/V); ε is the bed porosity (unitless); d_M is the diameter of filter grain (L); α is the sticking coefficient describing the fraction of successful attachments, varying between 1 (all contacts results in attachments) and 0 (no contacts result in attachments); and η is the single collector collision efficiency. A single-collector efficiency η is defined as η=(particle strike ratio)/$v_0 C_{in} \pi R_c^2$, where v_0 is the approaching fluid velocity, C_{in} is the inlet concentration of particles to the filter, and Rc is the radius of the single collector. The efficiency is assumed to be a superposition of efficiencies of the individual mechanisms: $\eta=\eta_B+\eta_I+\eta_G$, where subscripts indicate Brownian (B), interception (I), and gravitation (G) (Kim & Kang, 2012).

Although their wide popularity and relative simplicity, both models present some shortages:

- their applicability has been tested and validated only for some kind of practices like sand filters (Mikkelsen et al., 1996; Newton, 2005), wetlands, ponds, vegetated swales, sediment basins, biofilters (Wong et al., 2006) and infiltration trenches (Browne et al., 2011);
- even though k-C* model seems to be applicable to predict output concentration for several pollutants, such as TSS (Total Suspended Solids), TP (Total Phosphorous) and Heavy Metals (Wong et al., 2006), it looks not really adequate to predict output concentration of total nitrogen (TN) and derived compounds (Babatunde et al., 2011; Frazer-Williams, 2010);
- none of these models can predict changes in sediment removal over time, namely performance decay due to the filter clogging induced by pollutants and solid matter (Siriwardene et al., 2007).

Therefore, it is evident that these drawbacks do not allow to use any of the previous models directly to predict porous pavement performance efficiencies, but some modifications need to be proposed and successfully verified. Recent studies have tried to extend the validity of the k-C* model for the most common range of permeable paving: monolithic porous asphalt (PA), modular Hydrapave (HP) and monolithic Permapave (PP) (Yong et al., 2013; Yong et al., 2011). These works strive to understand the main physical processes that govern clogging and develop a simple model that predicts clogging through porous pavements over their lifespan. A laboratory experiment, over 26 accelerated years, has been performed and performances under variable drying and wetting conditions have been tested, particularly under a continuous time scale.

Despite good results obtained, an ‘universal formulation’, able to predict the behaviour of different types of porous paving under different conditions, both in terms of infiltration rate decay (due to media clogging) and treatment efficiency (pollutant concentration over time) has not yet been found.

The aim of this thesis is to develop a reliable model for predicting sediment behaviour and pollutant concentration in permeable paving over their lifespan, moving beyond of “clean bed” filtration theory and its limitations and considering the effects of media clogging due to the subsequent deposition and accumulation of particles over time.

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Chapter 4: Software

4.1 Introduction

Planning a framework for urban stormwater management requires a site analysis, an evaluation of ground capabilities and the consequent drawing of a development master plan of the area. Once the general plan of the area has been created, changes in characteristics of overland flow and pollutant loads help to identify, select and design appropriate structural or non-structural BMPs in order to achieve project aims.

Site analysis involves checking of regional land use as well as territorial and climatic characteristics. The most important areas of regional planning might include utilization of "blue-green corridors" and protection areas.

At a more focused level, the following site characteristics are considered (Lloyd et al., 2002): geology and soils, landforms, drainage patterns (including assessment of the 100 year ARI flood levels), climate (including historical rainfall patterns and evaporation rates), significant natural features (that is, remnant vegetation, habitat of threatened or endangered species, wetlands, etc.), existing urban infrastructure (that is, underground gas lines or water supply mains) and historical/cultural features (that is, heritage buildings, archaeological sites, etc.).

As regards land capabilities assessment, it may be verified that morphological land characteristics will be able to sustain future land use of the area, once the site will be fully developed. When all these information will be gathered, a land use plan can be prepared that will contain scheme and location of each service drawn at proper scale. In addition, gathered information from previous site analysis and evaluation, could suggest more than one possible arrangements. In that case, priority may be given to the solution that will provide the highest number of benefits, remaining within the available budget. Minimization of maintenance costs of stormwater management systems can be achieved taking into account of site planning design specifications.

Examples of planning provisions that can improve overall effectiveness of the stormwater management scheme include (Lloyd et al., 2002):

- Whenever possible, orientate roads to run diagonally across the contour to achieve a grade of 4% or less to help incorporate BMPs into the streetscape;

- Promote cluster lot arrangements around public open space to allow greater community access to, and regard for associated natural and landscaped water features forming the local stormwater management scheme;
- Maintain and/or re-establish vegetation along waterways, and establish public open spaces down drainage lines to promote them as multi-use corridors linking public and private areas and community activity nodes.

This approach is coherent with principles underlying the modern sustainable urban development, well known as “smart cities” or WSUD – Water Sensitive Urban Design. WSUD reflects a new paradigm in the planning and design of urban environments that is ‘sensitive’ to the issues of water sustainability and environmental protection (Brown R.R. and Clarke J.M., 2007). “Smart city” is a concept which in turn proposes a better life quality within urban environments, which helps people to implement their projects of health and work, instead of hinder them with increasing chaotic complexity.

A "smart city" is an urban space, well directed by a far-sighted policy, which addresses challenge that globalization and economic crisis arise in terms of competitiveness and sustainable development (Benanti, 2011).

Pursuit these policies implies an increasing use of sustainable management practices within urban areas. Selection of the most appropriate techniques to achieve goals set during the design stage should take into account some aspects such as volume control, water quality improvement as well as costs containment. Compliance with these criteria can be verified only through an in depth modelling of each single LID or their combination in a network of interconnected elements, in order to enhance their efficiency (BGC – Blue Green Corridors). Therefore simulation models must have appropriate characteristics to simulate both the technical-technological elements described above as well as phenomena affecting their behaviour and functionality.

4.2 Background on modelling software available

Models are used to answer questions, support decision-making and assess alternatives. Models are used as a tool to describe and understand the dynamics of physical systems including watersheds and receiving waters such as lakes, rivers, estuaries, and coastal areas (USEPA, 2005).

Currently available models in literature are numerous but, at the same time, based on a few simple concepts. They can be classified in multiple ways, depending on the main characteristics wish to emphasize or according to the final simulation purpose (Tab. 4. 1).

Conceptual	only the most prominent processes are described and/or several processes may be lumped into a single expression
Continuous	simulate seasons, years, or decades
Distributed	consider a hydrological compartment as a spatially variable system
Dynamic	time dimension with specific rates for different processes, creating time-series for temporal variability
Emission	summarise leakage coefficients and/or empirical emission data for different contribution classes to reveal the outlet conditions
Equifinality	the model is too complex in relation to the information in the data used for calibration
Eulerian	consider changes as they occur at a fixed point in the fluid
Event-based	simulate transport development only during a single storm
Finite-difference	finite approximations to the conventional derivative of a continuous function
Holistic	views in which the individual elements of a system are determined by their relations to all other elements of that system
Imission	estimated transport or concentration at the catchment outlet is related to upstream characteristics
Lagrangean	consider changes which occur as you follow a fluid particle
Lumped	the hydrological compartment is described in terms of average quantities
Mechanistic	all processes are described based on physical, chemical, and biological laws
Semi-distributed	conceptual functional relationships for hydrological processes that are applied to a relatively small number of what are assumed to be homogeneous parts of the catchment treated as "lumped units"
Source	apportionment estimation of contribution from various sources to the total load of pollution
Steady state	have no time component but describe average temporal conditions for the period studied

Tab. 4. 1 – An example of models classification (Adapted from Arheimer & Olsson, 2003).

A common and widely accepted classification uses to divide models in two categories:

- *Flow models*: models covering hydrological and hydraulic aspects of modelling: rates of input from rain or wastewater, and the hydraulic response of the sewer system in terms of flow-rate and depth. Some sewer system models also include water quality: the presence and behaviour of pollutants entering and flowing through the system.
- *Quality models*: provide information on the rate at which pollutants flow into the structures from the sewer system, and how the pollutants are distributed in the storm flow. In the same way that flow models gave output in the form of hydrographs (flow or depth) at specified points, quality models would give

pollutographs, the variation of concentration of pollutants with time (Butler & Davies, 2011).

In order to pursuit an accurate and reliable simulation of the different BMPs and their functionality, both previous aspects should be taken into account by any software which aims this goal. As stated in Chapter 3, in fact, SUDS and others sustainable practices provide multiple benefits to society, both in terms of qualitative and quantitative aspects. Therefore, a proper LIDs simulation software should be able to provide detailed information on the capabilities of each BMP working standalone or within an interconnected blue-green network (BGC), as well as hydrograph and pollutograph at outlet section of each practice (and within the related sewage system).

The large number of models is the consequence, however, of the different algorithms used, and thus the different combinations of basic ideas that result to be fundamental for a good BMP modelling. The related background concepts aim to reduce overland stormwater volumes and pollutant loads, heat islands and save energy, as well as create optimal social realities, that will include community recreational areas (socio-political aspect).

Therefore, it is important to locate the correct BMP placement areas as well as their dimensions, in order to achieve the desired quali-quantitative abatements. Below follow a review of the most used simulation software. For each of them, a brief description is shown, together with the main characteristics and the major sustainable practices modelled (Piro et al., 2012a).

4.2.1 DAnCE4Water

Software house/Institution: University of Innsbruck, Monash University, Melbourne Water

Category/Status: Under development

Description

Dance4Water software is developed within the EU Framework Programme 7 PREPARED: Enabling Change. Based on a grid representation of the urban environment of similar sized blocks, accept as input data different GIS information including: land use, population densities, topography, soil character, natural and man-made water systems. DAnCE4Water is a model (concept) that integrates both the *social* and the *biophysical* aspects of city and *water infrastructure* development as they evolve over time.

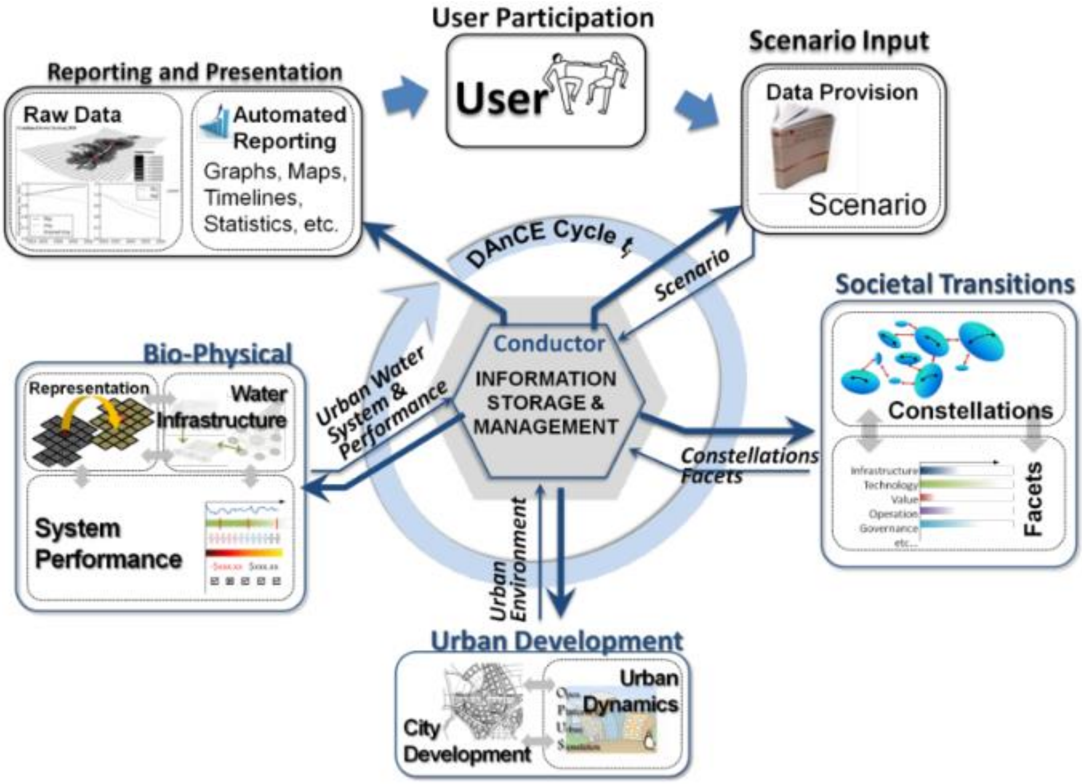


Fig. 4. 1 - DAnCE4Water Model Framework (Rauch et al., 2012).

The tool comprises six modules:

- UPM: User Participation Module
- SIM: Scenario Input Module
- STM: Societal Transitions Module
- UDM: Urban Development Module
- BPM: Bio-physical Module
- RPM: Reporting and Presentation Module.

It allows the assessment of urban infrastructure dynamics in response to the social and environmental driving factors on water supply system (Rauch et al., 2012). Therefore, the majority of LIDs are modelled such as: bioretention areas, constructed wetlands, dry/wet detention basins, vegetated filter strips, green roofs, infiltration basins, filtration trenches and sand filters.

4.2.2 GSI-CALC

Software house/Institution: Kitsap County Public Works Department

Category/Status: Open source

Description

GSI-Calc allows sizing of LID BMPs, or "green stormwater infrastructure" (GSI), as a function of contributing impervious area, prevalent soil types in the region, representative site infiltration rates, and mean annual precipitation. This program is intended to assist developers and regulatory agency reviewers in sizing and designing LID BMPs without need for continuous simulation modelling, thereby reducing the barriers to the implementation of LID. GSI-Calc is applicable to projects for sites located in the lowland areas of Western Washington region. GSI-Calc can be used to size the following BMPs: bioretention cells and porous pavements (with different slopes and bottom geometry). Modelling was performed using MGSFlood Version 4 developed by MGS Engineering Consultants, Inc. (GSI-Calc User's manual, 2011).

4.2.3 KCRTS

Software house/Institution: King County Department of Natural Resources and Parks, Water and Land Resources Division

Category/Status: Commercial

Description

The King County Runoff Time Series (KCRTS) program was developed as a hydrologic modelling tool for different land cover conditions and soil types in regions of King County using the U.S. Environmental Protection Agency's HSPF10 model. The program can assist the designer to (KCRTS Reference Manual, 2009):

- Generate runoff time series records using HSPF derived unit area runoff files for different rainfall regions and pervious land covers
- Use pre-simulated runoff files of hourly and 15-minute time steps
- Software supports full historical runoff records as well as standard 8-year runoff files
- Create/Modify reservoir data files
- Route time series records through a reservoir
- Sum time series or add base flow to a time series
- Create time series records for water surfaces based on level-pool routing

- Analyse time series records for annual peaks and associated flow/stage frequencies
- Analyse time series records for flow/stage duration and exceedance probability
- Compute from time series records the discharge volume for a period of record
- Extract/Plot a Hydrograph from a time series record, and
- Determine approximate dimensions of a *retention/detention (R/D) facility* meeting user specified design requirements.

4.2.4 MGSFlood

Software house/Institution: MGS Engineering Consultants, Inc.

Category/Status: Commercial

Description

MGSFlood is a general, continuous, rainfall-runoff computer model developed for the Washington State Department of Transportation specifically for stormwater facility design in Western Washington. The program uses the Hydrological Simulation Program-Fortran (HSPF) routine for computing runoff from rainfall. HSPF uses multi-year inputs of hourly precipitation and evaporation, keeps a running accounting of the moisture within the soil column and in groundwater storage, and simulates a multi-year time series of hourly runoff. Other features comprise (MGSFlood User Manual, 2009):

- Ability to simulate a large number of sub basins and links
- Variable Time Step Routine that Allows for Much Faster Simulations
- Ability to import sub basins from Excel CSV files which can be created from GIS, or CAD
- “Single Click” pond and infiltration trench sizing and Optimization routine
- Bio-Retention Facility and Green Roof Simulation Routines
- Physically-based pond and trench infiltration routines that accounts for groundwater mounding
- Simulation of stream channels with complex shapes, including floodplains
- Routines for performing Wetland Hydroperiod Analyses
- Computes Water Quality Treatment Design Parameters (Volume and Discharge rate)
- Routines for Computing and Graphing Streamflow frequency, duration statistics, and hydrographs
- Exports storm hydrographs to routing programs such as SWMM Extran.

4.2.5 MUSIC

Software house/Institution: eWATER CRC, Monash University

Category/Status: Commercial

Description

Music (Model for Urban Stormwater Improvement Conceptualisation) is a model based on proven Australian science and extensive user experience that helps to visualise and compare design strategies to manage urban stormwater hydrology and pollution impacts. Music provides the ability to simulate both quantity and quality of runoff from catchments ranging from a single house block up to many square kilometres, and the effect of a wide range of treatment facilities on the quantity and quality of runoff downstream. By simulating the performance of stormwater improvement measures, Music determines if proposed systems can meet specified objectives, both from a hydrologic and water quality perspective. Music will simulate the performance of a group of stormwater management measures, configured in series or in parallel to form a "treatment train". Music runs on an event or continuous basis, allowing rigorous analysis of the merit of proposed strategies over the short-term and long-term.

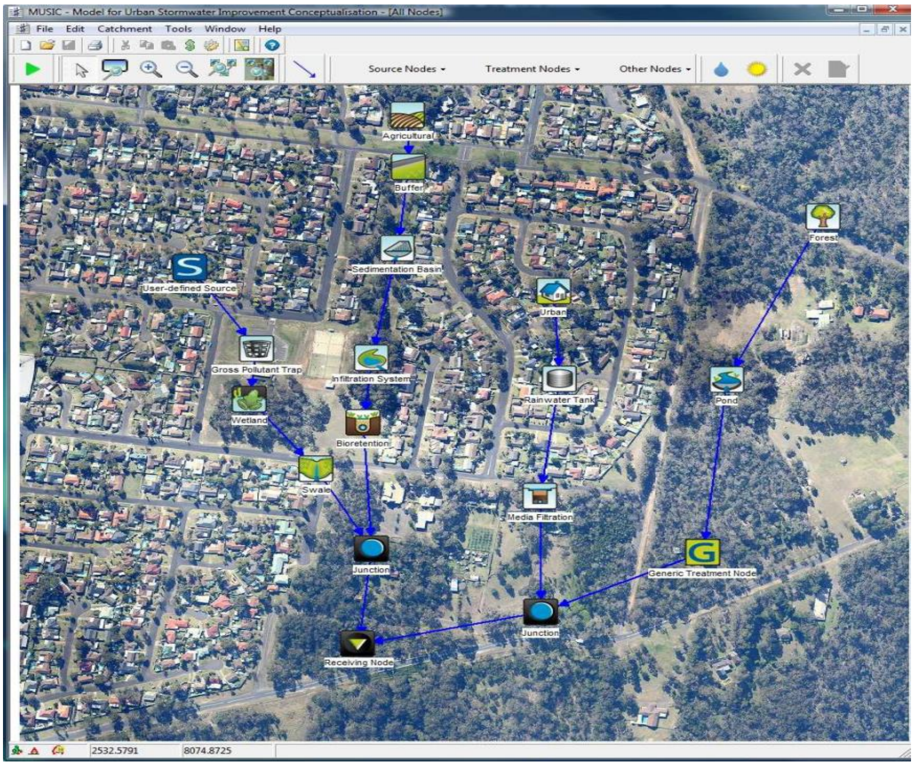


Fig. 4. 2 – An example project showing different LID types supported by Music (Music 5 User Manual, 2012).

The software, initially developed for Australian climate conditions, is going to be adapted to other environments and regions, such as UK, France, Germany, Singapore and Malaysia. Already it supports a wide range of treatment devices: buffer strips, detention basin, rainwater tanks, bioretention, sedimentation basin, media filtration, infiltration, wetland, gross pollutant trap, swale, pond and a generic treatment node (defined by user) (Fig. 4. 2) (Music 5 User Manual, 2012).

4.2.6 PC-SWMM

Software house/Institution: CHI (Computational Hydraulics International)

Category/Status: Commercial

Description

PCSWMM is a software that integrate the full US EPA SWMM5 engine, taking into accounts for various hydrologic processes producing runoff from rural and urban areas. It provides intelligent tools for streamlining model development, optimization and analysis, including:

- time-varying rainfall
- evaporation of standing surface water
- rainfall interception from depression storage
- infiltration of rainfall into unsaturated soil layers
- percolation of infiltrated water into groundwater layers
- interflow between groundwater and the drainage system
- handle networks of unlimited size
- model special elements such as culverts, storage/treatment units, flow dividers, pumps, weirs, and orifices
- retention and infiltration through Low Impact Development / Green Infrastructure devices
- dry-weather pollutant build-up over different land uses
- pollutant wash off from specific land uses during storm events
- direct contribution of rainfall deposition
- reduction in dry-weather build-up due to street cleaning
- reduction in wash off load due to BMPs (permeable pavers, bio-retention areas, rain gardens, green roofs, vegetative swales and buffer strips, cisterns, infiltration trenches (CHI software, 2011).

4.2.7 P8

Software house/Institution: USEPA, Minnesota PCA & Wisconsin DNR

Category/Status: Open source

Description

P8 simulates the generation and transport of stormwater runoff pollutants in urban watersheds. P8 (abbr. "Program for Predicting Polluting Particle Passage Through Pits, Puddles, and Ponds"), despite its limitations, has been used by state and local regulatory agencies as a consistent framework for evaluating proposed developments. Principal applications include:

- prediction of water quality components including total suspended solids (sum of the individual particle fractions), total phosphorus, total Kjeldahl nitrogen, copper, lead, zinc, and total hydrocarbons
- simulation of BMP types including detention ponds (wet, dry, extended), infiltration basins, swales, buffer strips, or other devices with user-specified stage/discharge curves and infiltration rates
- estimation of groundwater storage and stream base flow in watershed-scale applications.

Anyway, device simulations are limited by the following factors:

- No backwater effects, i.e., the outflow from a given device cannot depend on the water elevation or outflow from in a downstream device (with the exception of a splitter device).
- Precipitation/evaporation directly to/from devices is ignored. This is usually not a problem, since devices account for small fraction of watershed area. Otherwise, device area can be explicitly included in the specified watershed area.
- Devices are assumed to be completely-mixed. Effects of plug flow can be simulated by splitting one device into two or more consecutive devices.
- Particle re-suspension is not simulated. Maximum simulated velocities are tabulated for comparison with scouring criteria.
- Particle interactions (flocculation) are not directly simulated, except insofar as NURP settling velocities (measured) reflect such processes.
- Not Calibrated for dissolved substances. Any dissolved or particulate substance with first-order decay, second-order decay, and/or first-order settling kinetics can be modelled, given calibration data (Palmstrom and Walker, 1990).

4.2.8 PURRS

Software house/Institution: Peter Coombes, Newcastle University, Australia

Category/Status: Commercial

Description

The PURRS (Probabilistic Urban Rainwater and Wastewater Reuse Simulator) model was used for event based stormwater peak discharge calculations (Coombes, 2003). The PURRS model uses continuous simulation techniques to assess the long-term performance of source control measures including rainwater tanks, water efficient appliances, wastewater reuse and other stormwater management devices on urban allotments at short time steps (< 6 minutes), and determines the impact of rainwater tanks and other lot scale water reuse measures on the provision of water supply, sewage and stormwater infrastructure (Coombes, 2004). The model uses pluvial data and the description of the site to calculate peak flows through an on-site detention (OSD) tank. As the model is not a design tool, the sizing of an OSD tank for a given frequency of storm event (e.g. 1 in 5 year storm event) was carried out by a trial and error method. The figure below (Fig. 4. 3) indicates one manner in which the PURRS model can be used to simulate the effect of rainwater tanks on urban water supply and stormwater infrastructure (WBM Oceanics Australia, 2006).

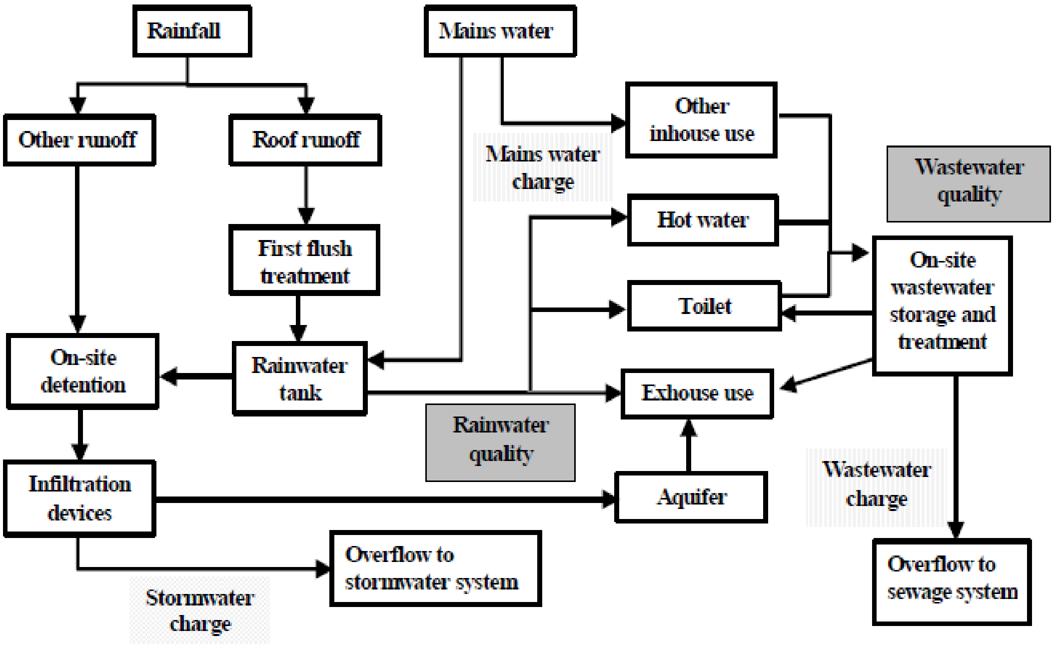


Fig. 4. 3 - Schematic of PURRS Model (WBM Oceanics Australia, 2006).

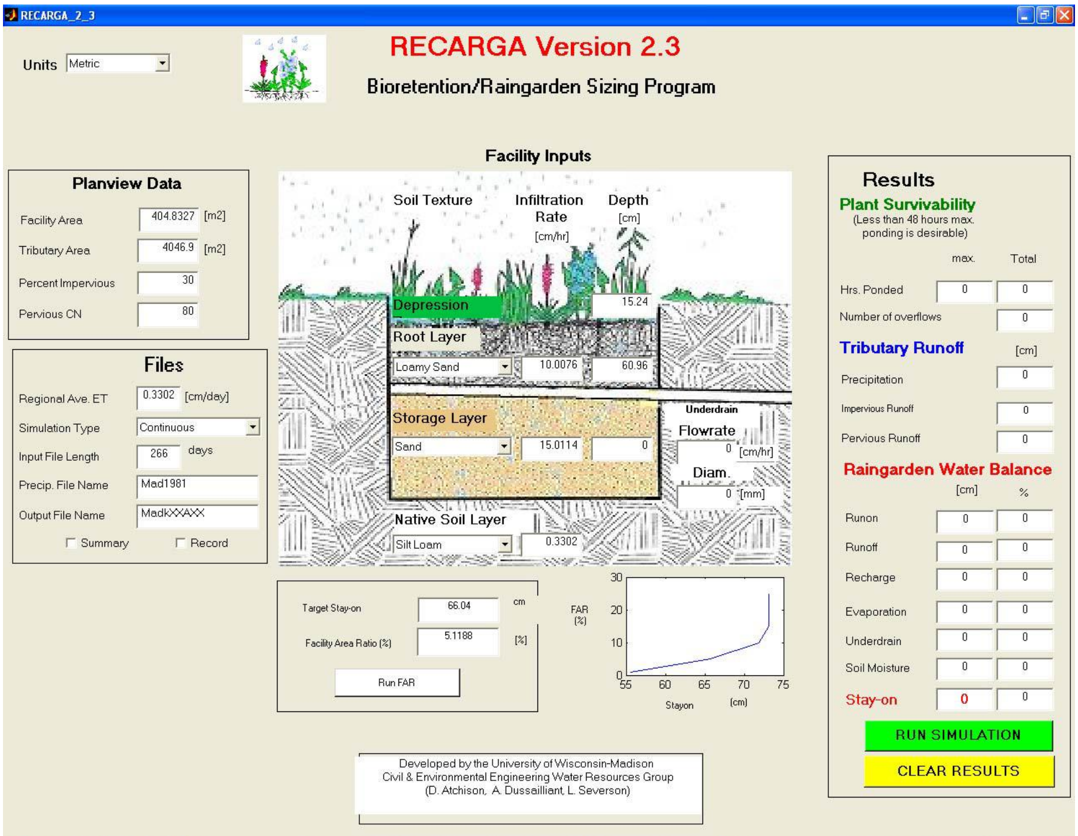
4.2.9 RECARGA

Software house/Institution: Wisconsin, Department of Natural Resources

Category/Status: Open source

Description

The RECARGA model provides a design tool for evaluating the performance of bioretention facilities, raingarden facilities and infiltration basins. The model, written in Matlab® and designed to model individual facilities with surface ponding up to 3 distinct soil layers and optional underdrains under user-specified precipitation and evaporation conditions, does not directly model water quality but many inferences on water quality performance can be obtained from quantifying runoff reduction and adsorption/filtration processes. It continuously simulates the movement of water throughout the facility (ponding zone, soil layers and underdrains), records the soil moisture and volume of water in each water budget term (infiltration, recharge, overflow, underdrain flow, evapotranspiration, etc.) at each time step and summarizes the results. Those can be used to size facilities to meet specific performance objectives, and for analysing the potential impacts of varying the design parameters (Atchison D. & Severson L., 2004).



RECARGA_2_3

Units: Metric

RECARGA Version 2.3

Bioretention/Raingarden Sizing Program

Planview Data

Facility Area: 404.8327 [m2]

Tributary Area: 4046.9 [m2]

Percent Impervious: 30

Pervious CN: 80

Files

Regional Ave. ET: 0.3302 [cm/day]

Simulation Type: Continuous

Input File Length: 266 days

Precip. File Name: Mad1981

Output File Name: MadkXXAXX

☐ Summary ☐ Record

Facility Inputs

	Soil Texture	Infiltration Rate [cm/hr]	Depth [cm]
Depression			15.24
Root Layer	Loamy Sand	10.0076	60.96
Storage Layer	Sand	15.0114	0
Native Soil Layer	Silt Loam	0.3302	

Underdrain

Flowrate: 0 [cm/hr]

Diam.: 0 [mm]

Target Stay-on: 66.04 cm

Facility Area Ratio (%): 5.1188 [%]

Results

Plant Survivability

(Less than 48 hours max. ponding is desirable)

	max.	Total
Hrs. Ponded	0	0
Number of overflows		0

Tributary Runoff [cm]

Precipitation: 0

Impervious Runoff: 0

Pervious Runoff: 0

Raingarden Water Balance

	[cm]	%
Runon	0	0
Runoff	0	0
Recharge	0	0
Evaporation	0	0
Underdrain	0	0
Soil Moisture	0	0
Stay-on	0	0

Developed by the University of Wisconsin-Madison
Civil & Environmental Engineering Water Resources Group
(D. Atchison, A. Dussailliant, L. Severson)

Fig. 4. 4 - The RECARGA 2.3 Model (Atchison D. & Severson L., 2004).

4.2.10 SUSTAIN

Software house/Institution: TETRA TECH Inc., in collaboration with US EPA

Category/Status: Open source

Description

SUSTAIN (System for Urban Stormwater Treatment and Analysis INtegration) is a software that help address key stormwater management issues such as:

- Evaluate and select management options to achieve a pollutant loading target
- Develop cost-effective management options to implement a municipal stormwater program
- Evaluate pollutant loadings and identify appropriately protective management practices for a source water protection study
- Determine a cost-effective mix of green infrastructure (GI) measures to meet optimal flow reduction goals in a combined sewer overflow (CSO) control study.

SUSTAIN includes hydrologic/hydraulic and water-quality modelling in watersheds and urban streams. It has the capability to search for optimal management solutions at multiple scales (Fig. 4. 5) to achieve desired water-quality objectives based on cost-effectiveness (Shoemaker et al., 2009).

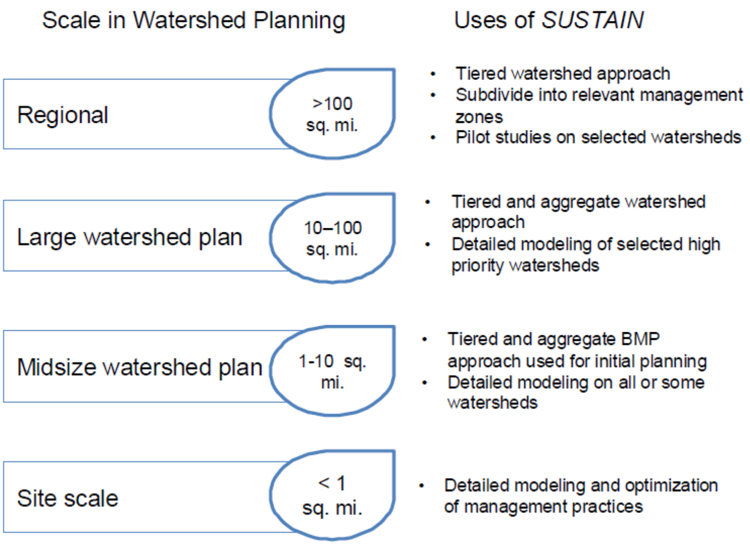


Fig. 4. 5 - *SUSTAIN*'s multiple scales of application (Shoemaker et al., 2009).

Integrated under a common ArcGIS platform, *SUSTAIN* is a decision support system was developed to:

- assist stormwater management professionals in developing implementation plans for flow and pollution control to protect source waters and meet water quality goals.

- assist watershed and stormwater practitioners to develop, evaluate, and select optimal BMP combinations at various watershed scales on the basis of cost and effectiveness.

The following structural BMP options are currently supported: Bioretention, Cistern, Constructed Wetland, Dry Pond, Grassed Swale, Green Roof, Infiltration Basin, Infiltration Trench, Porous Pavement, Rain Barrel, Sand Filter (non-surface), Sand Filter (surface), Vegetated Filter strip, Wet Pond (SUSTAIN website, 2012).

The software aims to be used in many contexts and different scales to solve optimization problems regarding LID sizing, aggregation and combination in order to meet water quality criteria. In addition, the integration within ArcGIS Platform represents certainly a lead point that together with the free availability, it could make this software the best of this review. However, the current version still has lot of bugs, which hopefully will be removed with next versions.

4.2.11 SWAT

Software house/Institution: Agricultural Research Service (USDA-ARS) in collaboration with Texas A&M AgriLife Research

Category/Status: Open source

Description

The SWAT (Soil and Water Assessment Tool) is a small watershed to river basin-scale model to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds

The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the subwatershed area and are not identified spatially within a SWAT simulation. Alternatively, a watershed can be subdivided into only subwatersheds that are characterized by dominant land use, soil type, and management (Gassman et al., 2007).

4.2.12 SWMM

Software house/Institution: USEPA – United States Environmental Protection Agency in joint development collaboration with CDM, Inc., Cambridge

Category/Status: Open source

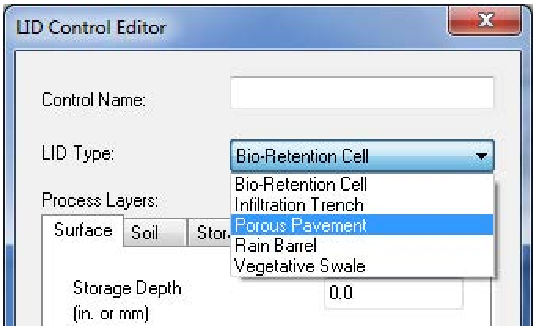
Description

EPA's Storm Water Management Model (SWMM) is likely the most used rainfall-runoff simulation model throughout the world. The software, used primarily but not exclusively for urban areas, allows single-event or long-term (continuous) simulation. Flow routing is performed for surface and sub-surface conveyance and groundwater systems, including the option of fully dynamic hydraulic routing in the Extran Block (dynamic wave flow routing). Nonpoint source runoff quality and routing may also be simulated, as well as storage, treatment and other BMPs. The last official release of SWMM now available is the version 5.0.022 (April 2011), developed from the completely revised version 5 (Rossman L.A., 2005).

SWMM allow qualitative and quantitative modelling of hydraulic and hydrologic processes such as:

- time-varying rainfall
- evaporation of standing surface water
- snow accumulation and melting
- rainfall interception from depression storage
- infiltration of rainfall into unsaturated soil layers
- percolation of infiltrated water into groundwater layers
- interflow between groundwater and the drainage system
- nonlinear reservoir routing of overland flow
- runoff reduction via Low Impact Development (LID) controls.

In particular, EPA has only recently extended SWMM 5 to explicitly model the hydrologic performance of specific types of low impact development (LID) control, such as Bio-Retention Cell, Infiltration Trench, Porous Pavement, Rain Barrel and Vegetative Swale (Fig. 4. 6).



LID Control Editor

Control Name:

LID Type: Bio-Retention Cell

Storage Depth (in. or mm) 0.0

Fig. 4. 6 - USEPA SWMM 5 - LID Control Editor.

The updated model allows engineers and planners to accurately represent any combination of LID controls within a study area to determine their effectiveness in managing stormwater and combined sewer overflows.

SWMM can also estimate the production of pollutant loads associated with runoff through the drainage system network of pipes, channels, storage/treatment units and diversion structures. The following processes can be modelled for any number of user-defined water quality constituents:

- dry-weather pollutant build-up over different land uses
- pollutant wash-off from specific land uses during storm events
- direct contribution of rainfall deposition
- reduction in dry-weather build-up due to street cleaning
- reduction in wash-off load due to BMPs
- entry of dry weather sanitary flows and user-specified external inflows at any point in the drainage system
- routing of water quality constituents through the drainage system
- reduction in constituent concentration through treatment in storage units or by natural processes in pipes and channels (Rossman L.A., 2005).

Specifically as regards the BMPs functioning, each LID control is represented by a combination of vertical layers whose properties are defined on a per-unit-area basis (Fig. 4. 7). This allows LIDs of the same design but differing areal coverage to easily be placed within different subcatchments in a study area.

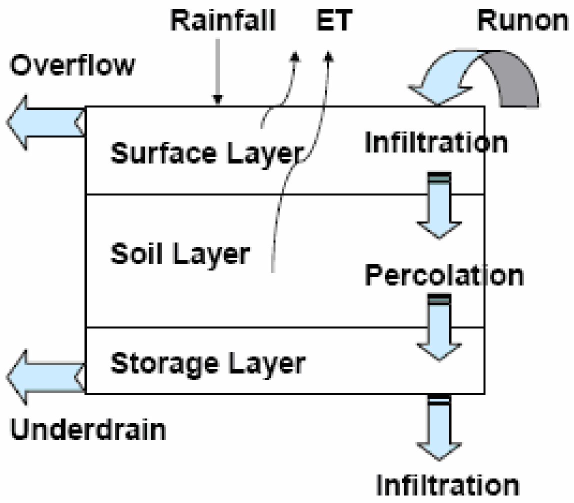


Fig. 4. 7 - USEPA SWMM 5 – Schematic of LID representation (EPA SWMM Help, 2011).

During a simulation SWMM performs a moisture balance that keeps track of how much water moves between and is stored within each LID layer.

As regards pollutant reduction and water quality improvement, although some LID practices can also provide significant benefits in these aspects, at this time SWMM only models their hydrologic performance (Rossman L.A., 2005).

In fact, to take into account for spatial variation in pollutant build-up and wash-off rates within subcatchments or BMPs, SWMM groups categories of development activities or land surface characteristics into '*Land Uses*'.

For each land use category the following processes can be defined: *Pollutant Buildup* and *Pollutant Washoff*. *Pollutant Buildup* that accumulates within a land use category is described (or "normalized") by either a mass per unit of subcatchment area or per unit of curb length. Mass is expressed in pounds for US units and kilograms for metric units. The amount of build-up is a function of the number of preceding dry weather days and can be computed using a Power, Exponential or Saturation function. *Pollutant Washoff* from a given land use category occurs during wet weather periods and can be described as Exponential or Rating Curve wash-off or using the Event Mean Concentration (Rossman L.A., 2005).

As it is possible to notice, both properties depend from the number of preceding dry weather days and length of wet weather periods, namely, from runoff characteristics. Therefore, at the moment, SWMM does not have any mathematical expression or treatment function to directly evaluate the removal efficiency of LID practices.

Another issue is the malfunctioning or maintenance issues associated with BMPs. Reduced removal efficiencies are likely without regular maintenance, and effects of clogging or other reduction in proper performance should be included in any modelling procedure.

Currently SWMM take into account about clogging phenomena only through a "*clogging factor*", defined as 'the total volume of treated runoff it takes to completely clog the bottom of the layer divided by the void volume of the layer'. Within the formula:

$$CF = \frac{Y_{c\log} \cdot Pa \cdot CR \cdot \left(1 + VR\right) \cdot \left(1 - ISF\right)}{\left(T \cdot VR\right)}$$

- *Yclog* is the number of years it takes to fully clog the system;
- *Pa* is the annual rainfall amount over the site;
- *CR* is the pavement's capture ratio (area that contributes runoff to the pavement divided by area of the pavement itself);

- *VR* is the system's Void Ratio;
- *ISF* is the Impervious Surface Fraction, and
- *T* is the pavement layer Thickness.

As stated by Rossman (2012), “the clogging factor is a crude attempt to give the user some ability to account for loss of infiltration capacity over time. At this point it is purely speculative.”

In fact, an evident drawback and uncertainty of the formulation is the necessity to know in advance how much time the considered pavement takes to become clogged. Even if different studies has already been conducted on this point (Yong et al., 2011; Shackel et al., 2008; Abbott & Comino, 2003), the obtainable *Yclog* values represent a merely indication and they will never be the same occurring in a specific site.

Therefore, it is possible to summarise that SWMM is certainly one of the most versatile LID simulation package available but, it has evident weaknesses that need to be overcome in order to make it more reliable about the simulation of the water quality behaviour of these practices.

4.2.13 WATER BALANCE MODEL

Software house/Institution: Department of Soil Science, University of British Columbia; powered by QUALHYMO

Category/Status: Commercial

Description

The Water Balance Model (WBM) for British Columbia is an on-line tool that helps users to gauge the potential for developing or redeveloping communities while maintaining the original hydrologic condition. Using rainfall volume as a performance target to quantify the effectiveness of various stormwater source control strategies, the model gives users a convenient pre-design planning tool that they can access over the Internet. The model evaluates the effectiveness of applying different stormwater source controls under different development conditions (British Columbia University, 2010). It is a decision support tool that bridges engineering and planning, that helps communities to create neighbourhoods that integrate both good planning and innovative engineering designs, for overall objectives of greater sustainability, such as:

- minimal environmental impacts
- enhanced social values

- economic stability, and
- recreational opportunities

The WBM provides a continuous simulation of the runoff from a development (or redevelopment) area, or from a watershed (or sub-catchment) with multiple land uses, given the following inputs:

- *Continuous rainfall data* (time increment of one hour or less) and *evapotranspiration data* (daily) over a long period of record (at least a year). Historic rainfall data can be modified to create climate change scenarios.
- *Site design parameters* for each land use type being modelled (e.g. road width, rooftop coverage, surface parking coverage, population density).
- *Source control information* for each land use type, including:
    - extent of source control application (e.g. % of road and % of building lots with a certain types of source controls)
    - source control design parameters (e.g. area and depth of infiltration facilities, soil depth for green roofs or absorbent landscaping, volume of rainwater reuse cisterns)
- *Soils information***,** including surface soil parameters (e.g. maximum water content, vegetation rooting depth) .

The water balance model is a predesign tool that is best suited in a decision support or policy evaluation role at the strategic or functional planning stages (British Columbia University, 2010).

4.2.14 WinDES

Software house/Institution: Micro Drainage Limited

Category/Status: Commercial

Description

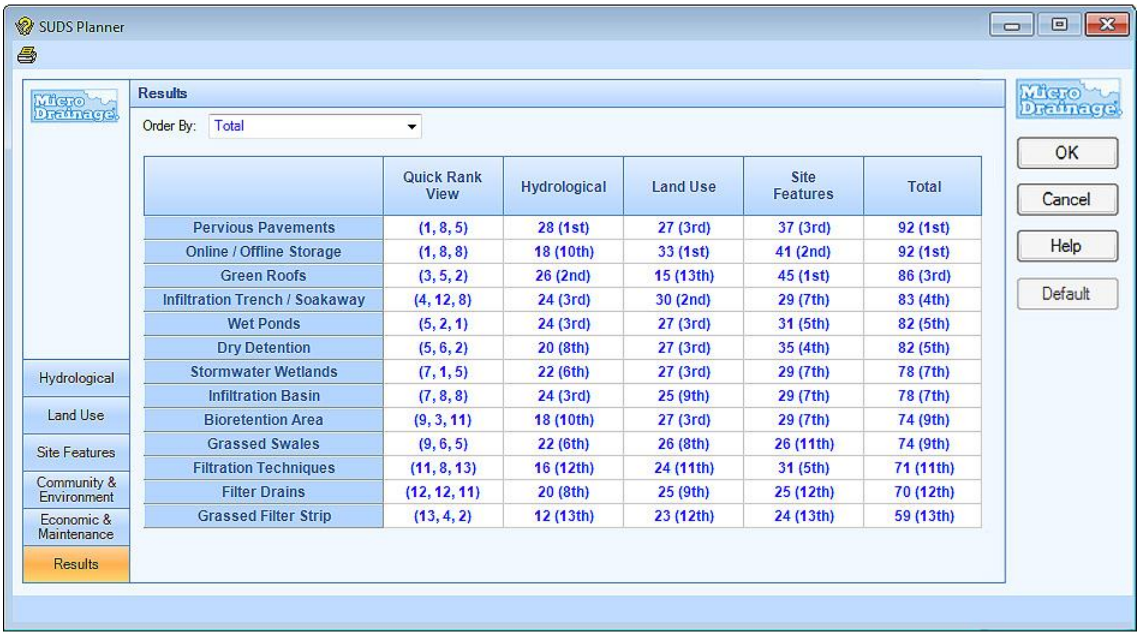
WinDES is a software developed by Micro Drainage which includes a range of fully integrated modules, developed for the design and modelling of surface water and waste water systems (Fig. 4. 8).

Fig. 4. 8 - WinDES software modules (MicroDrainage Limited, 2013).

The modules, designed to meet the latest United Kingdom legislative requirements (UK National SUDS – Sustainable Urban Drainage System – Standards, Sewers for Adoption and Code for Sustainable Homes guidelines) can be used in isolation or combined with other modules for additional integrated functionality.

The software permits to design and analyse drainage systems, including a flow simulation module and a costing and quantities package; in addition it uses the met Office database of rainfall data across the United Kingdom to enable engineers and hydrologists to extract/interpolate site specific rainfall data to test the performance of drainage and hydrological networks using continuous analysis.

In particular, regarding the best management practices modelling, there is a module called 'SuDS planner' used to plan the subcatchments required to satisfy the water quality, quantity and amenity aspects at source, site and regional levels (Fig. 4. 9). This module is able to furnish the existing hydrological characteristics of the site (such as topography and height map), then identify the existing receptors and pathways, namely the 'blue corridors' (FloodFlow Analysis). The identification of existing blue corridor routes will enable the pathways to be treated with due respect, highlight existing areas at greatest risk to flooding and produce the optimum infrastructure layout. This powerful software can handle projects ranging in size from small developments to new cities (Micro Drainage Ltd, 2013).



Results

Order By: Total

	Quick Rank View	Hydrological	Land Use	Site Features	Total
Pervious Pavements	(1, 8, 5)	28 (1st)	27 (3rd)	37 (3rd)	92 (1st)
Online / Offline Storage	(1, 8, 8)	18 (10th)	33 (1st)	41 (2nd)	92 (1st)
Green Roofs	(3, 5, 2)	26 (2nd)	15 (13th)	45 (1st)	86 (3rd)
Infiltration Trench / Soakaway	(4, 12, 8)	24 (3rd)	30 (2nd)	29 (7th)	83 (4th)
Wet Ponds	(5, 2, 1)	24 (3rd)	27 (3rd)	31 (5th)	82 (5th)
Dry Detention	(5, 6, 2)	20 (8th)	27 (3rd)	35 (4th)	82 (5th)
Stormwater Wetlands	(7, 1, 5)	22 (6th)	27 (3rd)	29 (7th)	78 (7th)
Infiltration Basin	(7, 8, 8)	24 (3rd)	25 (9th)	29 (7th)	78 (7th)
Bioretention Area	(9, 3, 11)	18 (10th)	27 (3rd)	29 (7th)	74 (9th)
Grassed Swales	(9, 6, 5)	22 (6th)	26 (8th)	26 (11th)	74 (9th)
Filtration Techniques	(11, 8, 13)	16 (12th)	24 (11th)	31 (5th)	71 (11th)
Filter Drains	(12, 12, 11)	20 (8th)	25 (9th)	25 (12th)	70 (12th)
Grassed Filter Strip	(13, 4, 2)	12 (13th)	23 (12th)	24 (13th)	59 (13th)

Fig. 4. 9 - WinDES by Micro Drainage - SUDS Planner (Micro Drainage Ltd, 2013).

4.2.15 WINSLAMM

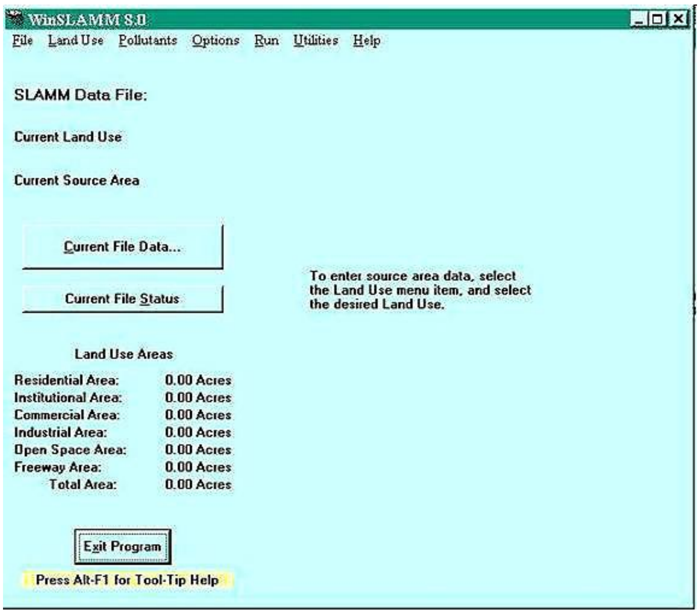
Software house/Institution: PV & Associates, LLC

Category/Status: Commercial

Description

The first version of the software called SLAMM (Source Loading and Management Model) was developed by Dr Robert Pitt from University of Alabama in the late 1970s. Since that version, the software has been improved and adapted for Windows® environment, becoming WinSLAMM (Source Loading and Management Model for Windows). Initially this model was designed to better understand the relationships between sources of urban runoff pollutants and runoff quality. Therefore, new functions has been added over time, including presently the modelling of a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales) (PV & Associates LLC, 2013).

One of the most important characteristics of the program is its ability to consider many stormwater controls (affecting source areas, drainage systems, and outfalls) together, for a long series of rains. Another is its ability to accurately describe a drainage area in sufficient detail for water quality investigations, but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results.



SLAMM Data File:

Current Land Use

Current Source Area

To enter source area data, select the Land Use menu item, and select the desired Land Use.

Land Use Areas

Residential Area:	0.00 Acres
Institutional Area:	0.00 Acres
Commercial Area:	0.00 Acres
Industrial Area:	0.00 Acres
Open Space Area:	0.00 Acres
Freeway Area:	0.00 Acres
Total Area:	0.00 Acres

Press Alt-F1 for Tool-Tip Help

Fig. 4. 10 - WinSLAMM 8 Main menu (Pitt R., 2013).

WinSLAMM incorporates long-term local rain data along with soils, land use, source area, and other local watershed factors in order to:

- Quantify pollutant sources in complex urban watersheds;
- Predict the performance and impact of many interacting development and control options, such as: calculating pollutant loads and runoff, volumes from various management scenarios, calculating the costs of conventional stormwater control practices, analysing outlet options for wet detention ponds, calculating routing and storage impacts of porous pavement control, determining if biofilters meet regulatory requirements, analysing street dirt washoff and catchbasin cleaning;
- Estimate the effectiveness of: filter strips, rain barrels and cisterns, hydrodynamic devices, stormwater media filters, grass swale drainage systems, beneficial uses of stormwater, disconnection of impervious areas.

WinSLAMM is normally used to predict source area contributions and outfall discharges. However, the model has been used in conjunction with SWMM to examine the ultimate receiving water effects of urban runoff. A more refined version of a SLAMM-to-SWMM interface processor is currently under development (PV & Associates LLC, 2013).

4.2.16 WWHM

Software house/Institution: Washington State Department of Ecology, AQUA TERRA Consultants and Clear Creek Solutions, Inc.

Category/Status: Open source

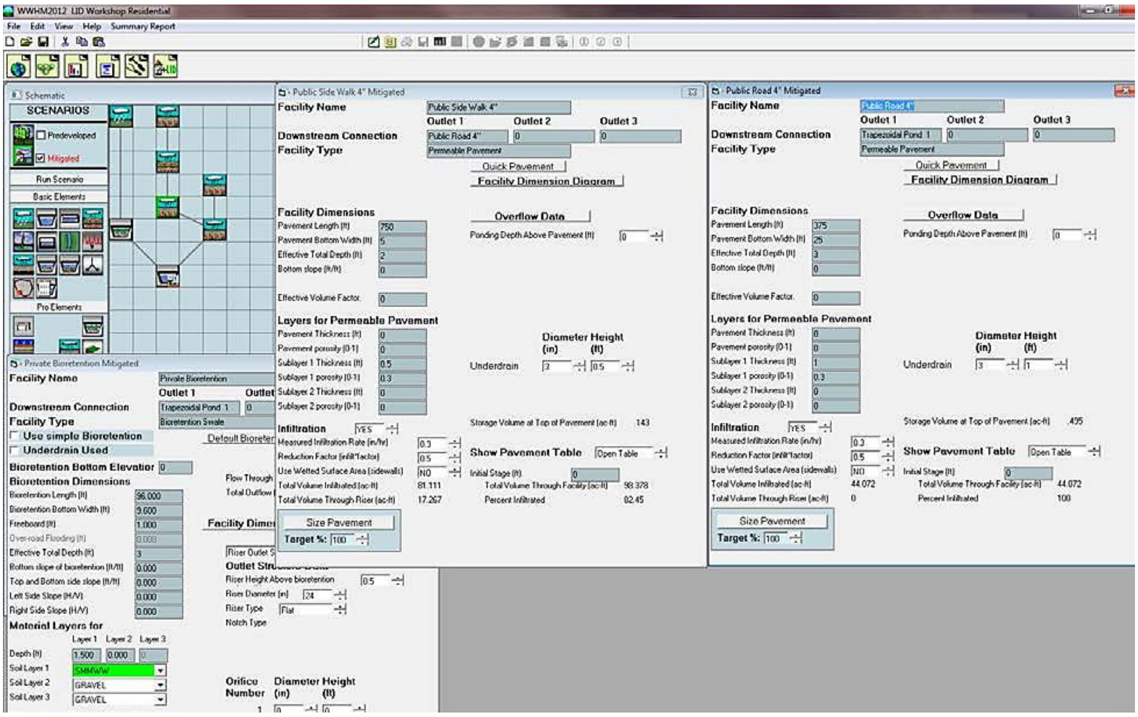
Description

The Western Washington Hydrology Model (WWHM) is a modelling software that allows to size stormwater control facilities to mitigate the effects of increased runoff (peak discharge, duration, and volume) from proposed land use changes that impact natural streams, wetlands, and other water courses (Clear Creek Solutions, Inc., 2012). Based on the HSPF (Hydrologic Simulation Program – Fortran) algorithm (Bicknell et al., 1997), the latest version includes modelling elements that more accurately represent the stormwater LID (low impact development) facilities. In particular, specific changes and additions include:

- Updated precipitation data through water year 2009 (September 2009).

- Model simulations using a 15-minute time step in place of an hourly time step (old version).
- 15-minute precipitation data in place of hourly data (old version).
- New bioretention swale element that accurately represents bioretention and rain gardens with or without underdrains and/or infiltration to the native soil.
- New CAVFS (compost amended vegetated filter strips) element to accurately represent roadside bioretention-based water quality facilities.
- New green roof element to accurately model storage, evapotranspiration, and runoff from vegetated roofs.
- New porous pavement element to accurately model the movement of water through the pavement and subgrade.
- Multiple LID facilities can be modelled as treatment trains (Fig. 4. 11).

The software is open source and available online for download and installation, but the uniform methodology used is applicable only for the 19 counties of Western Washington (Clear Creek Solutions, Inc., 2012). Moreover, as many of the previous cited software, modelling of SUDS practices is only hydrological and hydraulic, allowing the user to compute the target volumes and flows for offline and online water quality facilities. Any pollutants removing algorithm available.



Public Side Walk 4" Mitigated

Facility Name: Public Side Walk 4"
Downstream Connection: Outlet 1: Public Road 4"; Outlet 2: 0; Outlet 3: 0
Facility Type: Permeable Pavement

Facility Dimensions
Pavement Length (ft): 750
Pavement Bottom Width (ft): 5
Effective Total Depth (ft): 2
Bottom slope (ft/ft): 0
Effective Volume Factor: 0
Ponding Depth Above Pavement (ft): 0

Layers for Permeable Pavement
Pavement Thickness (ft): 0
Pavement porosity (0-1): 0
Sublayer 1 Thickness (ft): 0.5
Sublayer 1 porosity (0-1): 0.3
Sublayer 2 Thickness (ft): 0
Sublayer 2 porosity (0-1): 0
Underdrain: Diameter (in): 3; Height (ft): 0.5
Storage Volume at Top of Pavement (ac-ft): 143

Infiltration: YES
Measured Infiltration Rate (in/hr): 0.3
Reduction Factor (infilt*factor): 0.5
Use Wetted Surface Area (sidewalls): NO
Total Volume Infiltrated (ac-ft): 81.111
Total Volume Through Riser (ac-ft): 17.267
Show Pavement Table: Open Table
Initial Stage (ft): 0
Total Volume Through Facility (ac-ft): 98.378
Percent Infiltrated: 82.45
Target %: 100

Public Road 4" Mitigated

Facility Name: Public Road 4"
Downstream Connection: Outlet 1: Trapezoidal Pond 1; Outlet 2: 0; Outlet 3: 0
Facility Type: Permeable Pavement

Facility Dimensions
Pavement Length (ft): 375
Pavement Bottom Width (ft): 25
Effective Total Depth (ft): 3
Bottom slope (ft/ft): 0
Effective Volume Factor: 0
Ponding Depth Above Pavement (ft): 0

Layers for Permeable Pavement
Pavement Thickness (ft): 0
Pavement porosity (0-1): 0
Sublayer 1 Thickness (ft): 1
Sublayer 1 porosity (0-1): 0.3
Sublayer 2 Thickness (ft): 0
Sublayer 2 porosity (0-1): 0
Underdrain: Diameter (in): 3; Height (ft): 1
Storage Volume at Top of Pavement (ac-ft): .495

Infiltration: YES
Measured Infiltration Rate (in/hr): 0.3
Reduction Factor (infilt*factor): 0.5
Use Wetted Surface Area (sidewalls): NO
Total Volume Infiltrated (ac-ft): 44.072
Total Volume Through Riser (ac-ft): 0
Show Pavement Table: Open Table
Initial Stage (ft): 0
Total Volume Through Facility (ac-ft): 44.072
Percent Infiltrated: 100
Target %: 100

Private Bioretention Mitigated

Facility Name: Private Bioretention
Downstream Connection: Outlet 1: Trapezoidal Pond 1; Outlet 2: 0
Facility Type: Bioretention Swale
☐ Use simple Bioretention
☐ Underdrain Used
Bioretention Bottom Elevation: 0

Bioretention Dimensions
Bioretention Length (ft): 96.000
Bioretention Bottom Width (ft): 9.600
Freeboard (ft): 1.000
Over-road Flooding (ft): 0.000
Effective Total Depth (ft): 3
Bottom slope of bioretention (ft/ft): 0.000
Top and Bottom side slope (ft/ft): 0.000
Left Side Slope (H/V): 0.000
Right Side Slope (H/V): 0.000

Material Layers for
Depth (ft): Layer 1: 1.500; Layer 2: 0.000; Layer 3: 0
Soil Layer 1: SMMWW
Soil Layer 2: GRAVEL
Soil Layer 3: GRAVEL

Riser Outlet S
Outlet Structure
Riser Height Above bioretention: 0.5
Riser Diameter (in): 24
Riser Type: Flat
Notch Type
Orifice Number 1: Diameter (in): 0; Height (ft): 0

Fig. 4. 11 - WWHM2012 Interface - Multiple LID facilities modelling (Clear Creek Solutions, Inc., 2012).

4.2.17 XP-SWMM

Software house/Institution: XP-Solutions

Category/Status: Commercial

Description

XP-SWMM is a complete software for dynamic modelling of stormwater, combined sewers and fluvial systems. This package simulates the rainfall-runoff process, evaluates the performance of the drainage system, including the analysis of flow and pollutant transport in natural systems such as lakes, rivers, floodplains and the interactions with groundwater.

This model solves the full St. Venant equations, allowing the analysis of backwater effect in conduits and floodplains and giving a true representation of hydraulic conditions. The hydraulic engine of XP-SWMM is the same of the excellent EPA SWMM5 (§ 4.2.12), strengthened with the fully coupling of 1D network flow with 2D overland flow to accurately model interaction between flood waters and drainage systems, including underground pipes and natural channels.

The software allows, also, the modelling of pollutant loads within catchments using the same SWMM approach (build-up and wash off formulas), even so maintaining the same drawbacks. The water quality and quantity modelling used for routing in conduits and storage units, is applied also within the Best Management Practices (BMPs) or Low Impact Development (LID) strategies. The model will quantify the effect of the treatment technology in terms of reduced flow (peak or total volume) and contaminant load for practices such as rain gardens, green roofs, rain barrels, street sweeping, infiltration trenches, dry detention basins, wet ponds, swales, porous pavement, filter strips (XP-SWMM Website, 2013).

4.3 Conclusions

An urban drainage system must guarantee at least two main functions: an effective hydraulic defence of the neighbouring town and the quality control of discharges from wastewater systems into water bodies (Piro P. et al., 2012b). Main challenges to face are certainly those represented by climate change, with heavy implications on the traditional hydrologic design (Benedini, 2004). Therefore, the widespread adoption of the innovative urban drainage practices has become essential because, even if fully accepted nowadays, they are still not largely realized within the urban environment (Marsalek, 2005).

Green infrastructures represent a solution to be widely adopted in order to maintain an high water quality, due to the numerous environmental advantages furnished. Conversely to the traditional "grey" infrastructures, realized only with a single aim (typically rapidly drain waters away from cities), the green infrastructures absolve different purposes such as mitigation of floods, stormwater management, air quality control and others.

In this chapter, a series of alternatives for the simulation of BMPs and LID practices has been analysed. The lately Italian and European laws issued (EC Directive 2007/60/EC; Italian Legislative Decree 152/2006), promoting the adoption of BMPs and LID practices to protect and preserve natural environment, has forced the software houses to update their models including new modules for the qualitative and quantitative assessment of stormwater runoff. Then, new information on the performances of BMPs practices has been collected and many software (such as EPA SWMM) has been updated to incorporate these new technologies. The enhancement of the simulation capabilities of these software will help landscape planners and designers to find the optimal combination (in terms of cost-effectiveness with the objectives decided during the design stage) for the efficient treatment of wet weather flows.

BMPs modelling at watershed scale furnishes substantial benefits to the resident communities. Use of properly calibrated models is essential to evaluate and compare different urban catchments management strategies, in order to ensure the achievement of local goals. Based on the literature review performed, it is possible to suggest the following conclusions and recommendations.

Detailed models typically require a high level of experience, significant amounts of data, and time for setup and testing (USEPA, 2005).

In addition, many of the analysed models require experience and training to apply and for interpretation of the results. Typically, data required and time needed depend from the complexity of the problem considered. Some models, such as those open source, do not have any technical support, conversely to those commercial where, usually, support is included into the purchase price (i.e., MUSIC, PCSWMM). Many models include interfaces and software tools, such as post-processors, which can help to make application and interpretation of model results more efficient. Anyway, this characteristic is not available for all models, and it is missing especially in those free distributed.

Concerning BMPs and LID simulation, this kind of analysis is performed by all considered model in this review, but with different level of detail. Not all stormwater management practices are implemented in all software then, the use of a particular model can lead to limitations of simulation capabilities.

Another issue is the malfunctioning or maintenance issues associated with BMPs. Reduced removal efficiencies are likely without regular maintenance, and effects of clogging or other reduction in proper performance should be included in any modelling procedure (USEPA, 2006).

In addition, many of the model based on the SWMM engine still have its same drawbacks previously discussed, such as:

- water quality modelled only in terms of hydraulic performance of LID (build-up and wash-off laws);
- effect of clogging (loss of treatment efficiency during time), typical of many infiltration facilities (i.e., porous pavement, infiltration trenches), totally ignored or roughly modelled using empirical laws;
- lack of mathematical expression or treatment function able to directly evaluate the removal efficiency of BMPs.

Furthermore, a common disadvantage of other models not ‘SWMM-based’, is that usually they simulate lesser practices (one or fewer) than a generic comprehensive model (e.g., RECARGA, SWAT). Finally, many models (especially those free distributed) have the major drawback to work only in specific countries or regions, due to the simplification included that are obviously valid only in restricted areas (e.g., GSI-CALC, KCRTS, Water Balance Model, WWHM).

In conclusion, the proposed review shows that a comprehensive model that can be used in all circumstances and for all aims still does not exist. Overall, even the well-known and widely adopted models (such as USEPA SWMM or eWater-CRC MUSIC) need to be enhanced, especially as regards the water quality modelling of LID practices. Improvements in terms of pollutant loads and treatment efficiency predictions must be achieved, introducing new formulations able to predict the output concentration of different pollutants (Total Suspended Solids – TSS, Total Phosphorous – TP, Total Nitrogen – TN, heavy metals) for each stormwater management practice. A significant contribution in this way comes from this research, where three new formulations are proposed in order to predict the output concentration for the main street contaminants and the most diffused kinds of porous pavements. The laboratory experiment, the data analysis and modelling and the main results are discussed in the next Chapter 5.

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Chapter 5: BMPs Modelling: Porous pavements

5.1 Introduction

The necessity to retrofit urban environments in order to make them more resilient to climate change effects, has prompted toward an even more widespread adoption of sustainable practices such as LID, BMPs, WSUD and SUDS. Therefore, at the same time, the demand of new algorithms able to simulate their behaviour has rapidly increased, in terms of mitigation of runoff volumes and associated nonpoint source pollution. After the description of properties and characteristics of each practice (see Chapter 3) and a background on the modelling software available and their working concepts (see Chapter 4), in this chapter two applications will be presented and discussed. The first is an example of Blue-Green Corridors implementation in an highly urbanized catchment. The overland flow network of a catchment subarea has been retrofitted through the hypothetical implementation of a certain percentage of green roof and porous pavements. The results, as will be demonstrated, led to the necessity of a water quality algorithm improvement for porous pavements. In fact, in the second part of the chapter, the data collected from a laboratory porous paver installation has been analysed. A correlation analysis performed on the available data has shown that the key variables were: flows (wet conditions), twelve hours cumulated flows (historical conditions) and cumulative input volumes and masses (clogging conditions). Based on that, further investigations were conducted and three new formulations (one for each porous pavement type) has been proposed and validated using the Nash-Sutcliffe coefficient as goodness of fit.

5.2 SWMM BMPs Modelling

5.2.1 Experimental Site

The Liguori Catchment (LC) encloses the city of Cosenza, in Calabria, southern Italy. The catchment (Fig. 5. 1), studied for several years by the Department of Soil Conservation of the University of Calabria, has been instrumented by installing a monitoring station, consisting of a tipping-bucket rain gauge and an ultrasonic sensor for measuring water levels (depths) at the sewer outfall. Furthermore, since 2004, sewer flow samples have been collected to characterize flow quality during wet and dry weather conditions (Piro et al., 2012).

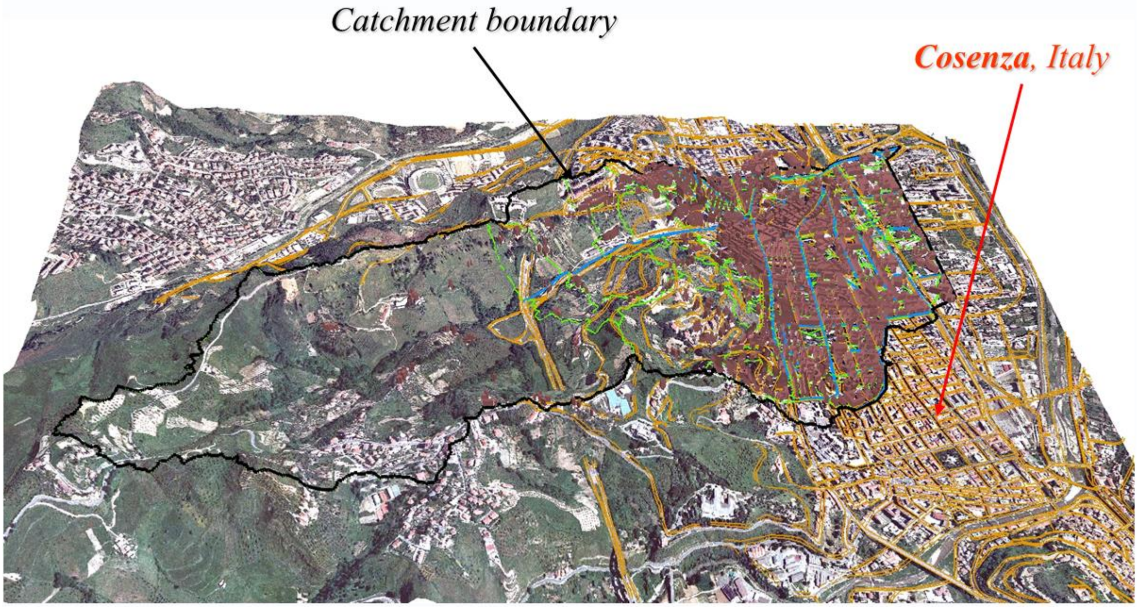


Fig. 5. 1 - The Liguori Catchment (LC) situated in Cosenza, Calabria, southern Italy.

It is approximately 414 ha in size and has a population of around 50,000 inhabitants. Half of the area (eastern part) is predominantly occupied by the city (10.2 % by buildings, 37.6 % by roads and 0.8 % by gardens) while the remaining 51.4 % is covered by natural vegetation. The elevation in the catchment ranges between 205 m and 431 m while the slope varies from 0 % (flat area) up to 213 %. Further physical watershed and sewershed information can be found in the literature (Piro and Sole, 2001). Within the catchment, a subarea has been identified whose extent is around 33 ha, thus representing almost 8 % of the whole watershed (Fig. 5. 2).

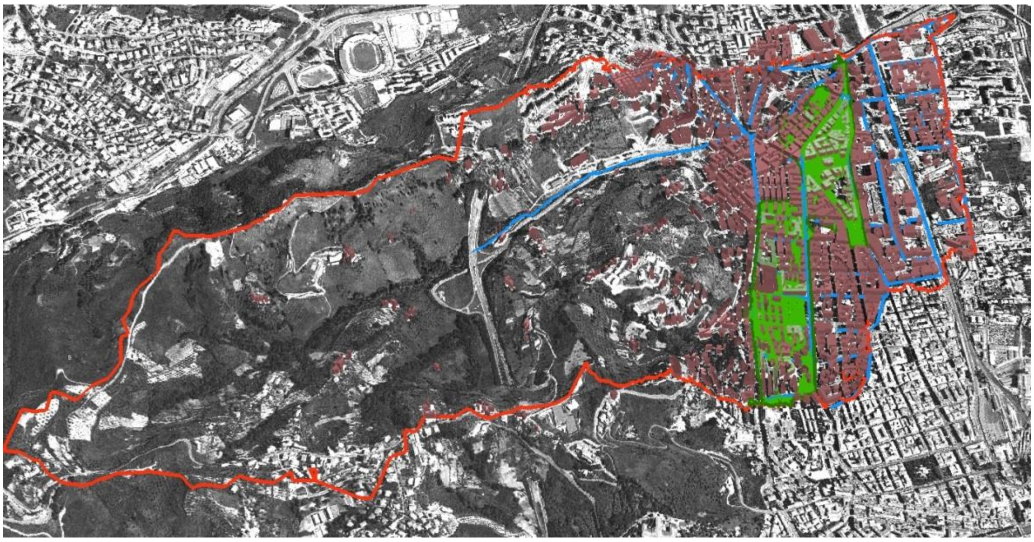


Fig. 5. 2 - Representation of the Liguori Catchment, with the study subarea highlighted (green).

This is mostly a residential area, whose surface is covered with high quality residential, retail, leisure and commercial facilities. In this area a first attempt of sustainable practices implementation has been performed. Generally it is known that in urban areas find uncovered spaces where implement green techniques is extremely difficult. Indeed this is what arisen from a survey of the area, in which available spaces are almost null. Because of this, in order to choose only “actually feasible” practices in terms of political/urban/cultural applicability, two kinds of sustainable urban drainage systems (see Ch. 3 for details) has been selected (Fig. 5. 3):

- porous pavements (about 45000 square meters – 13% of the total subarea),
- extensive green roofs (about 40000 square meters – 12% of the total subarea).

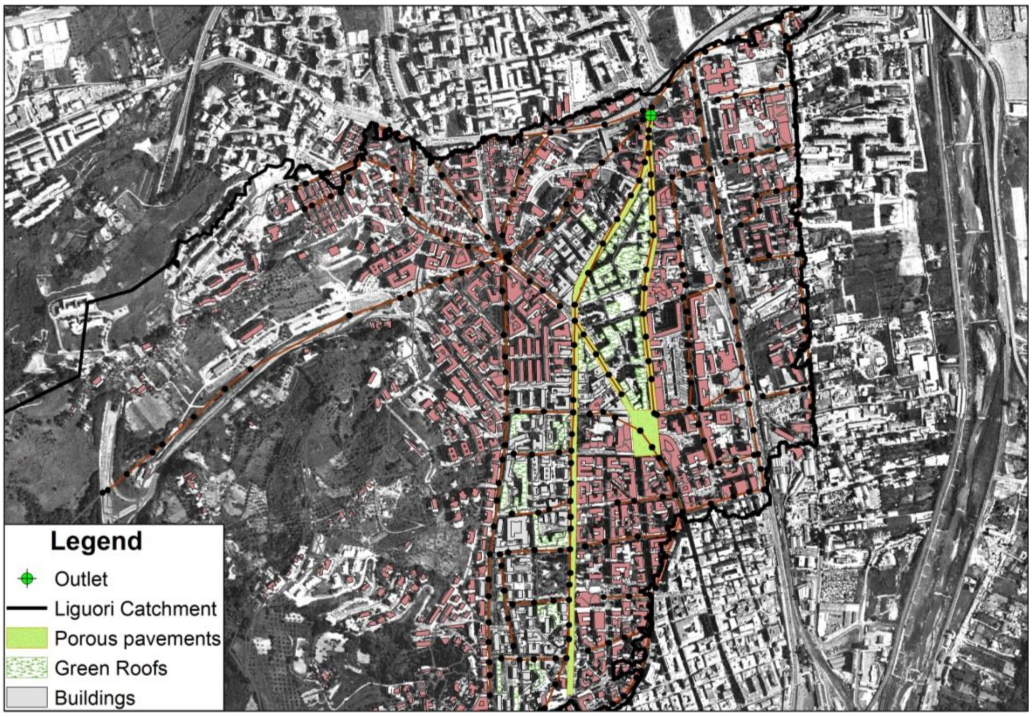


Fig. 5. 3 – Porous pavements and green roofs implemented for simulations.

To establish how the BGCs performance could affect the water quality in the examined watershed, detailed spatial analysis has been conducted and hydrologic modelling has been employed. The first one has been done using ESRI ArcMap, a commonly used geographic information system (GIS) software package. The natural overland flow network, obtained using the procedure shown in Chapter 3, has been enhanced with the implementation of these LIDs. Then, the water quality performance of the new stormwater network has been assessed modelling the elements in SWMM (Storm Water Management Model) as shown below, using historical rainfall data.

5.2.2 Annual Simulations

Hydrological analysis in urban environment require an accurate definition of sub-catchments and overland flow paths, which can be obtained utilizing an hydraulically corrected DEM (Digital Elevation Model) for the study area. Consequently, within the study has been used a LiDAR DTM with 1 meter horizontal resolution, initially subjected to a pre-processing phase in order to remove noises and other potential DEM errors (§2.6). Because of the lack of information on the manholes position, the system has been modelled using 'fictive manholes'. The position of these has been retrieved from the intersection between the known sewage network and the overland flow network obtained from the pre-processed LiDAR DTM (Tomei, 2011). In order to use the model to obtain reliable results, calibration and verification phases are required. The calibration allows, after the network has been loaded into SWMM, to get modelled results as close as possible to the measured data (Fig. 5. 4).

Fig. 5. 4 - Liguori's sewage network implemented in EPA SWMM.

In the present study, the input data and parameters required by the SWMM model to simulate drainage flow hydrographs are physiographic characteristics of the catchment (e.g., area and slope), geometric characteristics of the sewer pipes (diameter, length, slope and material), and the hydrological/hydraulic parameters such as the width of the subcatchments, catchment roughness described by the Manning coefficient, surface depression depths, and the infiltration rates for pervious areas. Based on a previous study (Piro and Carbone, 2010), the flow calibration parameters taken into account and calibrated were: surface roughness of the impervious (N-Imperv) and pervious (N-perv) surfaces in the catchment, and the depths of surface depressions on impervious (Dstore-Imperv) and pervious (Dstore-Perv) areas (Tab. 5. 1).

Parameter	n_{IMP}	n_{PERV}	$d_{STOR-IMP}$	$d_{STOR-PERV}$	C_1	C_2	C_3	C_4	n
	$m^{1/3}/s$	$m^{1/3}/s$	mm	mm	Kg/ha	1/day			$m^{1/3}/s$
	0.011	0.22	2.2	5	225	0.08	0.025	2.15	0.011

n_{IMP}	Manning's n for overland flow over the impervious portion of the subcatchment
n_{PER}	Manning's n for overland flow over the pervious portion of the subcatchment
$d_{storeIMP}$	Depth of depression storage on the impervious portion of the subcatchment
$d_{storePER}$	Depth of depression storage on the pervious portion of the subcatchment
n	Manning's roughness coefficient of the conduit
C_1	The maximum buildup that can occur for residential area
C_2	Build up rate constant
C_3	Wash off coefficient
C_4	Wash off exponent

Tab. 5. 1 - Parameters obtained by SWMM calibration (Piro and Carbone, 2010).

In order to perform also the water quality modelling, in each subcatchment a ‘residential’ land use has been defined. The amount of build-up (function of the number of preceding dry weather days) was computed using a first order exponential function. In this manner the build up follows an exponential growth curve that approaches a maximum limit asymptotically.

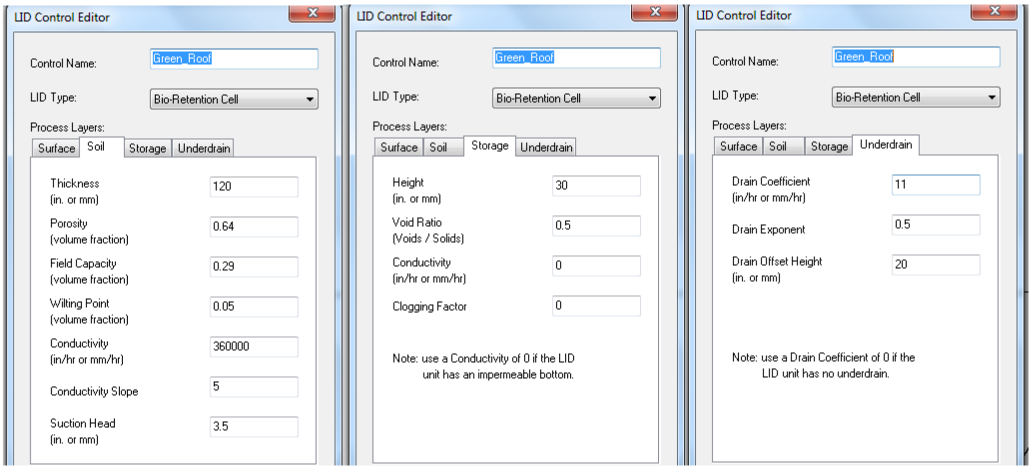
$$B = C_1\left(1 - e^{-C_2 \cdot t}\right)$$

where, C_1 = maximum build up possible (mass per unit of Area), C_2 = build up rate constant (1/days) and t = number of previous dry days. To describe the properties associated with pollutant wash off over the land use during wet weather events the following exponential function was used.

$$W = C_3 \cdot q^{C_4} B$$

where, C_3 = wash off coefficient, C_4 = wash off exponent, q = runoff rate per unit area (mm/hour), and B = pollutant build up in mass (kg) per unit area. Wash off mass units are the same as those used to express the pollutant concentration (milligrams).

As stated in the previous paragraph, a first attempt of LID implementation has been performed, enhancing the overland flow network through the use of green roofs and porous pavements. As regards the green roof, SWMM allows its modelling using the ‘Bio-retention Cell’ object. The required parameters to define the objects has been gathered from literature (Palla et al., 2008, Tab. 5. 2).



Control Name: Green_Roof
LID Type: Bio-Retention Cell

Thickness (in. or mm): 120
Porosity (volume fraction): 0.64
Field Capacity (volume fraction): 0.29
Wilting Point (volume fraction): 0.05
Conductivity (in/hr or mm/hr): 360000
Conductivity Slope: 5
Suction Head (in. or mm): 3.5

Height (in. or mm): 30
Void Ratio (Voids / Solids): 0.5
Conductivity (in/hr or mm/hr): 0
Clogging Factor: 0

Note: use a Conductivity of 0 if the LID unit has an impermeable bottom.

Drain Coefficient (in/hr or mm/hr): 11
Drain Exponent: 0.5
Drain Offset Height (in. or mm): 20

Note: use a Drain Coefficient of 0 if the LID unit has no underdrain.

Fig. 5. 5 - Green Roof object definition in SWMM.

A typical green roof section is represented below (Fig. 5. 6), where:

- Growing Media (soil): it is the 12 cm soil layer depth. The soil is a mixture of lapillus, pumice, sand used in masonry, organic material, a mixture of peat and vegetative compound;
- Drainage Layer (storage): this is the storage layer, 3 cm in depth, wrapped by a layer of geosynthetic material.

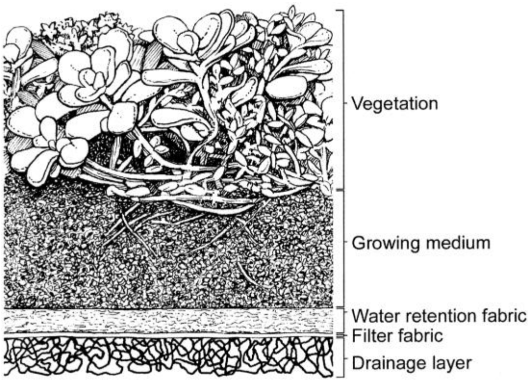
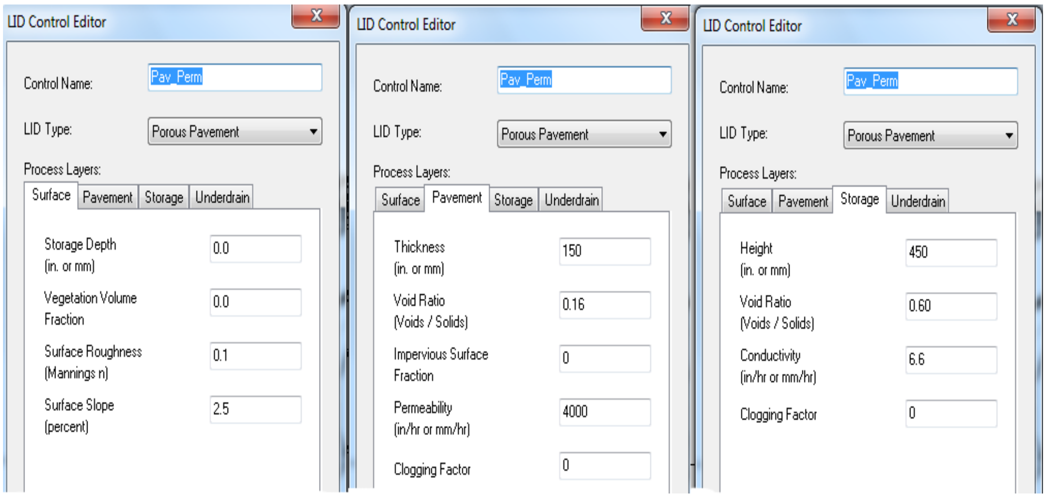


Fig. 5. 6 - Cross-section of a representative extensive green roof system including typically used layers (VanWoert et al., 2005).

	Porosity %	Wilting Point (-)	Field Capacity (-)	Conductivity m/s	Suction Head mm	Storage Height mm	Void Ratio (-)	Conductivity Drainage layer m/s
Green Roof	64	0.05	0.29	0.1	3.5	30	0.5	0

Tab. 5. 2 - Typical parameters for green roofs (Palla et al., 2008).

EPA SWMM allows also the porous pavement modelling, using the available template. Again the used parameters has been retrieved from literature (Hamzah et al., 2010; Mallick et al., 2000) and the relative values are summarised in Tab. 5. 3.



Control Name: Pav_Perm
LID Type: Porous Pavement

Surface:
Storage Depth (in. or mm): 0.0
Vegetation Volume Fraction: 0.0
Surface Roughness (Mannings n): 0.1
Surface Slope (percent): 2.5

Pavement:
Thickness (in. or mm): 150
Void Ratio (Voids / Solids): 0.16
Impervious Surface Fraction: 0
Permeability (in/hr or mm/hr): 4000
Clogging Factor: 0

Storage:
Height (in. or mm): 450
Void Ratio (Voids / Solids): 0.60
Conductivity (in/hr or mm/hr): 6.6
Clogging Factor: 0

Fig. 5. 7 - Porous pavement object defined in SWMM.

	Surface slope %	Thickness mm	Void Ratio %	Permeability mm/h	Storage Height (Sub Base) mm	Conductivity mm/h
Permeable Pav.	2.5	150	0.16	4000	450	6.6

Tab. 5. 3 – Typical parameters for porous pavements (Mallick et al., 2000).

A typical porous pavement cross-section is represented below (Fig. 5. 8), where:

- Pavers (surface): characteristics of the superficial layer in terms of transversal slope and surface roughness;
- Bedding layer (pavement): characteristic of the intermediate layer such as thickness, void ratio and hydraulic conductivity;
- Sub Base (storage): characteristic of storage layer representing the ‘in-situ’ soil such as storage capacity.

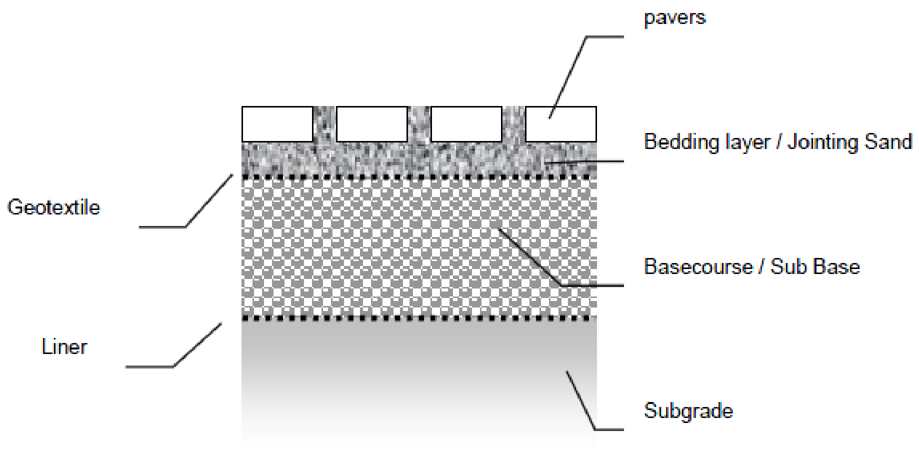


Fig. 5. 8 - Typical permeable paving cross-section (URS New Zealand Ltd., 2004).

After the template for each LID has been defined, the implementation of the LID in each subcatchment is performed through the LID Usage Editor. It specifies how a particular LID control will be deployed within the subcatchment. All geometric and topographic parameters of each subbasin has been extracted from the LiDAR DTM using ArcGIS 9.3 software. As regards the BMPs characteristics, the main researched parameters were:

- Area of Each Unit, representing the surface area devoted to each replicate LID unit (sq. ft or sq. m). If the LID occupies the whole subbasin area, the Full Subcatchment box is checked, then this field becomes disabled and displays the total subcatchment area divided by the number of replicate units;
- Top Width of Overland Flow Surface, namely the width of the outflow face of each identical LID unit (in ft or m). This parameter only applies to LID processes such as Porous Pavement and Vegetative Swales that use overland flow to convey surface runoff off of the unit. (The other LID processes, such as Bio-Retention Cells and Infiltration Trenches simply spill any excess captured runoff over their berms);
- % of Impervious Area Treated, namely the percent of the impervious portion of the subcatchment's non-LID area whose runoff is treated by the LID practice. (E.g., if rain barrels are used to capture roof runoff and roofs represent 60% of the impervious area, then the impervious area treated is 60%). If the LID unit treats only direct rainfall, such as with a green roof, then this value should be 0. If the LID takes up the entire subcatchment then this field is ignored (Fig. 5. 9).

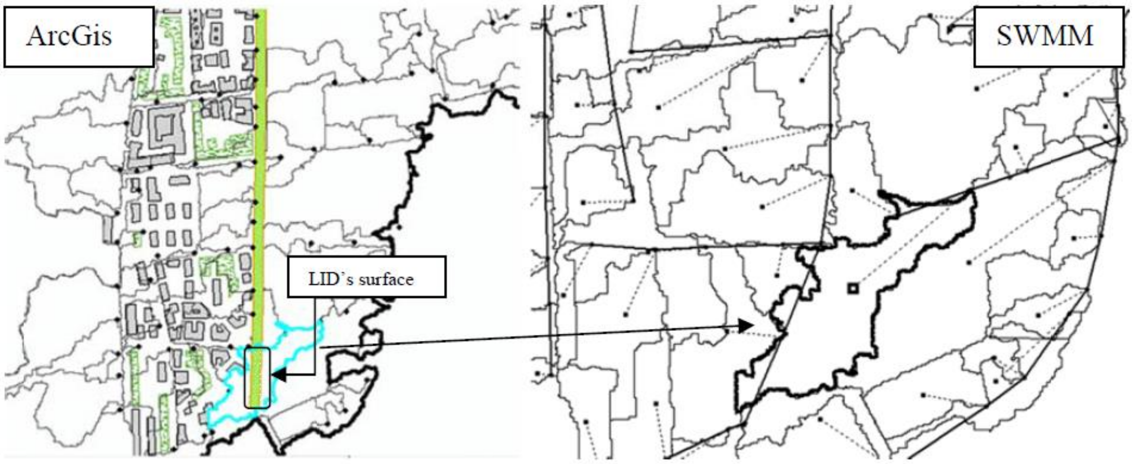


Fig. 5. 9 - Extraction of the subcatchment characteristic from ArcGIS to EPA SWMM.

In order to evaluate the impact of the implemented stormwater management techniques on the qualitative and quantitative runoff characteristics, two cases has been compared:

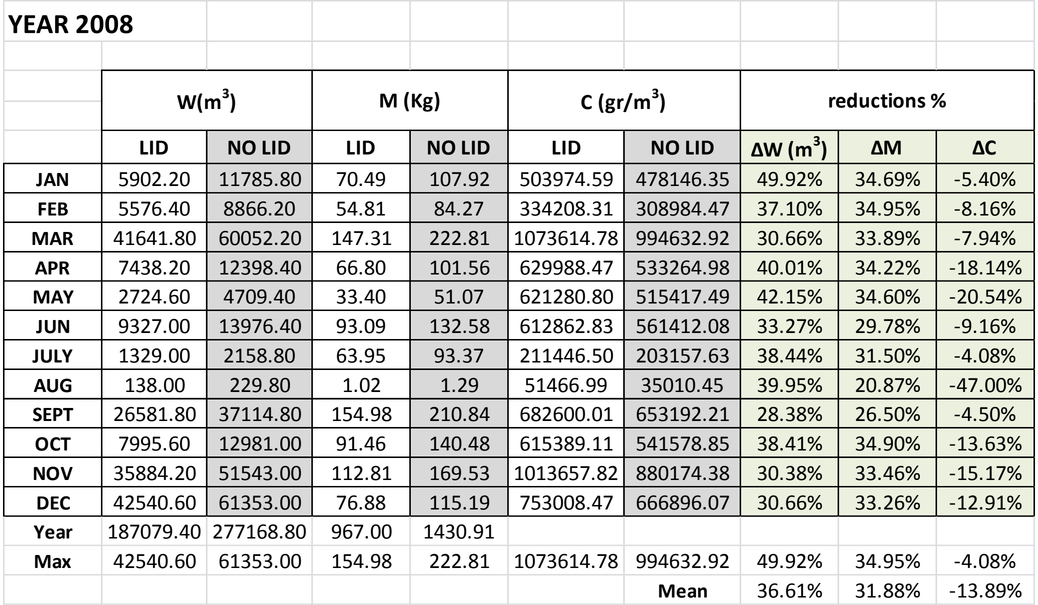
- SCENARIO A: overland flow network analysed under existing condition;
- SCENARIO B: overland flow network enhanced through the chosen LID (green roof and porous pavers).

To assess the BGC performance, a series of simulations was carried out, using historical rainfall time series (Tab. 5. 4) of four years (2008-2011), under these 2 scenarios.

Date	Rainfall duration (hours)	Rainfall depth (m)	Max rain (mm/h)	Average rain (mm/h)	Peak (m^3/s)	Average (m^3/s)	Flow Volume (m^3)
01/01/08	354.50	0.023	32.80	2.51	0.87	0.014	2.23E+09
01/01/09	559.25	0.035	43.20	2.31	0.88	0.014	3.25E+09
03/01/10	585.00	0.037	54.40	2.22	0.90	0.008	4.30E+09
04/01/11	254.25	0.018	32.00	2.40	0.87	0.006	1.43E+09

Tab. 5. 4 - Main characteristics of historical rain time series used for simulations.

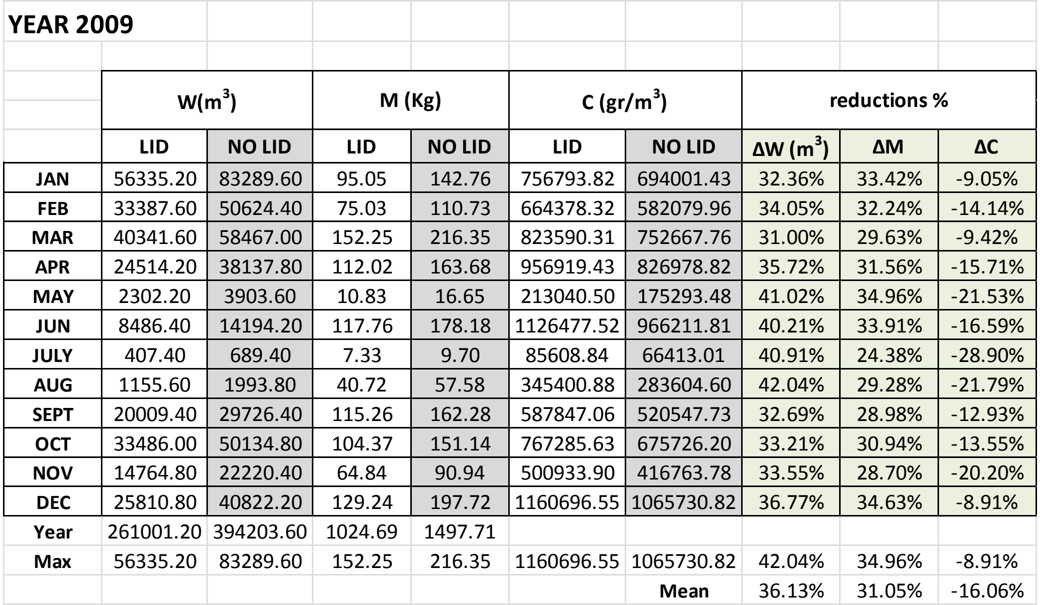
During the annual simulations, the analysis has been performed in terms of volumes, masses of pollutants and concentrations retrieved at the subarea outlet. Hereinafter tables with volumes, masses and concentrations recorded at the subcatchment outlet for each year are shown (Tab. 5. 5, Tab. 5. 6, Tab. 5. 7, Tab. 5. 8). Following, also, charts showing the behaviour of volumes, masses and concentration reductions in each simulated year are reported.



YEAR 2008

	W(m^3)		M (Kg)		C (gr/m^3)		reductions %		
	LID	NO LID	LID	NO LID	LID	NO LID	ΔW (m^3)	ΔM	ΔC
JAN	5902.20	11785.80	70.49	107.92	503974.59	478146.35	49.92%	34.69%	-5.40%
FEB	5576.40	8866.20	54.81	84.27	334208.31	308984.47	37.10%	34.95%	-8.16%
MAR	41641.80	60052.20	147.31	222.81	1073614.78	994632.92	30.66%	33.89%	-7.94%
APR	7438.20	12398.40	66.80	101.56	629988.47	533264.98	40.01%	34.22%	-18.14%
MAY	2724.60	4709.40	33.40	51.07	621280.80	515417.49	42.15%	34.60%	-20.54%
JUN	9327.00	13976.40	93.09	132.58	612862.83	561412.08	33.27%	29.78%	-9.16%
JULY	1329.00	2158.80	63.95	93.37	211446.50	203157.63	38.44%	31.50%	-4.08%
AUG	138.00	229.80	1.02	1.29	51466.99	35010.45	39.95%	20.87%	-47.00%
SEPT	26581.80	37114.80	154.98	210.84	682600.01	653192.21	28.38%	26.50%	-4.50%
OCT	7995.60	12981.00	91.46	140.48	615389.11	541578.85	38.41%	34.90%	-13.63%
NOV	35884.20	51543.00	112.81	169.53	1013657.82	880174.38	30.38%	33.46%	-15.17%
DEC	42540.60	61353.00	76.88	115.19	753008.47	666896.07	30.66%	33.26%	-12.91%
Year	187079.40	277168.80	967.00	1430.91					
Max	42540.60	61353.00	154.98	222.81	1073614.78	994632.92	49.92%	34.95%	-4.08%
						Mean	36.61%	31.88%	-13.89%

Tab. 5. 5 - Volumes, masses, concentration and their reductions obtained in the subarea outlet for year 2008.



YEAR 2009

	W(m^3)		M (Kg)		C (gr/m^3)		reductions %		
	LID	NO LID	LID	NO LID	LID	NO LID	ΔW (m^3)	ΔM	ΔC
JAN	56335.20	83289.60	95.05	142.76	756793.82	694001.43	32.36%	33.42%	-9.05%
FEB	33387.60	50624.40	75.03	110.73	664378.32	582079.96	34.05%	32.24%	-14.14%
MAR	40341.60	58467.00	152.25	216.35	823590.31	752667.76	31.00%	29.63%	-9.42%
APR	24514.20	38137.80	112.02	163.68	956919.43	826978.82	35.72%	31.56%	-15.71%
MAY	2302.20	3903.60	10.83	16.65	213040.50	175293.48	41.02%	34.96%	-21.53%
JUN	8486.40	14194.20	117.76	178.18	1126477.52	966211.81	40.21%	33.91%	-16.59%
JULY	407.40	689.40	7.33	9.70	85608.84	66413.01	40.91%	24.38%	-28.90%
AUG	1155.60	1993.80	40.72	57.58	345400.88	283604.60	42.04%	29.28%	-21.79%
SEPT	20009.40	29726.40	115.26	162.28	587847.06	520547.73	32.69%	28.98%	-12.93%
OCT	33486.00	50134.80	104.37	151.14	767285.63	675726.20	33.21%	30.94%	-13.55%
NOV	14764.80	22220.40	64.84	90.94	500933.90	416763.78	33.55%	28.70%	-20.20%
DEC	25810.80	40822.20	129.24	197.72	1160696.55	1065730.82	36.77%	34.63%	-8.91%
Year	261001.20	394203.60	1024.69	1497.71					
Max	56335.20	83289.60	152.25	216.35	1160696.55	1065730.82	42.04%	34.96%	-8.91%
						Mean	36.13%	31.05%	-16.06%

Tab. 5. 6 -Volumes, masses, concentration and their reductions obtained in the subarea outlet for year 2009.

YEAR 2010									
	W(m^3)		M (Kg)		C (gr/m^3)		reductions %		
	LID	NO LID	LID	NO LID	LID	NO LID	ΔW (m^3)	ΔM	ΔC
JAN	40993.20	64257.00	98.96	146.50	1126097.99	1016714.02	36.20%	32.45%	-10.76%
FEB	48075.00	72831.00	78.36	113.77	610511.69	516345.70	33.99%	31.12%	-18.24%
MAR	22120.80	33255.60	57.85	87.66	344008.65	307904.37	33.48%	34.00%	-11.73%
APR	10836.60	17317.20	97.06	149.18	1118468.23	991575.60	37.42%	34.93%	-12.80%
MAY	17668.20	25821.00	92.47	131.17	610806.35	529011.72	31.57%	29.51%	-15.46%
JUN	14985.00	21763.80	81.86	127.00	511765.19	474797.16	31.15%	35.55%	-7.79%
JULY	2524.20	3926.40	86.90	118.92	338851.19	303321.63	35.71%	26.93%	-11.71%
AUG	103.80	161.40	0.33	0.33	34887.51	22431.09	35.69%	-0.91%	-55.53%
SEPT	19033.20	29005.20	153.57	236.05	831868.94	782733.79	34.38%	34.94%	-6.28%
OCT	28521.60	43360.20	96.73	139.12	781785.46	690709.30	34.22%	30.47%	-13.19%
NOV	52232.40	72898.80	120.65	160.65	733611.99	634642.79	28.35%	24.90%	-15.59%
DEC	27399.00	41229.60	104.64	157.92	897668.01	790099.59	33.55%	33.74%	-13.61%
Year	284493.00	425827.20	1069.39	1568.27					
Max	52232.40	72898.80	153.57	236.05	1126097.99	1016714.02	37.42%	35.55%	-6.28%
						Mean	33.81%	28.97%	-16.06%

Tab. 5. 7 - Volumes, masses, concentration and their reductions obtained in the subarea outlet for year 2010.

YEAR 2011									
	W(m^3)		M (Kg)		C (gr/m^3)		reductions %		
	LID	NO LID	LID	NO LID	LID	NO LID	ΔW (m3)	ΔM	ΔC
JAN	18657.00	31906.80	90.38	150.90	904571.50	802928.69	41.53%	40.10%	-12.66%
FEB	7197.60	12295.80	60.93	95.43	722048.66	647615.58	41.46%	36.16%	-11.49%
MAR	25802.40	37885.80	118.05	182.04	873611.26	795674.82	31.89%	35.15%	-9.80%
APR	10840.20	17341.80	105.11	157.65	746609.08	695015.92	37.49%	33.33%	-7.42%
MAY	13944.60	22674.60	63.56	95.89	795583.65	681501.43	38.50%	33.72%	-16.74%
JUN	1702.80	2880.60	23.53	35.14	407954.81	326851.14	40.89%	33.05%	-24.81%
JULY	306.00	533.40	2.48	3.16	116357.88	79802.55	42.63%	21.62%	-45.81%
AUG	4.80	0.00	0.00	0.00	0.00	0.00			
SEPT	16667.40	22660.20	100.63	121.42	287331.40	269203.91	26.45%	17.12%	-6.73%
OCT	14416.20	19801.80	56.38	69.77	524029.13	426141.25	27.20%	19.19%	-22.97%
NOV	13603.80	19044.00	83.58	130.41	700422.56	575048.18	28.57%	35.91%	-21.80%
DEC	34272.60	52726.80	118.54	176.53	1122148.31	983571.35	35.00%	32.85%	-14.09%
Year	157415.40	239751.60	823.16	1218.33					
Max	34272.60	52726.80	118.54	182.04	1122148.31	983571.35	42.63%	40.10%	-6.73%
						Mean	35.60%	30.74%	-17.67%

Tab. 5. 8 - Volumes, masses, concentration and their reductions obtained in the subarea outlet for year 2011.

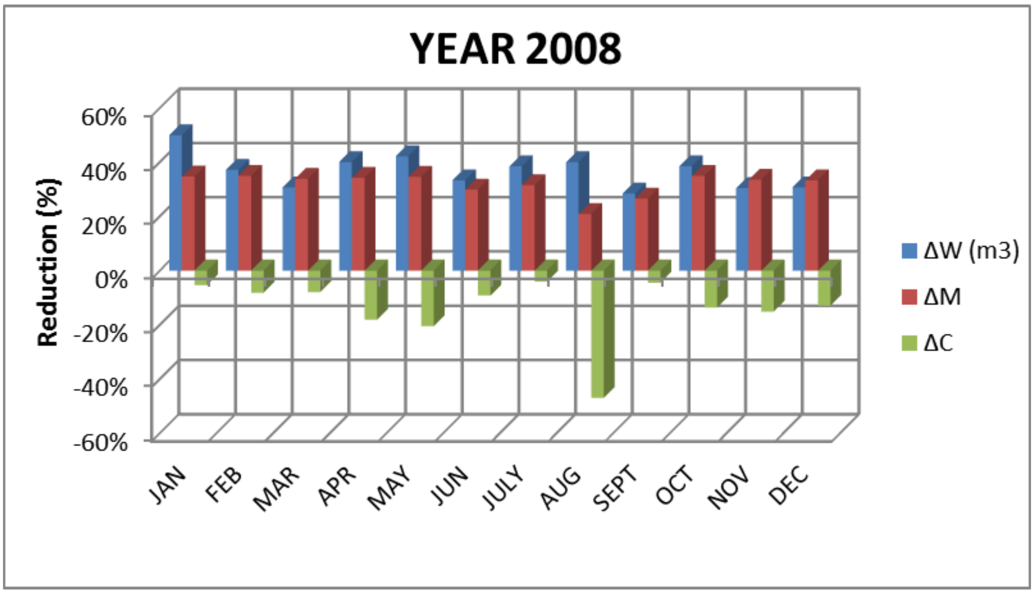


Fig. 5. 10 - Volumes, masses reduction and concentration increment for year 2008.

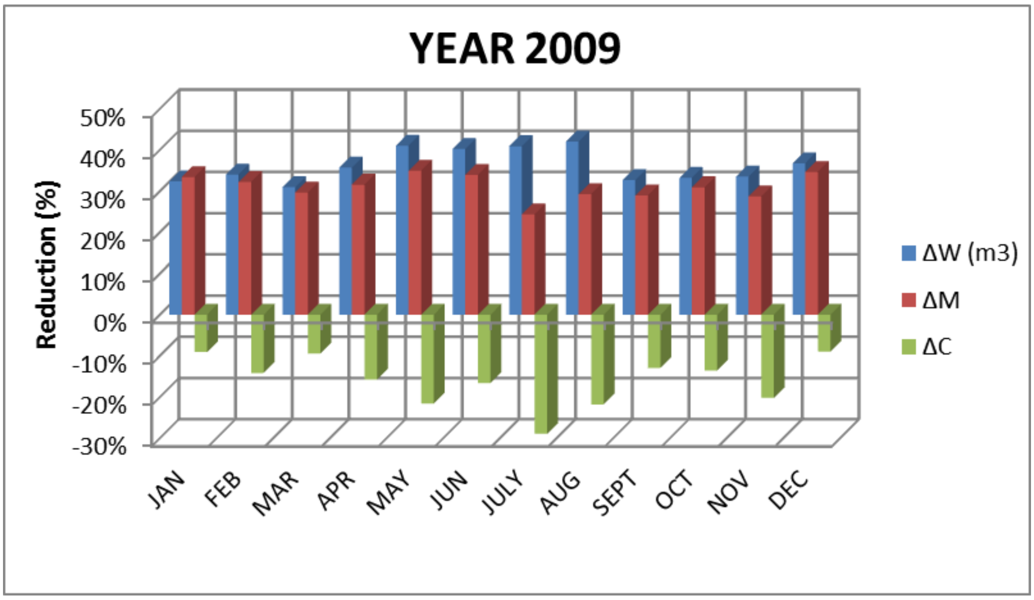


Fig. 5. 11 - Volumes, masses reduction and concentration increment for year 2009.

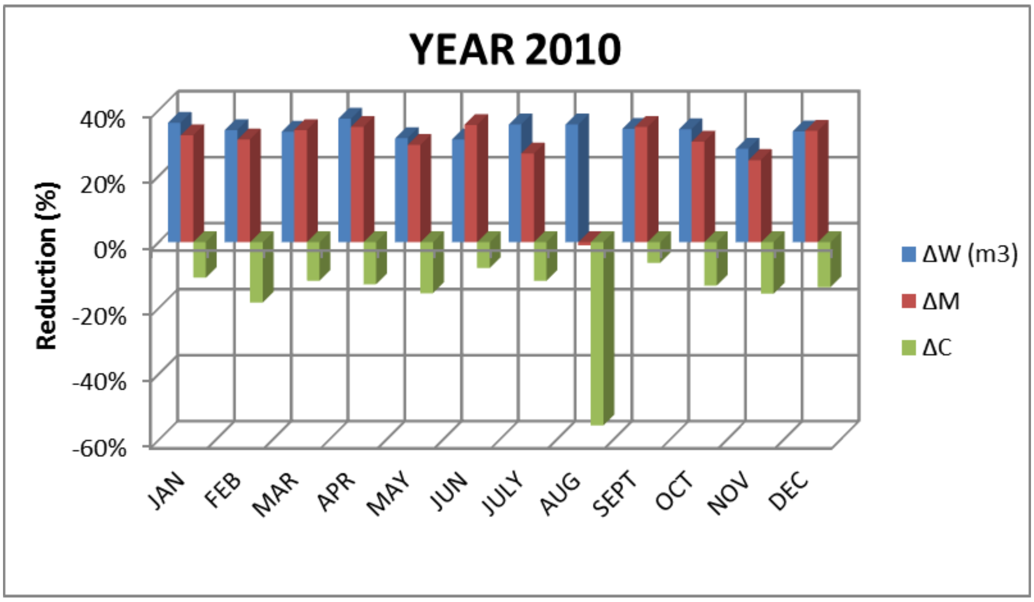


Fig. 5. 12 - Volumes, masses reduction and concentration increment for year 2010.

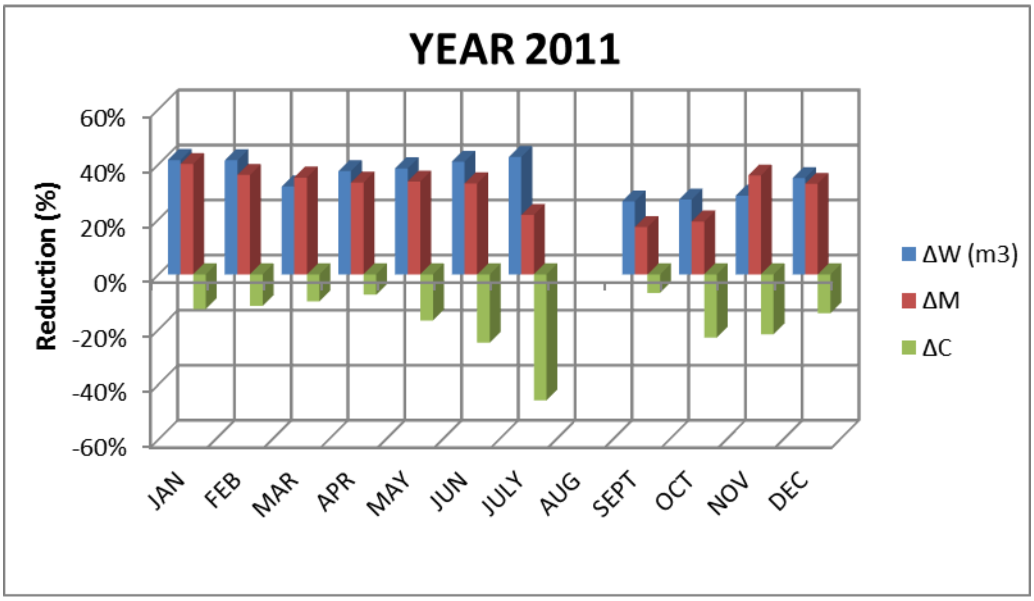


Fig. 5. 13 - Volumes, masses reduction and concentration increment for year 2011.

The performed analysis, carried out subjecting the catchment to an annual rainfall input, show how the percentage reduction of volumes into the network is around 35 % on average each year. Mass of Total Suspended Solids discharged is around 30 % on average while the relative concentration undergoes an increment around 15 %. The latter result looks quite unusual, because it was expecting to have also a reduction of concentration implementing more BMPs into the catchment. The explanation comes from the analysis of the algorithm used by SWMM to simulate the runoff quality behaviour (Fig. 5. 14). Normally the runoff flows superficially along the catchment; part of the stormwater infiltrates into the ground. The presence of BMPs increases the latter quote, decreasing runoff, therefore the mass of pollutants reaching the outlet.

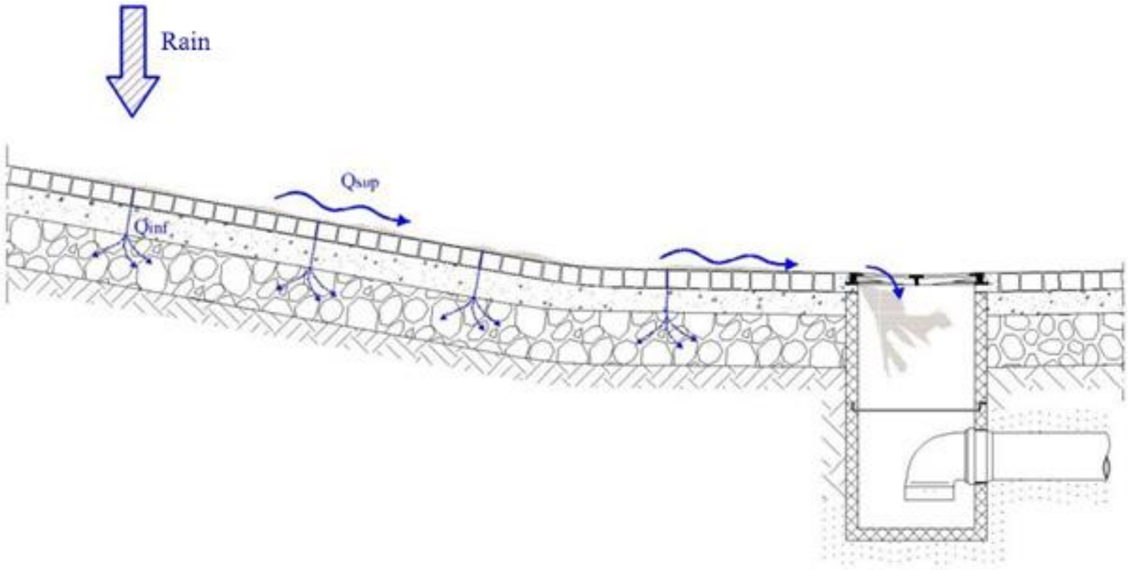


Fig. 5. 14 - Physical explanation of the EPA SWMM runoff quality algorithm.

SWMM takes into account of the reduction of pollutants only in terms of reduction of overland flow, converted by build-up and wash off formulas into discharged mass. Then, actually SWMM totally lacks of quality algorithms for LIDs simulation.

5.2.3 Continuous Simulations (4 years)

After the previous results, related to the annual simulations of the enhanced overland flow network, the same analysis has been repeated considering the pavement subjected to a continuous simulation, where the input rainfall data was only a single time series made from the single annual time series putted all together. This further step was necessary to examine the behaviour of the stormwater management practices affected by the clogging phenomenon. As stated in Chapter 4, currently SWMM take into account about clogging phenomenon only through a "*clogging factor*", defined as 'the total volume of treated runoff it takes to completely clog the bottom of the layer divided by the void volume of the layer'. Clogging progressively reduces the pavement's permeability in direct proportion to the cumulative volume of runoff treated. Based on the clogging formula proposed by SWMM and using the parameter in Tab. 5. 9, the clogging factor used for the porous pavement implemented into the Liguori Channel is

117.1 (dimensionless). As regards the green roof, no clogging factor has been calculated because, if properly designed, these practices should never clog during their lifespan.

Yclog	20 year	number of years it takes to fully clog the system
Pa	988.3 mm/year	annual rainfall amount over the site
CR	1	Pavement's Capture Ratio (area that contributes runoff to the pavement divided by area of the pavement itself)
VR	0.6	System's Void Ratio
ISF	0	Impervious Surface Fraction
T	450 mm	pavement layer thickness

Tab. 5. 9 - Value of parameters used to calculate the Clogging Factor for porous pavers falling into Liguori Channel.

Ultimately, in this case, three scenarios has been analysed: the two scenarios A and B described before with moreover the third 'SCENARIO C', made of overland flow network with LIDs subjected to the clogging of the porous pavers layer. The first analysis has been performed for the 'average year', whose values has been obtained as the average of the monthly values of the annual simulations. The results show a decreasing trend for the efficiency in terms of missing infiltrated volumes when the clogging phenomenon is considered (Tab. 5. 10).

	AVERAGE YEAR					
	LID avg (m^3)	NO LID avg (m^3)	Clog avg (m^3)	ΔW LID	ΔW Clog	Diff %
JAN	30471.90	47809.80	31846.95	36%	33%	3%
FEB	23559.15	36154.35	28945.65	35%	20%	15%
MAR	32476.65	47415.15	38610.30	32%	19%	13%
APR	13407.30	21298.80	19136.25	37%	10%	27%
MAY	9159.90	14277.15	12727.05	36%	11%	25%
JUN	8625.30	13203.75	12154.80	35%	8%	27%
JUL	1141.65	1827.00	1685.85	38%	8%	30%
AUG	350.55	596.25	571.65	41%	4%	37%
SEPT	20572.95	29626.65	26945.10	31%	9%	22%
OCT	21104.85	31569.45	29562.60	33%	6%	27%
NOV	29121.30	41426.55	39593.40	30%	4%	25%
DEC	32505.75	49032.90	47320.95	34%	3%	30%
Year	222497.25	334237.80	289100.55			
Max	32505.75	49032.90	47320.95			
RMSE	11777.10	17481.93	14966.28			
Mean	18541.44	27853.15	24091.71			

Tab. 5. 10 - Simulated results for the 'average year'.

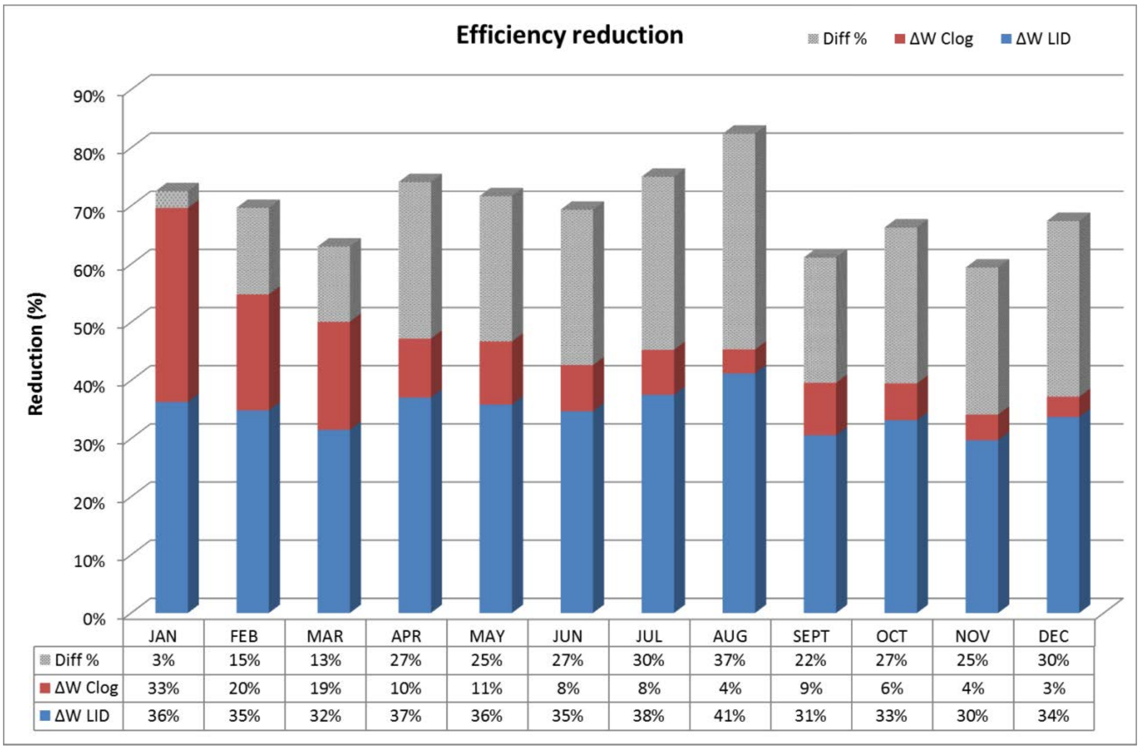
The efficiency has been calculated as follows. As regards the LID when void obstruction of the porous layer is not considered:

$$\Delta W\ LID = \frac{W_{NOLID} - W_{LID}}{W_{NOLID}} \cdot 100 \quad [\%]$$

while, when the clogging phenomenon is taken into account:

$$\Delta W\ Clog = \frac{W_{NOLID} - W_{Clog}}{W_{Clog}} \cdot 100 \quad [\%]$$

The results are more evident when plotted in a chart (Fig. 5. 15). It is more evident that, when no clogging effect is considered, the volumes efficiency reduction is kept almost constant around the 35 % (blue bars). Whereas, when the consecutive clogging of the porous layer of the pavement is taken into account, the efficiency decreases from 33 % in January to 3 % in December (red bars).



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
▨ Diff %	3%	15%	13%	27%	25%	27%	30%	37%	22%	27%	25%	30%
🟥 ΔW Clog	33%	20%	19%	10%	11%	8%	8%	4%	9%	6%	4%	3%
🟦 ΔW LID	36%	35%	32%	37%	36%	35%	38%	41%	31%	33%	30%	34%

Fig. 5. 15 - Efficiency reduction for the average year.

From the yearly simulation performed it is also possible to notice that, when the clogging of porous pavements is considered, the simulated volumes lie between the scenario without LIDs and the scenario with LIDs without clogging in each year (Fig. 5. 16, Fig. 5. 17, Fig. 5. 18, Fig. 5. 19).

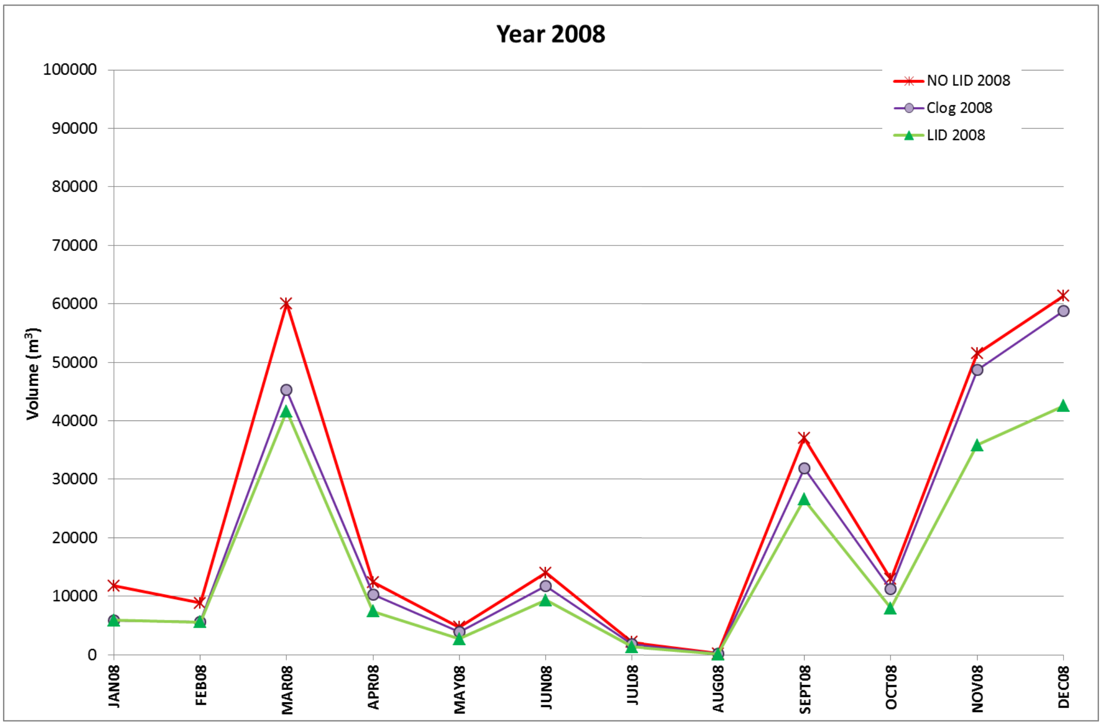


Fig. 5. 16 - Volumes trend for the annual simulation of 2008.

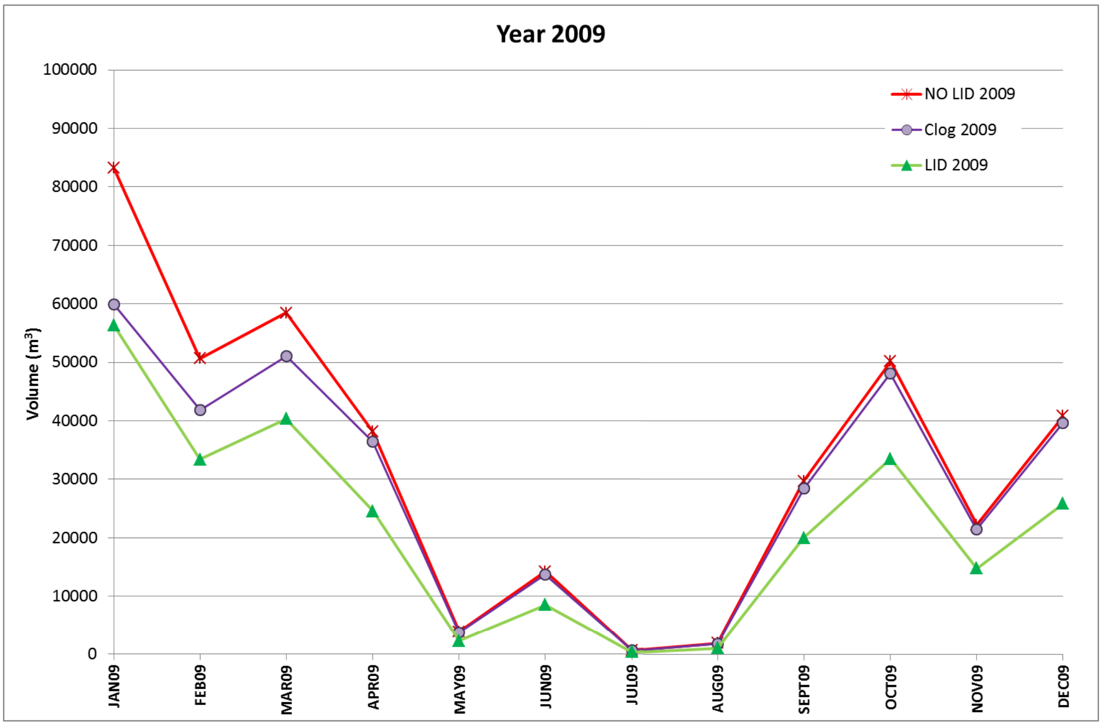


Fig. 5. 17 - Volumes trend for the annual simulation of 2009.

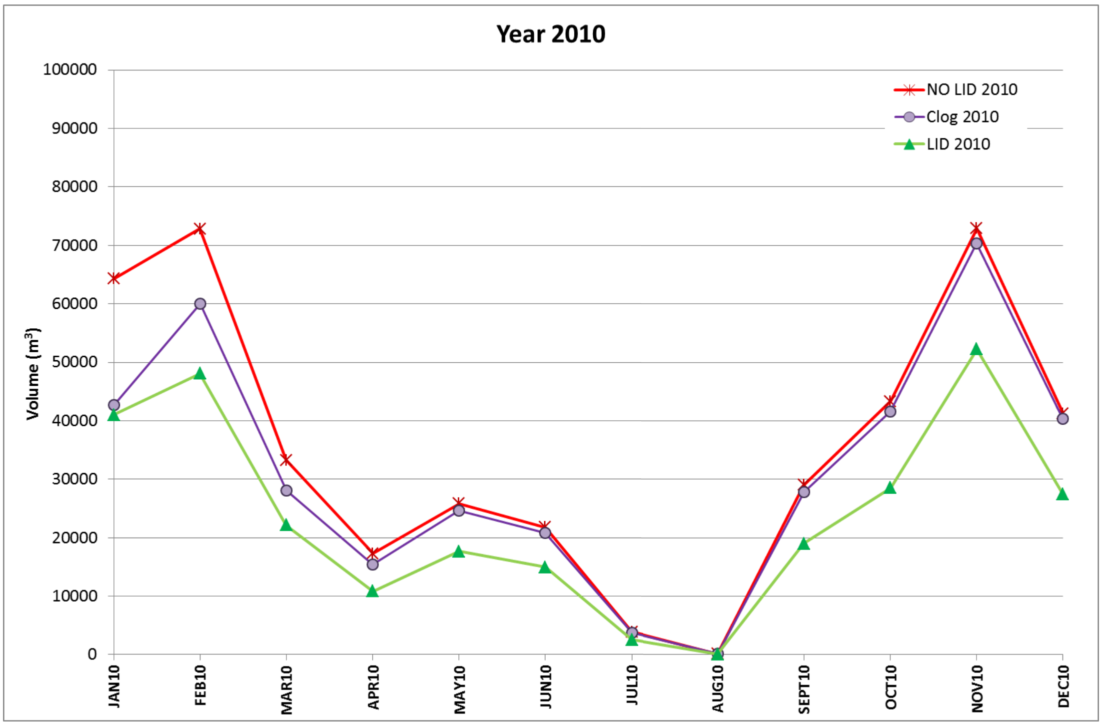


Fig. 5. 18 - Volumes trend for the annual simulation of 2010.

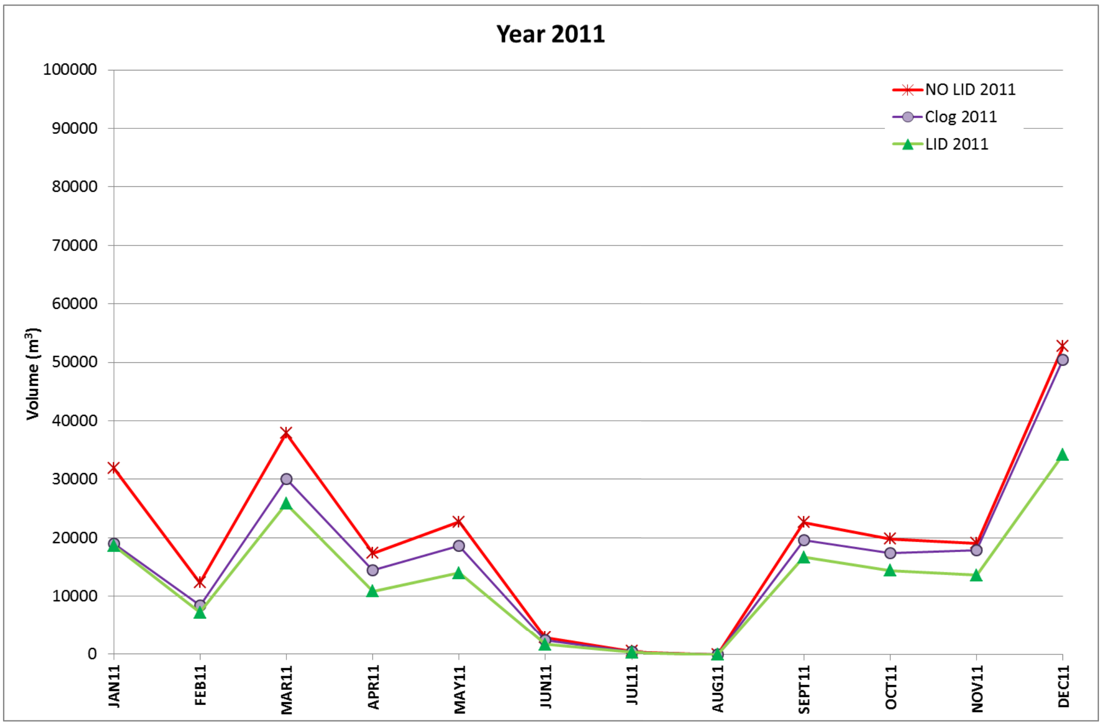


Fig. 5. 19 - Volumes trend for the annual simulation of 2011.

The situation is clearly different when a continuous simulation (4 years) is performed, considering the historical annual time series together (2008-2011).

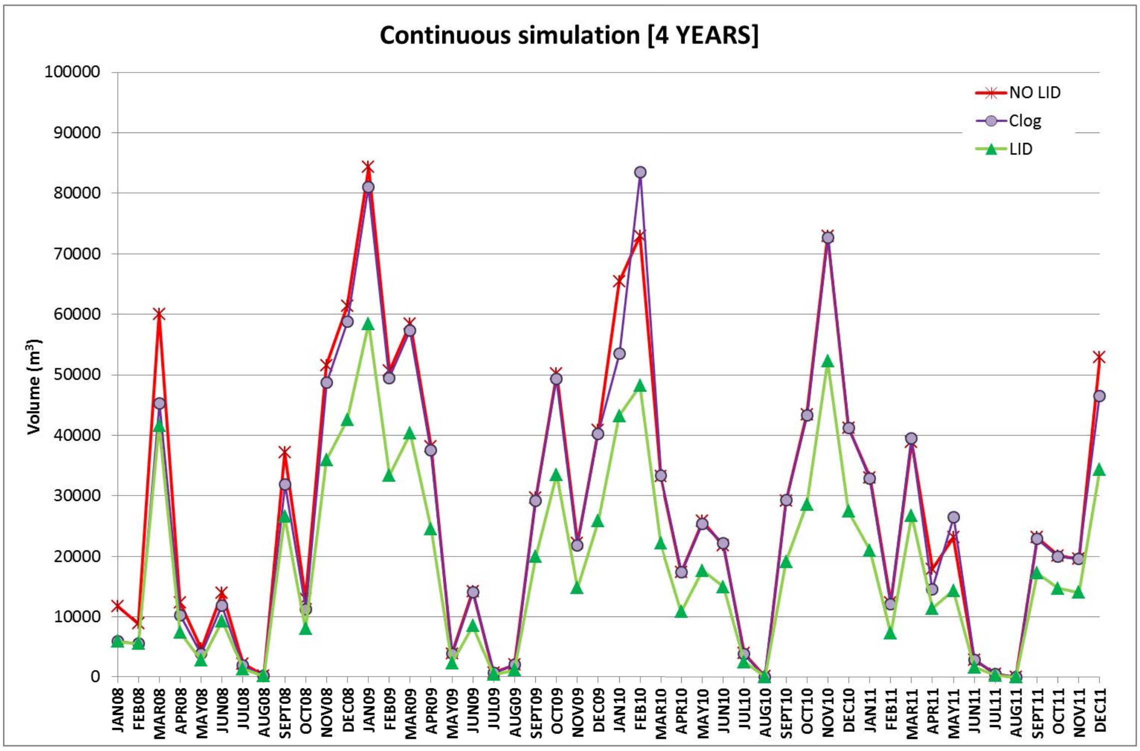


Fig. 5. 20 - Continuous simulation (2008-2011): volumes variation at outlet section.

As it is possible to notice during the first two years (2008, 2009), the simulated behaviour is similar to the annual trend, while the simulation 'LID with clogging' experiences an unexpected behaviour: during the months of February 2010, November 2010 and May 2011 the volumes of the clogged LID are even higher than the volumes occurring without any BMP implemented. This is an unexpected behaviour because even if the LID is totally clogged, the expected volume should be at most as same as the case without LID, never higher. But, as defined during the calculation of the clogging factor, the number of years the pavement takes to fully clog the system has been set to twenty then, it is not justifiable the system totally clog just after three/four years of simulation.

The presence of a strange behaviour is confirmed also by the plot of the efficiencies of the two cases, with and without LID, during the continuous simulation. In fact, again the rate of infiltrated runoff fluctuates around the 35 % for the scenario B (ΔW LID) while for scenario C, the efficiency reduction decreases from 50 % to 0 % during the simulated four years (Fig. 5. 21).

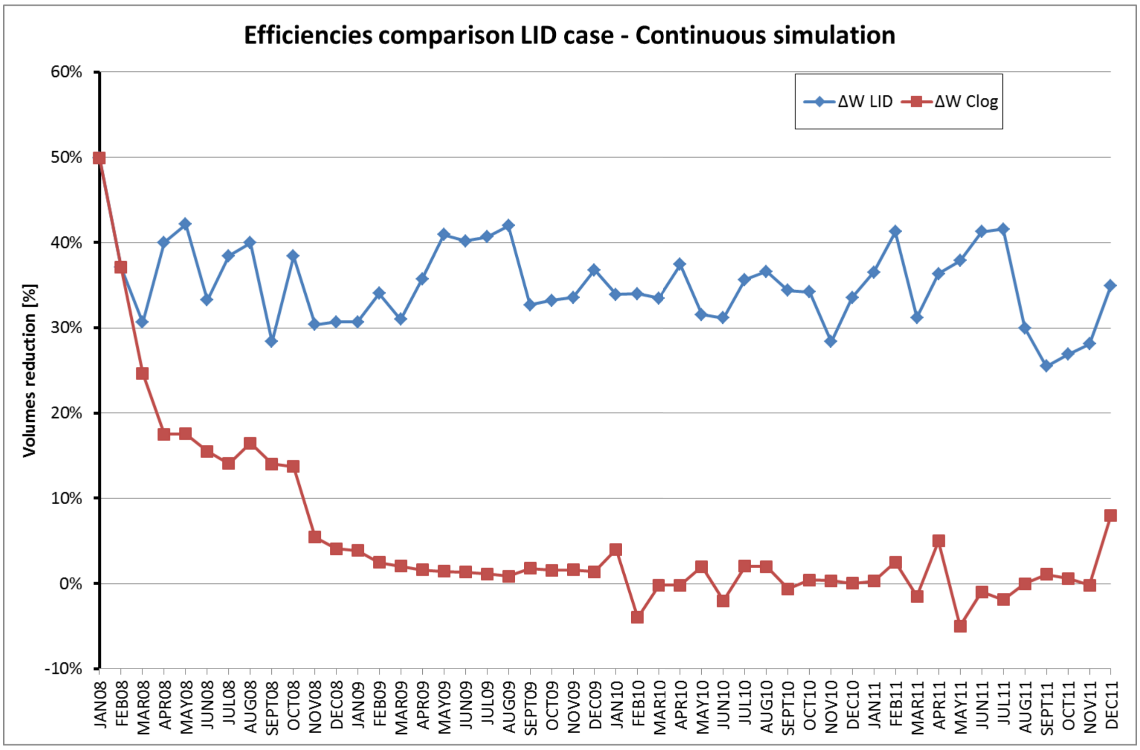


Fig. 5. 21 – Behaviour of the efficiencies of the infiltrated volumes during the continuous simulation.

In particular, the first two year (2008, 2009) are characterised by an exponential decay while, after that, the efficiency should be always constant to 0 %, without any strange trend. Instead, during the last two simulated years (2010, 2011), the efficiency varies in an unexpected way, causing the increment of the runoff volumes even above the case without BMPs implemented.

The performed simulations clearly show how the clogging phenomenon is erroneously interpreted by EPA SWMM. This led to an enhancement of the quality model used worldwide to predict the behaviour of the porous pavement installation. The porous pavement modelling has been carried out using the data collected into the experimental rig of the Monash University of Melbourne, as explained in the next paragraph.

5.3 Porous Pavement modelling

Although EPA SWMM results are interesting and indicative of LID operation, they are not very accurate, especially concerning the qualitative simulation of the stormwater management practices. The weird results in terms of clogging efficiency achieved particularly for continuous simulations, suggest the necessity of an improvement of the qualitative algorithm for all best management practices. In this research, the improvement effort has been done for porous pavement systems, that have been demonstrated to be one of the most easily retrofitting LID option within developed urban areas. Pervious pavements are a permeable pavement surface with an underlying stone reservoir that temporarily stores surface runoff before infiltrating into the subsoil (Ferguson, 2005). A pervious pavement structure includes a surface layer, a base and a sub-base to allow stormwater to percolate into the sub-grade or to divert into stormwater drainage while retaining pollutants on the paver surface. Depending on the purpose of the pervious pavement and the sub-grade soil conditions, a geotextile will be placed between the sub-base layer and the sub-grade soil to avoid pollutants percolating into the groundwater (Fig. 5. 22).

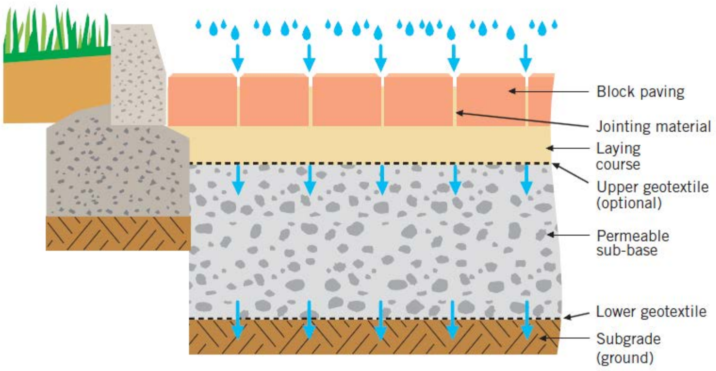


Fig. 5. 22 - A typical porous pavement cross-section – full infiltration case (Interpave, 2008).

All pervious pavements got similar sub-structural layouts. The thicknesses of different layers will be different according to geological conditions of the selected site. Furthermore, the sub-structure of pervious pavements will vary due to different pervious surface materials. There is a significant difference between porous and permeable pavements. Argue and Pezzaniti (2005) defined porous pavements and permeable pavements as follows. Porous pavements are a thick porous layer with a strong infiltration capacity. A porous pavement contains a grass or gravel surface with a well compacted graded sand and gravel base. On the other hand, permeable pavement surfaces are normally constructed by impervious paver concrete blocks with infiltration voids between the blocks. Infiltration capacities of permeable pavements are high due to the coarse aggregate between concrete blocks.

However, a porous pavement system replaces traditional pavement allowing runoff to infiltrate directly into the soil to receive water quality treatment (Yong et al., 2011).

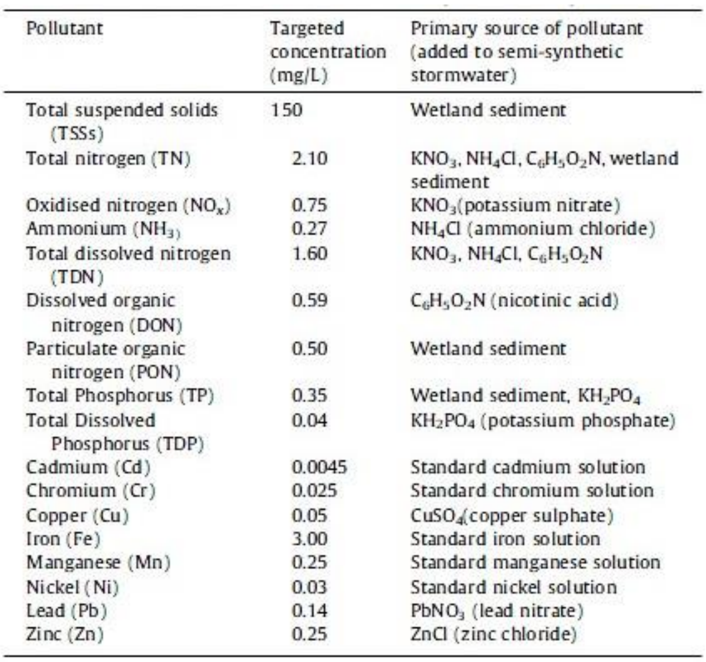
In order to assess the efficiency of different pervious pavement in reducing stormwater runoff and improve outflow stormwater quality a laboratory experiment has been conducted. Three different and widely used permeable pavement types has been compared to collect new information on the nature of pervious pavement clogging and the consequent treatment performance of these systems. The investigated systems were: monolithic porous asphalt (PA), modular Hydrapave (HP), and monolithic Permapave (PP). The test has been conducted into the Monash University laboratory (Melbourne, AU) in a compressed time scale, so that the wetting and the drying regimes have been emphasised in order to study the clogging process.

5.3.1 Laboratory experiment and data collection

The different porous pavers types were installed based on manufacturer guidelines in a 2.7 m x 0.45 m x 1.95 m rig, in three separate vertical compartments (Fig. 5. 23).

Fig. 5. 23 - The Monash University Melbourne experimental rig for the comparison of (from left to right) PA, HP and PP (Yong et al., 2011).

The rig included a 550 L tank with aerator coils and a pneumatic stormwater distribution system, which consists of a peristaltic pump and a rotating sprinkler to ensure a random and equal distribution of stormwater and sediments over the pavements (Yong C.F. and Deletic A., 2012). The mixture of pollutants used and their relative concentration were retrieved from samples collected into existent wetland areas in Melbourne. The obtained concentration has been compared with the 'typical' worldwide values accepted in literature and then, through a careful calculation, the correct amount of slurry to mix with water within the tank has been determined (Tab. 5. 11).



Pollutant	Targeted concentration (mg/L)	Primary source of pollutant (added to semi-synthetic stormwater)
Total suspended solids (TSSs)	150	Wetland sediment
Total nitrogen (TN)	2.10	KNO_3, NH_4Cl, $C_6H_5O_2N$, wetland sediment
Oxidised nitrogen (NO_x)	0.75	KNO_3(potassium nitrate)
Ammonium (NH_3)	0.27	NH_4Cl (ammonium chloride)
Total dissolved nitrogen (TDN)	1.60	KNO_3, NH_4Cl, $C_6H_5O_2N$
Dissolved organic nitrogen (DON)	0.59	$C_6H_5O_2N$ (nicotinic acid)
Particulate organic nitrogen (PON)	0.50	Wetland sediment
Total Phosphorus (TP)	0.35	Wetland sediment, KH_2PO_4
Total Dissolved Phosphorus (TDP)	0.04	KH_2PO_4 (potassium phosphate)
Cadmium (Cd)	0.0045	Standard cadmium solution
Chromium (Cr)	0.025	Standard chromium solution
Copper (Cu)	0.05	$CuSO_4$(copper sulphate)
Iron (Fe)	3.00	Standard iron solution
Manganese (Mn)	0.25	Standard manganese solution
Nickel (Ni)	0.03	Standard nickel solution
Lead (Pb)	0.14	$PbNO_3$ (lead nitrate)
Zinc (Zn)	0.25	ZnCl (zinc chloride)

Tab. 5. 11 - Targeted 'typical' pollutant concentrations in semi-synthetic stormwater that was used in the laboratory experiments (based on a review of worldwide data, Duncan, 1999; and Melbourne data, Francey et al., 2010; Taylor et al., 2005) – Yong et al., 2013.

Before commencing the real experiment, a series of hydraulic conductivity tests has been performed in order to assess the porosity of the three porous pavements systems with the filter layer unclogged. Then, the study has been conducted taking into account of sub-tropical Brisbane and Melbourne temperate climates under a variable drying/wetting regime. The inflow rates were retrieved from the frequency curve of a typical 10 year "effective" rainfall event for Brisbane. In correspondence of different percentile ranges, four flow rates has been chosen (A, B, C, D), and by multiplying each range with the relative average intensity an overall volume was obtained. The division of this volume with the average annual precipitation of Brisbane (1243 mm) determined the duration for each flow to simulate 1 year of rain (Tab. 5. 12). Considering the 4 flow rates, a total of 10 continuous wet weather days has been calculated to simulate 1243 mm of 1-year rainfall.

Frequency	Duration	Flow rate per ha.	Velocity	Velocity	Pavement area	Flow rate m^3/s	
Flow	(percentile range)	h	m^3/s	m/s	mm/h	m^2	m^3/s	mL/s
A	0–39	96	0.0006	5.8×10^{-8}	0.2	0.1564	9.0×10^{-9}	0.009
B	40–59	48	0.0029	2.9×10^{-7}	1.0	0.1564	4.5×10^{-8}	0.045
C	60–79	48	0.0071	7.1×10^{-7}	2.6	0.1564	1.1×10^{-7}	0.111
D	80–100	48	0.0609	6.1×10^{-6}	21.9	0.1564	9.5×10^{-7}	0.953

Tab. 5. 12 – Selection of flow rates from 10 year Brisbane rainfall time series (1988-1997) (Yong et al., 2011)

In addition, to study the rate of clogging under typical floods, a 1 in 5 year storm of 5 min duration in Brisbane (equivalent to a more than 1 in 100 year Melbourne storm) was selected; this represents the typical design storm where the porous pavers are likely to be developed.

The determination of the drying period were established performing a series of moisture loss tests. Different pavers samples has been collected. These samples were totally soaked with water and then left under atmospheric condition until a moisture loss of 80 % were reached. From the performed tests, an average period of 4 days was necessary to achieve the desired moisture loss. The same amount of moisture loss was achieved by using the fan heaters at temperature of 25 °C for 3 hours. From the analysis of the 10 years rainfall data of Brisbane, 21 dry events (dry for >= 4 days) were identified. To simulate all these events with 3 hours of fan heaters, 2.7 days are needed. Thence to simulate 1 year of drying/wetting regime in Brisbane, a total of 13 days are required. During the experiments the 4 flows were randomised, incorporating a drying event of 3 hours duration between each flow. Moreover, the 1 in 5 years storm has been inserted every 1 simulated month of experiment to replicate the conditions under which the systems may start to clog and cause flooding. The outflow rates has been continuously monitored at 1 min time intervals using the tipping-bucket rain gauges, checking the validity of the values with manual measurements under regular basis.

In total, 26 and 13 years of operation were simulated under Melbourne and Brisbane climate respectively.

About the water quality monitoring, an intense sampling regime has been conducted in which samples were collected from inflow and outflow and analysed for Total Suspended Solids (TSS), Total Phosphorus (TP), and Total Nitrogen (TN), in accordance with standard methods for the examination of water and wastewater (APHAAQQA-WPCF, 2005).

Moreover, for each sample, the particle size distribution (PSD) has been measured together with temperature and pH, in order to predict the behaviour of the metals in the system.

Clogging observations were made by regularly measuring the level of ponding above each pavement surface as they occurred. Each experiment continued until all the systems were clogged, defined as when ponding above the pavement surfaces were observed to overflow (30 mm above pavement surface), or when the outflow rate was 10 % of the initial outflow rate (Yong et al., 2013).

5.3.2 Data Analysis

The laboratory analysis of the collected sample allowed to obtain the inflow and outflow concentration of Total Suspended Solids (TSS), Total Phosphorous (TP) and Total Nitrogen (TN) for each permeable paver type. These data, together with the inflow (known) and outflow flow rates continuously monitored with a tipping-bucket rain gauges, has been rearranged with a 1 hour time step. Therefore, a correlation analysis has been performed in order to individuate the key variables affecting the porous pavement functioning. The magnitude of correlation between the analysed variables has been evaluated through the use of the Spearman coefficient, defined as the Pearson correlation coefficient between the ranked variables. For a sample of size *n*, the *n* raw scores X_i, Y_i are converted to ranks x_i, y_i, and ρ_s is computed from these:

$$\rho_s = \frac{\sum_i (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_i (x_i - \overline{x})^2}\sqrt{\sum_i (y_i - \overline{y})^2}}$$

Identical values (rank ties or value duplicates) are assigned a rank equal to the average of their positions in the ascending order of the values. It assesses how well the relationship between two variables can be described using a monotonic function. If there are no repeated data values, a perfect Spearman correlation of +1 or −1 occurs when each of the variables is a perfect monotone function of the other (Wikipedia, 2013).

The regression analysis has been performed between the measured output concentration and other variables (Tab. 5. 13):

- measured input concentration [mg/L], that is a common parameter of many different formulation used to predict the pollutant concentration;
- hydraulic loading *q* [ml/min], to take into account of the instantaneous flow rate flowing over the pavement;
- cumulative flow rates every 6 (q_6), 12 (q_{12}) and 24 (q_{24}) hours before the sampling time, to take into account about the historical drying/wetting regime the pavement has been subjected;
- cumulative inflow volumes ($\sum Vol\ In$) and cumulative trapped masses (*Acc.Mass*), that influence the clogging behaviour of the media filter.

Porous Asphalt (PA)							
	Input Conc	**Wet**	**History**			**Clogging**	
Pollutant	*[mg/L]*	*q [ml/*	*q6 [ml/*	*q12 [ml/*	*q24 [ml/*	*∑Vol In (L)*	*Acc.Mass [g]*
TSS Out	*0.33*	**0.56**	**0.57**	**0.58**	*0.49*	0.23	0.23
TP Out	*0.40*	0.28	*0.32*	*0.33*	*0.31*	*0.49*	*0.49*
TN Out	-0.20	*-0.42*	*-0.40*	*-0.44*	*-0.39*	-0.20	-0.20
HydraPave (HP)							
	Input Conc	**Wet**	**History**			**Clogging**	
Pollutant	*[mg/L]*	*q [ml/*	*q6 [ml/*	*q12 [ml/*	*q24 [ml/*	*∑Vol In (L)*	*Acc.Mass [g]*
TSS Out	*0.39*	**0.58**	**0.57**	**0.56**	**0.50**	0.15	0.15
TP Out	0.29	**0.60**	**0.62**	**0.63**	**0.61**	**0.54**	**0.54**
TN Out	*-0.31*	**-0.56**	**-0.57**	**-0.53**	**-0.52**	*0.40*	*0.40*
PermaPave (PP)							
	Input Conc	**Wet**	**History**			**Clogging**	
Pollutant	*[mg/L]*	*q [ml/*	*q6 [ml/*	*q12 [ml/*	*q24 [ml/*	*∑Vol In (L)*	*Acc.Mass [g]*
TSS Out	0.27	*0.41*	*0.39*	*0.41*	0.24	-0.15	-0.15
TP Out	*0.42*	**0.67**	**0.66**	**0.69**	**0.62**	0.26	0.26
TN Out	-0.07	*-0.39*	*-0.39*	*-0.36*	*-0.40*	*0.37*	*0.37*

Tab. 5. 13 - Table of Spearman's correlation coefficients for the individuated key variables.

As shown by the table, for Porous Asphalt, the higher magnitude of correlation is with the hydraulic loading and the cumulative flow rate q_6 and q_{12} for both TSS and TN (in this latter case the values of Spearman's coefficients are negative, indicating an inverse proportionality between these variables and the measured output concentration); TP does not show a strong correlation with the hydraulic loading or the historical flow regime, but it appears to be more influenced by the clogging phenomena. HydraPave shows an higher correlation for all pollutants with all considered variables and, also, it is greatly influenced by the degree of clogging of the system. The Permapave system shows a strong correlation with the instantaneous flow rate and its cumulative value, while it is not affected by the degree of clogging. This theoretical results is coherent with the laboratory results, because ponding in Permapave was not observed (Yong et al., 2013).

According to these results, the key variables selected to better describe the physical functioning of the porous pavements were: the cumulative flow q_{12} every 12 hours before the sampling time and the cumulative inflow volume $\sum Vol\ In$, in each time step, during the whole simulation. These variables affect the prediction of the pollutant concentration in output as well as the magnitude of clogging of the porous layer during time, as shown below.

5.3.3 k-C* Model

An efficient formula to predict the pollutant concentration at the outlet of a porous pavement cannot disregard of the physical mechanisms that happen inside it. One of these mechanisms, affecting all kinds of infiltration practices, is the potential clogging due to sediments conveyed into the overland flows, which can lead to reduced performance and eventually system failure. The loss of performance due to clogging into porous pavement is one of the major disadvantages that blocks their wide implementation (Galli, 1992; Nozi et al., 1999). Despite this is a well-known problem, the processes that govern this phenomenon are not well understood yet. The few relatively simple models available representing the clogging process for infiltration systems present some drawbacks such as a limited predictive potential of the clogging variability with time (Furumai, 2005) or a limited representation of the antecedent conditions (Dechesne et al., 2002; Dechesne et al., 2004; Le Coustumer and Barraud, 2007). A unified stormwater treatment model able to describe a range of stormwater treatment measures – including wetlands, ponds, infiltration systems and vegetated swales – has been presented by Wong et al., 2006. The model has been incorporated into a software package called Model for Urban Stormwater Improvement Conceptualization (MUSIC) (see Ch. 4.2.5) (Cooperative Research Centre for Catchment Hydrology, 2005), which is used by urban water managers to evaluate and prioritize stormwater treatment strategies based on predicted hydrologic and water quality outcomes. The model describes the water quality behaviour with a first-order kinetic decay formulation named "k–C* model" (see Ch. 3.7). Due to the successful application of this model to simulate many different infiltration practices, it has been selected also, as a first attempt, for porous pavement in order to test its validity in this case.

Thence, the measured output concentration for TSS, TP and TN has been modelled using the k-C^* model:

$$C_{out} = C^* + \left[\left(C_{in} - C^* \right) \cdot e^{-k \cdot \frac{L}{q}} \right]$$

where C_{out} is the output sediment concentration (mg/L), C_{in} is the input sediment concentration (mg/L), q is the hydraulic loading (m/year), L is the filter length (m), C^* is the background sediment concentration (mg/L), k is the decay rate constant (m/year).

To assess the predictive power of this formula, the Nash–Sutcliffe model efficiency coefficient has been used. The Nash-Sutcliffe Efficiency (NSE), proposed by Nash and Sutcliffe (1970), is widely adopted in the Anglo-Saxon world to evaluate behaviour and performance of the hydrologic models.

It is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Krause et al., 2005):

$$NSE = 1 - \frac{\sum \left(Conc_{Out}\, real - Conc_{Out}\, sim \right)^2}{\sum \left(Conc_{Out}\, real - \overline{Conc_{Out}\, real\, avg} \right)^2}$$

NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values < 0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi et al., 2007).

Then, the k-C* model has been validated versus the measured data in order to estimate the values of the calibration coefficients (k and C*) capable to maximise the value of the Nash Sutcliffe efficiency coefficient. Two kinds of calibration has been performed:

- Single calibration: the historical time series (outflow rates and concentration) for each pavers type has been individually considered and calibrated, obtaining 3 sets of parameters for each pollutant;

- Multiple calibration: for each pollutant, all available data coming from the three different porous pavement type has been considered as a single time series to be calibrated, obtaining 1 set of parameters each one.

To calibrate the model in both cases and for each time series, a Monte Carlo Markov Chain (MCMC) simplified analysis has been performed (Bolstad W.M., 2010). A uniform distribution was assumed as prior distribution for all parameters and their lower and upper limits were chosen according to precalibration information. In fact, a first estimate of the parameters was retrieved using Excel Solver® then, a Monte Carlo algorithm has been implemented in Matlab™ and left running for $1x10^{6}$ iterations, in order to get the best set of parameters maximising the NSE coefficient (Tab. 5. 14).

```
%Set up and Run a Monte Carlo simulation picking up random samples
%generated from a uniform distribution for each parameter.
%
%n= number of run of Monte Carlo (i.e. 100000 runs)
clear all;
clc;

n= 1000000; %Set here number of runs
disp(['>>>>>> Number of runs: ->->-> ', num2str(n)]);

% >>> Create arrays with random Values:
disp('>>>>>> Creating arrays with random Values... >>>>>> ');
%r= a +(b-a).*rand(n,1); with a=min,b=max bounds
a = zeros(n,1); %set '0' for TSS simulations
b = 1.5 +(4-1.5).*rand(n,1);
B = 9E-09 +(1E-02 - 9E-09).*rand(n,1);
k = 1E-05 +(1E-02 - 1E-05).*rand(n,1);

% Real values for Porous Asphalt
areaPav = 0.1564; %area of pavement
L = 0.685; %filter depth

% >>> Open Data file:
disp('>>>>>> Open Data File... >>>>>>');
file='data.txt';
fid = fopen(file);
buffer = fgetl(fid); %remove header row
C = textscan(fid, '%s %s %u %f %s %f %f %f %f');
fclose(fid);

% >>> Define Variable:
% cum_hours = C{3};
% week = C{4};
flowt = C{5}; %text flows
flowIN = C{6}; %numeric flows
volOUT = C{7}; %volumes
concINMeas = C{8}; %measured concentration in input
concOUTMeas = C{9}; %measured concentration in output

disp('>>>>>> Calculating constant quantities... >>>>>>');
```

```
%
% Convert flowIn in [mm/h]
QIn=(flowIN./areaPav)*(60/1000);

% Calculate VolIn in [L]
VolIN=flowIN.*(6/1000);

% Calculate q in [m/year]
q=flowIN.*(60*24*365/1000000/areaPav);

% Calculate q12 in [m/year]
q12=zeros(size(QIn));

for i=2:numel(q12)
    if i <= 120
        q12(i) = sum(QIn(1:i)*6)/((i-1)*6)*(24*365/1000);
    else
        q12(i) =(sum(QIn(i-120:i))*6)/(12*60)*(24*365/1000);
    end
end

% Calculate cumulative volumes in [m]
sumVolIN=((cumsum(VolIN))/(1000*areaPav));

% >>> Running Monte Carlo:
disp('>>>>>> Running Monte Carlo... >>>>>> ');
Ens=size(n);
for i=1:n

Ens(i)=MainF(a(i),b(i),B(i),k(i),L,flowt,q,q12,concINMeas,sumVolIN,...
        volOUT,concOUTMeas); %MainF: custom function
end

Ens2=Ens';
clear Ens;
MaxEns=max(Ens2);
BigMatrix=[a,b,B,k,Ens2];
del = char(9); %variable to add tabulation between label into results
file

% >>> Create file with results:
disp('>>>>>> Saving file "ResultsMC.txt"... >>>>>> ');
fid = fopen('ResultsMC.txt', 'wt+'); %'wt+' option allow create new
txt file!
fprintf(fid, '%s \r\n', 'Matrix of Results');
fprintf(fid, '%s %u \r\n', 'Number of runs: ', n);
fprintf(fid, '%s %5.3f \r\n', 'Max Ens: ', MaxEns);
fprintf(fid, '%s \r\n', '/-----------------------------------/');
%Print Label
fprintf(fid, '%s \r\n', ['a' del del 'b' del del 'B' del del...
    'k' del del 'Ens']);
%Print BigMatrix
dlmwrite('ResultsMC.txt', BigMatrix,'-append','delimiter','\t',...
    'precision', '%10.7f', 'newline','pc');
fclose(fid); %close file
disp('>>>>>> DONE <<<<<<');
```

Tab. 5. 14 - Matlab script implementing the Monte Carlo approach.

Each iterative simulation has taken approximately 10 hours, after which the right set of parameters has been obtained with the relative Nash-Sutcliffe coefficient and reported in the tables below (Tab. 5. 15; Tab. 5. 16):

	Porous Asphalt (PA)			***Hydrapave (HP)***			***Permapave (PP)***		
Pollutant	**C***	**k**	**E_{ns}**	**C***	**k**	**E_{ns}**	**C***	**k**	**E_{ns}**
TSS	5.17E+00	4.04E+03	**0.51**	3.38E+00	6.20E+03	**0.49**	7.72E+00	9.55E+03	0.10
TP	2.67E-01	2.08E+03	-0.13	2.32E-01	2.44E+03	0.31	2.32E-01	2.74E+03	0.33
TN	2.11E+00	2.31E+03	-1.80	2.42E+00	8.01E+03	-1.21	2.43E+00	1.31E+04	-0.88

Tab. 5. 15 - Calibration coefficients and relative Nash-Sutcliffe Efficiency (Ens) for the k-C* model, single calibration.

	PA+HP+PP		
Pollutant	**C***	**k**	**E_{ns}**
TSS	5.50E+00	6.49E+03	0.22
TP	2.43E-01	2.45E+03	0.11
TN	2.33E+00	5.35E+03	-1.07

Tab. 5. 16 - Calibration coefficients and relative Nash-Sutcliffe Efficiency (Ens) for the k-C* model, multiple calibration.

It is possible to notice how the k-C* model seems to work quite well for the estimate of Total Suspended Solids for Porous Asphalt, Hydrapave and Permapave. Relatively good results were achieved also for the modelling of the Total Phosphorous, at least for HP and PP. The model, however, shows its inefficiency for modelling of the behaviour of Total Nitrogen for all porous pavements types. As regards the multiple calibration, Nash-Sutcliffe efficiency coefficients are only discreet for TSS and TP, while the negative value for TN confirms that the model is not suitable for the modelling of this pollutant. Moreover, low coefficients for TSS and TP appear indicating a strict correlation of the phenomenon with the physical characteristics of each pavement type, suggesting that a modelling fully independent from these is not reliable.

The analysis of the graphical trends (Fig. 5. 24 ÷ Fig. 5. 32) show also, for the k-C* model, an underestimation of the concentration peaks in correspondence of the ‘Storm’ events and a general overestimation of others concentration values in correspondence of low flows for every pollutant and permeable pavers type. Moreover, the model shows an important limit because the predicted concentration is always the same in correspondence of the same input flow, meaning that the antecedent drying/wetting conditions (namely the pavement clogging conditions) are not considered.

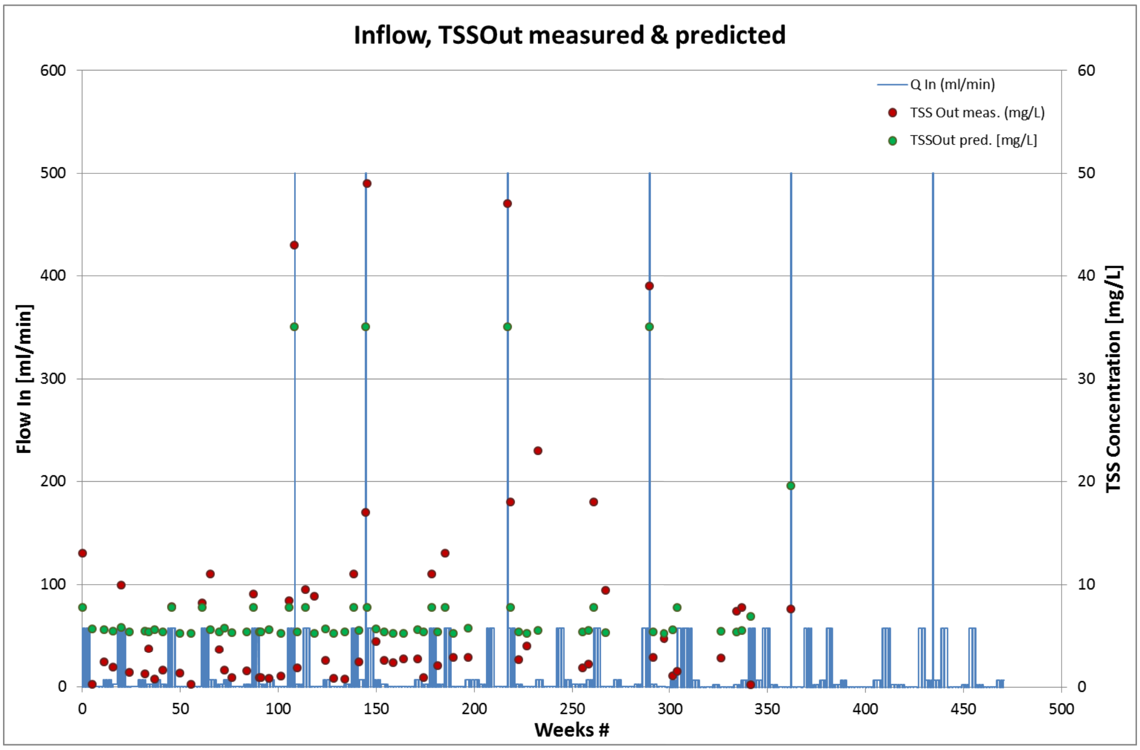


Fig. 5. 24 - Graph of measured and predicted TSS concentration for Porous Asphalt with k-C* model.

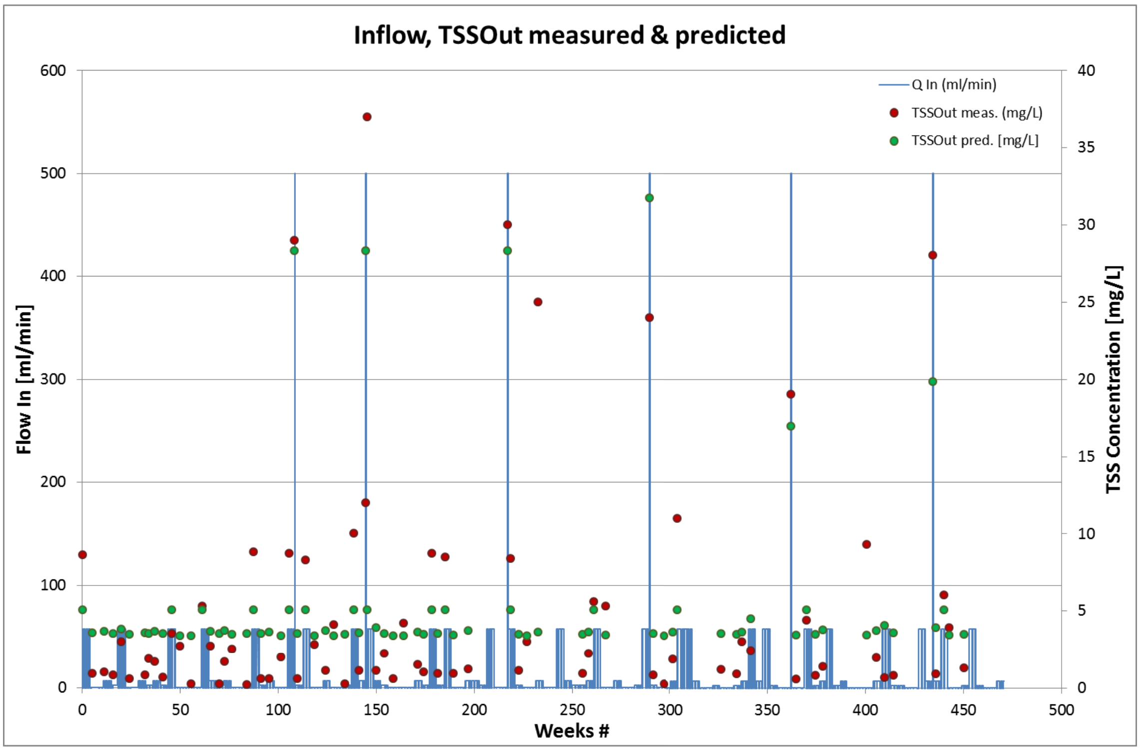


Fig. 5. 25 - Graph of measured and predicted TSS concentration for HydraPave with k-C* model.

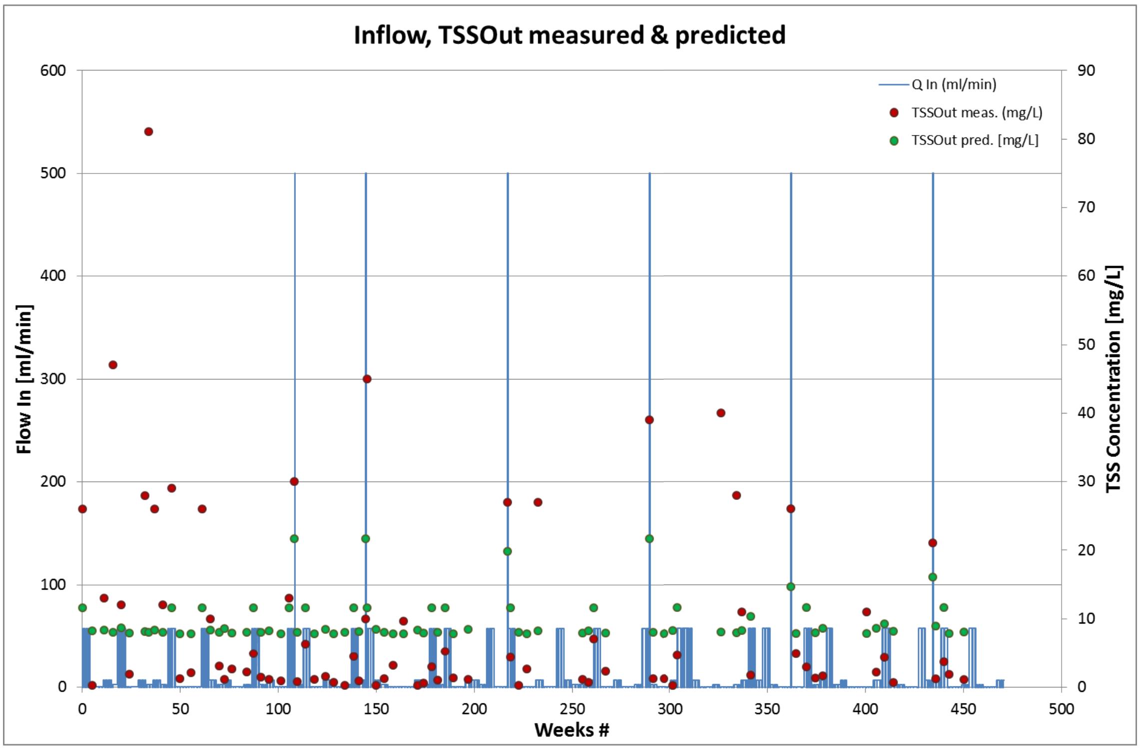


Fig. 5. 26 - Graph of measured and predicted TSS concentration for Permapave with k-C* model.

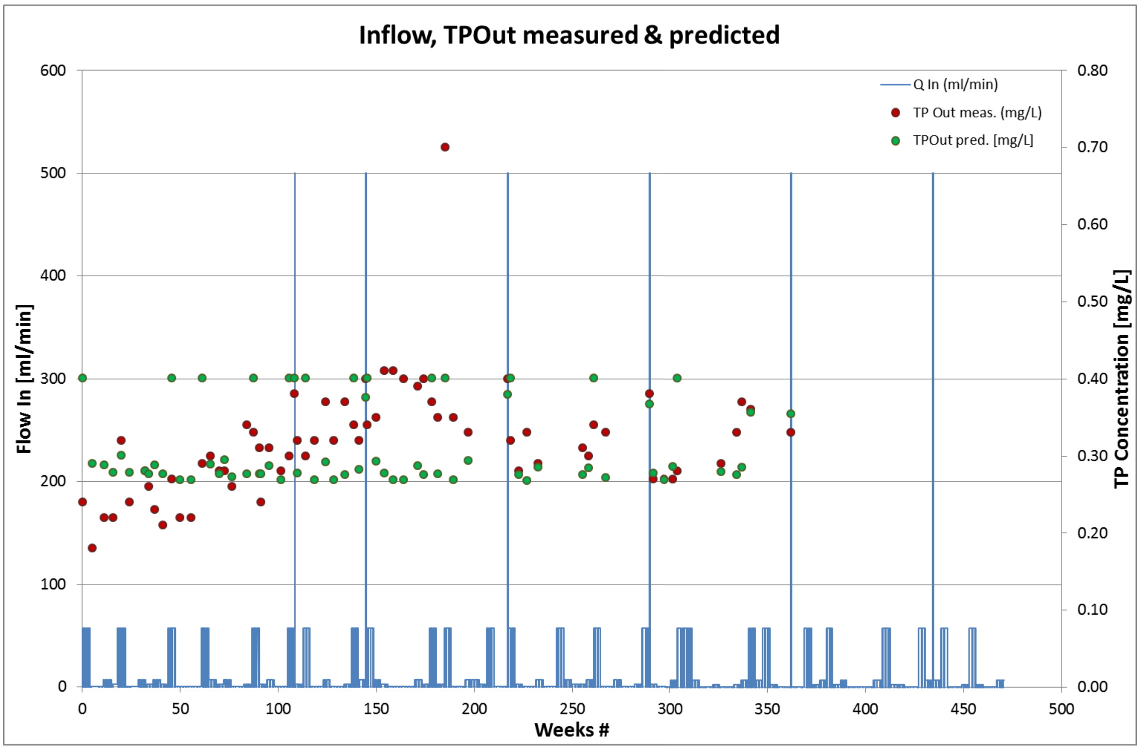


Fig. 5. 27 - Graph of measured and predicted TP concentration for Porous Asphalt with k-C* model.

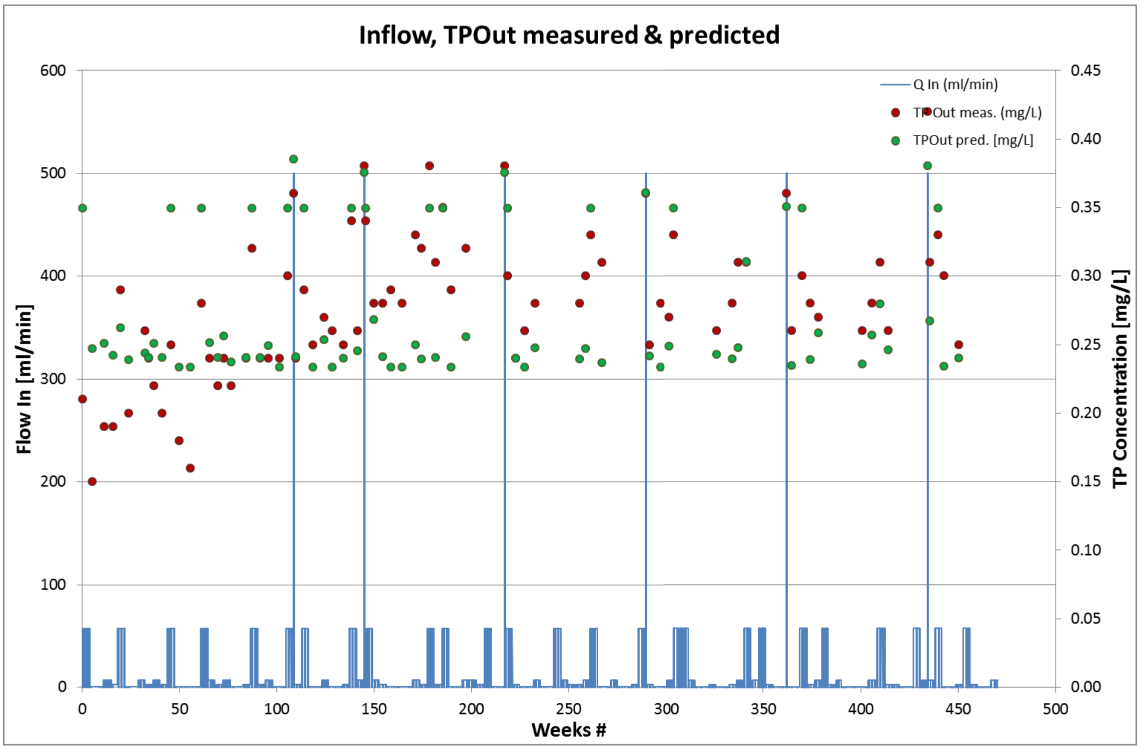


Fig. 5. 28 - Graph of measured and predicted TP concentration for HydraPave with k-C* model.

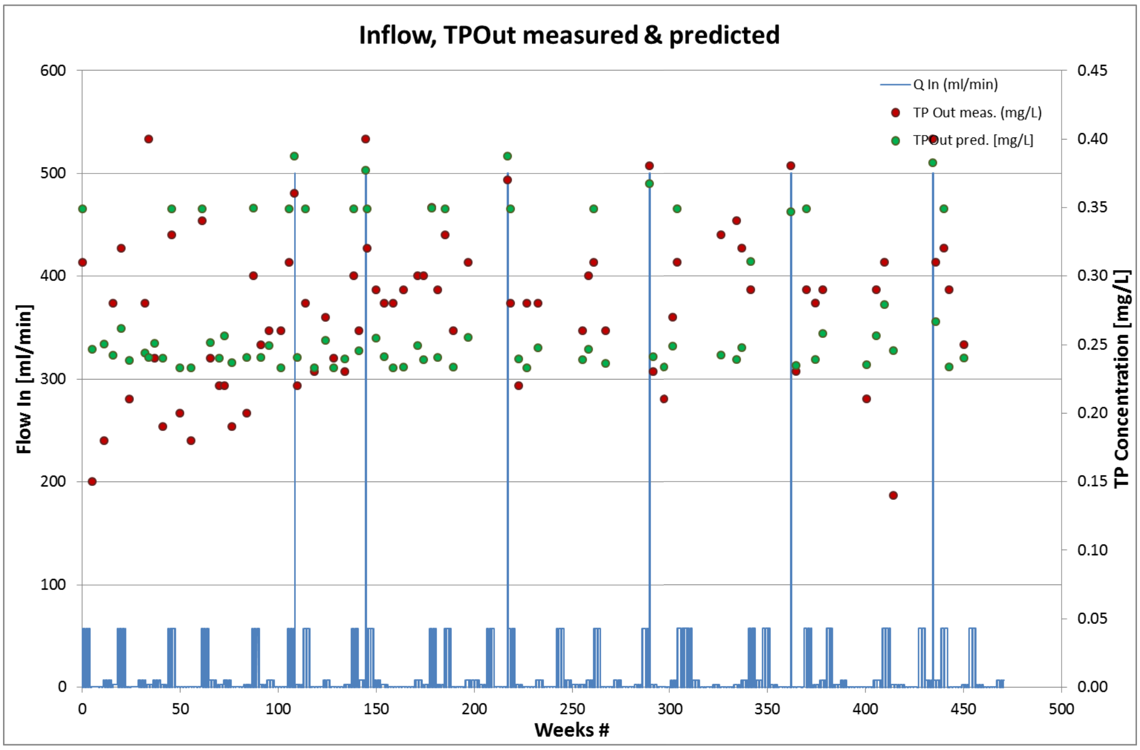


Fig. 5. 29 - Graph of measured and predicted TP concentration for Permapave with k-C* model.

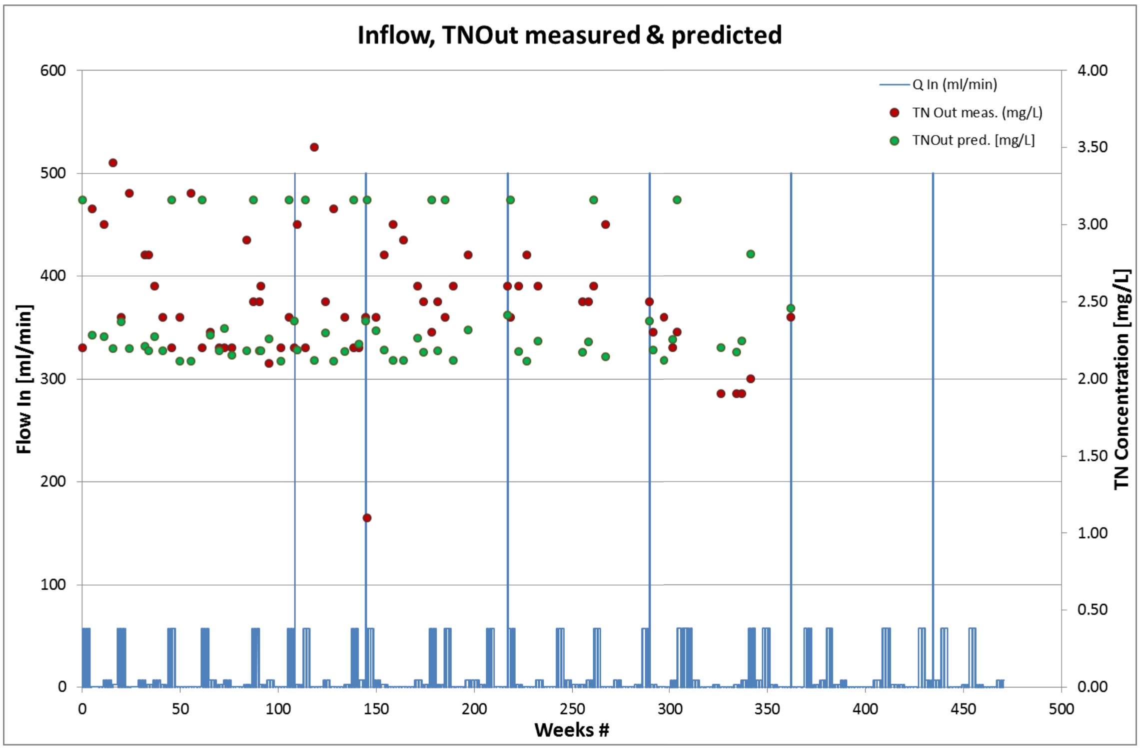


Fig. 5. 30 - Graph of measured and predicted TN concentration for Porous Asphalt with k-C* model.

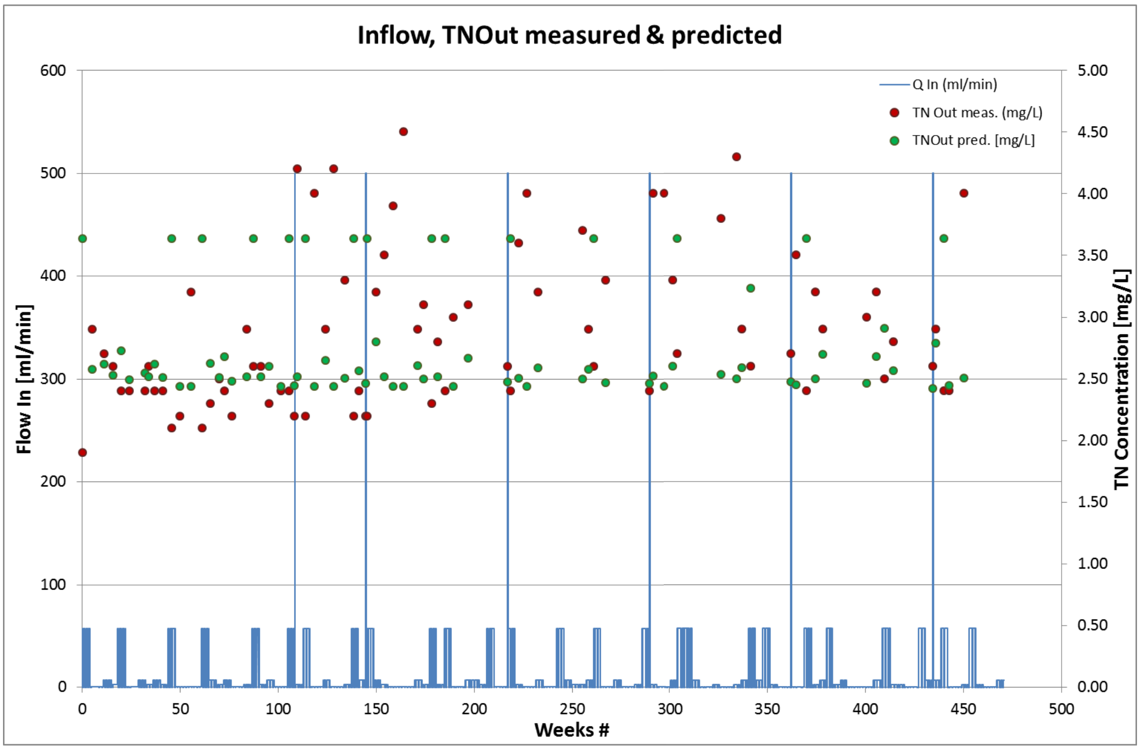


Fig. 5. 31 - Graph of measured and predicted TN concentration for HydraPave with k-C* model.

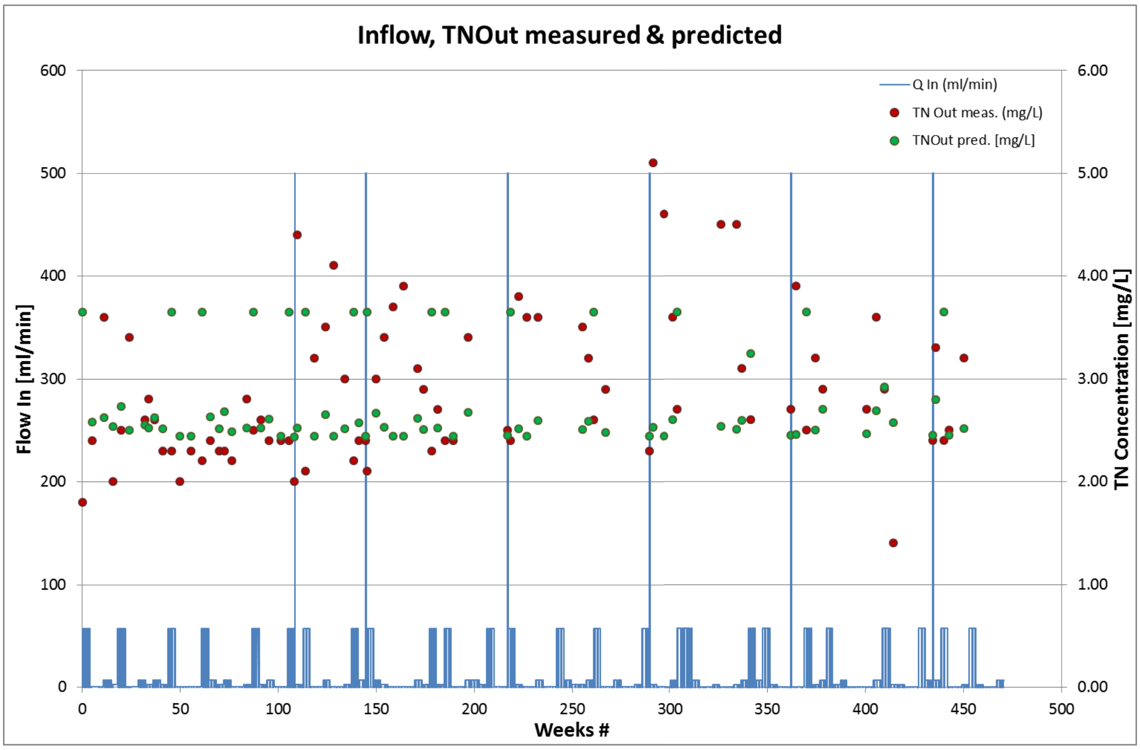


Fig. 5. 32 - Graph of measured and predicted TN concentration for Permapave with k-C* model.

5.3.4 New proposed shapes

Modelling results for k-C* model were quite disappointing. The graphic tendencies illustrate the limits of the model more than the Nash-Sutcliffe coefficient itself. In fact, the calculated efficiencies show a good behaviour of the model just for Total Suspended Solids and, partially, for Total Phosphorous while the performance prediction for the Total Nitrogen are very poor. However, the analysis of the graphic trend for all pollutants reveals that the answer of the model is always the same for the same input flow, independently from the temporal interval when it occurs. This highlights that the k-C* model it is able to reliably predict the sediment transport only in clean filter layers, but failed to predict sediment behaviour in aging (clogged) layers (Siriwardene et al., 2007).

Therefore it is clear that a new formulation it is necessary to correctly predict the pollutant concentration at porous pavements outlet. Based on the previous correlation analysis performed (§ 5.3.2) the key variables regulating the clogging behaviour into permeable pavements were identified (q_{12} and $\sum Vol\ In$). A series of attempts has been done in order to modify the k-C* model or create a new empirical model able to successfully simulate the clogging phenomenon through the inclusion of these new parameters. In every case, a subsequent Monte Carlo calibration has been applied in order to maximise the Nash-Sutcliffe Efficiency and finally, only formulations with the higher NSE has been selected and proposed for the simulation of the different pollutants behaviour into the varies types of pavement.

Total Suspended Solids – Shape 1

In order to model Total Suspended Solids (TSS) into the three different porous pavement types, the following formulation is proposed:

$$C_{out} = C^* + \left\lfloor \left(C_{in} - C^*\right) \cdot e^{-k \cdot L \cdot \left(\frac{1}{q} + \frac{1}{q_{12} \cdot B}\right)} \right\rfloor$$

This formula, defined hereinafter as ‘Shape 1’, it is a modification of the k-C* model where all symbols have the same meaning but it is present the new term ($1/q_{12} \cdot B$), with the presence of the cumulative flow every twelve hours q_{12} and a new calibration coefficient B.

Total Phosphorous – Shape 2

The modelling of the Total Phosphorous (TP) into the various permeable pavers has been performed through the proposed formula:

$$C_{out} = (a \cdot \Sigma V^b) + \left(C_{in} - (a \cdot \Sigma V^b)\right) \cdot e^{-k \cdot \frac{L}{q}}$$

This model represents, also, a modification of the original k-C* model. All symbols maintain the same meaning, while for the background sediment concentration a power law function has been hypothesized: $C^* = a \cdot \Sigma V^b$. The three calibration coefficients are: a, b, and k.

Total Nitrogen – Shape 3

For the modelling of the Total Nitrogen (TN) behaviour within the different permeable paving types, this formula is proposed:

$$C_{out} = a \cdot \frac{q}{L \cdot C_{in}} + B \cdot \left(\frac{\Sigma Vol}{q_{12}}\right)^b$$

The third formulation, hereinafter called 'Shape 3', is completely original due to the different behaviour of the TN compared with other pollutants. Within the formula appear the classic parameter C_{out}, output sediment concentration (mg/L), C_{in}, input sediment concentration (mg/L), q, hydraulic loading (m/year), L, filter length (m) and the ratio between the cumulative inflow volumes $\sum$Vol and the cumulative flow every 12 hours q_{12} to take into account about the clogging phenomena. a, b and B are three lumped parameters that need to be calibrated for each porous pavement system.

5.4 Results and discussion

The tables below show the results of the calibration performed for the three proposed shapes. For each formulation, values of the calibration parameters are listed, together with the correspondent Nash-Sutcliffe coefficient for both single (Tab. 5. 17; Tab. 5. 18; Tab. 5. 19) and multiple calibration (Tab. 5. 20).

	Porous Asphalt (PA)			
Pollutant	**C***	**B**	**k**	**E_{ns}**
TSS (Shape 1)	3.84E+00	1.05E-06	1.09E-03	**0.70**
	Hydrapave (HP)			
	C*	**B**	**k**	**E_{ns}**
	2.91E+00	3.08E-07	5.65E-04	**0.63**
	Permapave (PP)			
	C*	**B**	**k**	**E_{ns}**
	6.93E+00	6.34E-07	1.42E-03	0.15

Tab. 5. 17 - Nash-Sutcliffe Efficiency coefficients and calibration parameters for TSS (Shape 1), single calibration.

	Porous Asphalt (PA)			
Pollutant	**a**	**b**	**k**	**E_{ns}**
TP (Shape 2)	2.10E-01	1.10E-01	2.29E+03	*0.09*
	Hydrapave (HP)			
	a	**b**	**k**	**E_{ns}**
	1.83E-01	1.00E-01	2.58E+03	**0.59**
	Permapave (PP)			
	a	**b**	**k**	**E_{ns}**
	2.14E-01	3.00E-02	2.79E+03	0.36

Tab. 5. 18 - Nash-Sutcliffe Efficiency coefficients and calibration parameters for TP (Shape 2), single calibration.

	Porous Asphalt (PA)			
Pollutant	**a**	**b**	**B**	**E_{ns}**
TN (Shape 3)	6.69E-04	9.35E-02	2.27E+00	0.03
	Hydrapave (HP)			
	a	**b**	**B**	**E_{ns}**
	5.02E-04	1.42E-01	2.61E+00	0.28
	Permapave (PP)			
	a	**b**	**B**	**E_{ns}**
	3.47E-04	1.31E-01	2.62E+00	0.12

Tab. 5. 19 - Nash-Sutcliffe Efficiency coefficients and calibration parameters for TN (Shape 3), single calibration.

	PA+HP+PP			
Pollutant	**C***	**B**	**k**	**E_{ns}**
TSS (Shape 1)	4.92E+00	4.71E-07	9.93E-04	0.27
Pollutant	**a**	**b**	**k**	**E_{ns}**
TP (Shape 2)	2.06E-01	7.22E-02	2.57E+03	0.22
Pollutant	**a**	**b**	**B**	**E_{ns}**
TN (Shape 3)	4.71E-04	1.27E-01	2.53E+00	*0.05*

Tab. 5. 20 - Nash-Sutcliffe Efficiency coefficients and calibration parameters for TSS (Shape 1), TP (Shape 2) and TN (Shape 3), multiple calibration.

As it is possible to notice, in this case the Nash-Sutcliffe coefficients are higher than the correspondent values for the k-C* model. In particular, the highest efficiency has been obtained for the first formulation (TSS), but even for the shape 2 (TP) the coefficients are quite satisfactory. The lowest values were retrieved for the shape 3 (TN), probably because of the complex nitrogen chemistry, due to the several oxidation states that nitrogen can assume. Again, about the multiple calibration, the efficiency coefficients are higher than the correspondent k-C* model, but not sufficiently high in order to consider the phenomenon independent by the paving system.

To further verify the reliability of the three proposed shapes, an error analysis was also carried out. The performance of the k-C* model versus the three new formulations were compared through the calculation of the percentage relative error to the measured inlet concentration:

$$Err\,IN(\%) = \frac{(COutPred - CoutMeas)}{CInMeas}$$

and the percentage relative error to the measured outlet concentration:

$$Err\,OUT(\%) = \frac{(COutPred \text{ - } CoutMeas)}{CoutMeas}$$

Going into details, about the relative outlet error, a range of error thresholds between 10% and 90% has been considered. Then, for each error value, the percentage of points with an error greater than the threshold has been determined (Tab. 5. 21).

	k-C* Model			**Shape #1**	**Shape #2**	**Shape #3**
Err OUT (%)	TSS_kC*	TP_kC*	TN_kC*	TSS1	TP2	TN3
10%	69%	25%	29%	68%	25%	29%
20%	68%	16%	23%	64%	11%	18%
30%	65%	8%	19%	64%	5%	10%
40%	64%	4%	15%	62%	1%	5%
50%	62%	3%	11%	59%	1%	2%
60%	61%	3%	6%	56%	1%	1%
70%	60%	0%	4%	54%	0%	1%
80%	60%	0%	2%	53%	0%	1%
90%	58%	0%	1%	52%	0%	1%

Tab. 5. 21 - Relative outlet errors and percentage of points with error greater than the thresholds.

The calculation results has been plotted over three graphs, one for each pollutant TSS, TP and TN (Fig. 5. 33). The analysis of the figures shows how, for each error threshold, the percentage of points with a greater error is lower for the new proposed shapes instead of the k-C* model. This trend is confirmed for all the three pollutants, where the best performance are achieved for TN. Furthermore, it is possible to see that errors are relatively small, ranging between 10% and 30% for TP, 10% and 40% for TN while only TSS shows errors quite high, despite of the best Nash-Sutcliffe coefficients.

The situation is reversed when the relative inlet error is considered (Fig. 5. 34). All three new formulations show always a better trend compared to the k-C* model. However, in this case, the relative errors are lower for TSS and TP, ranging between about 20% and -20% while the worst performance are achieved for TN, with errors ranging between 40% and -40%, even if the cloud of points is quite scattered.

In fact, when the error analysis with percentage thresholds is repeated by referring to the relative inlet errors, the best performance are again achieved for TSS and TP while for TN the results are quite good, but less than the other two pollutants.

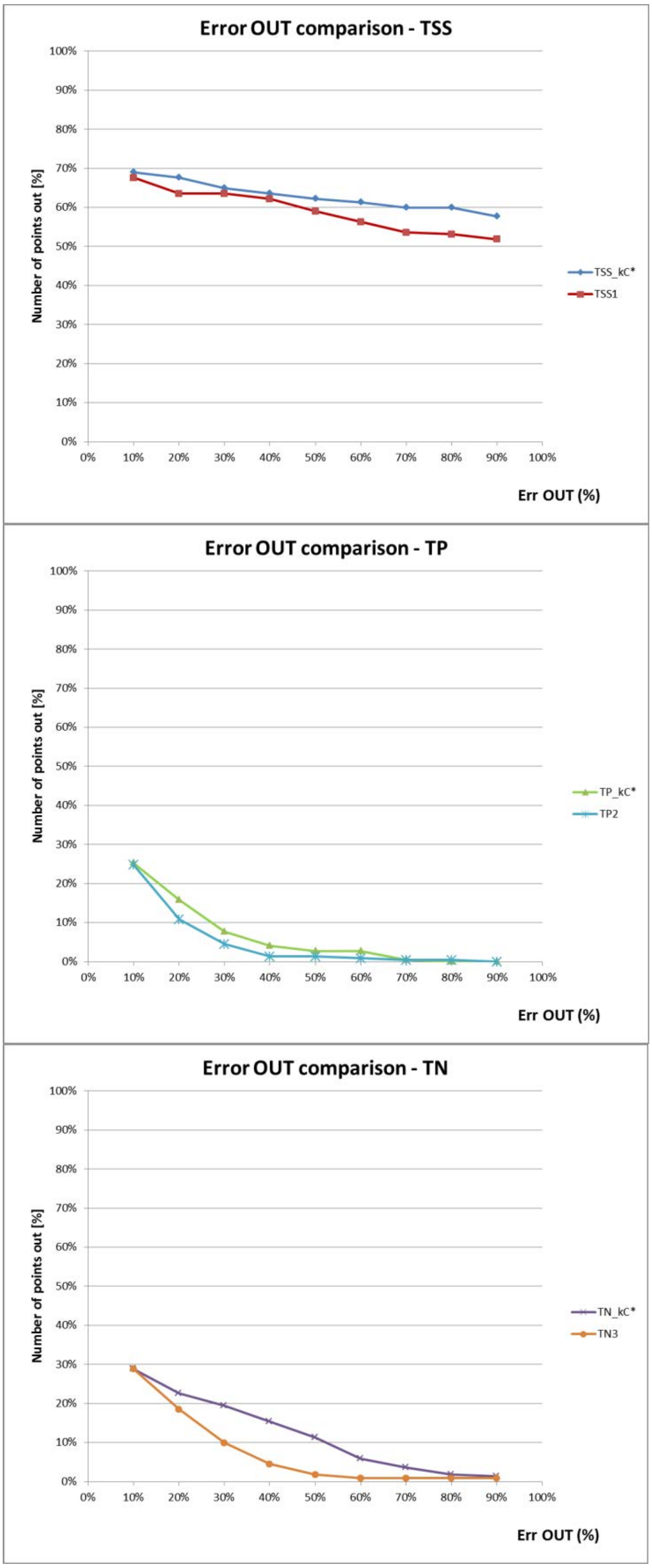


Fig. 5. 33 – Graphs of the relative outlet errors for TSS, TP and TN with the indication of the number of points out of each threshold.

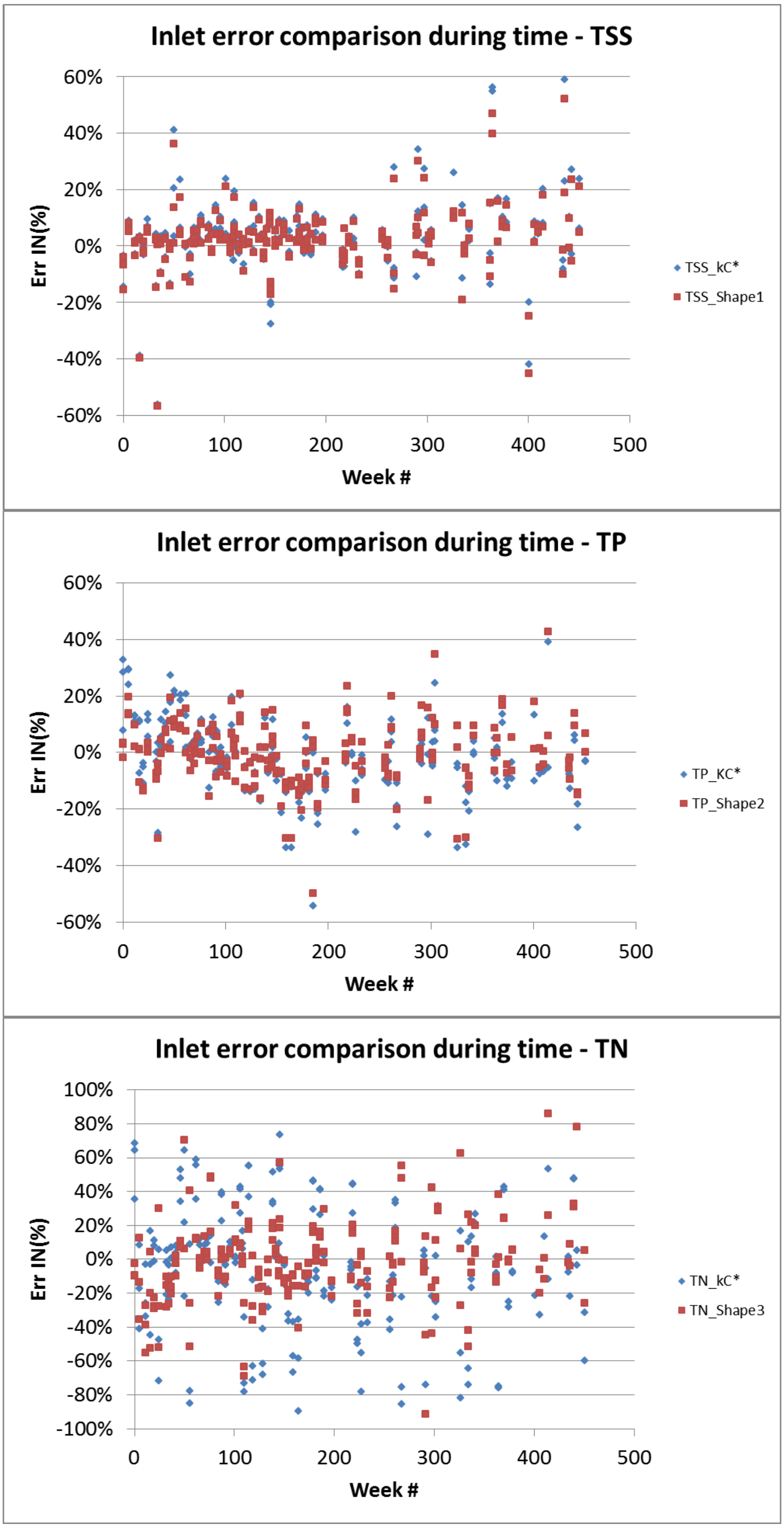


Fig. 5. 34 - Percentage inlet error comparison for TSS, TP and TN during the simulated time.

	k-C* Model			Shape #1	Shape #2	Shape #3
Err IN (%)	TSS_kC*	TP_kC*	TN_kC*	TSS1	TP2	TN3
10%	17%	19%	27%	12%	14%	27%
20%	7%	6%	21%	5%	2%	15%
30%	2%	0%	17%	2%	1%	9%
40%	2%	0%	12%	1%	0%	7%
50%	1%	0%	6%	0%	0%	5%
60%	0%	0%	2%	0%	0%	4%
70%	0%	0%	0%	0%	0%	3%
80%	0%	0%	0%	0%	0%	2%
90%	0%	0%	0%	0%	0%	2%

Tab. 5. 22 - Relative inlet errors and percentage of points with error greater than the thresholds.

Considering the results in Tab. 5. 22 and reported in the following graphs (Fig. 5. 35, Fig. 5. 36, Fig. 5. 37), it is possible to see that errors are very low, ranging between 10% and 20% for TSS and TP while ranging between 10% and 40% for TN. In all cases, the proposed shapes give better results than the k-C* model, with a percentage of points with an error greater than the threshold less than 20% for TSS and TP and, anyway, less than 30% even for TN.

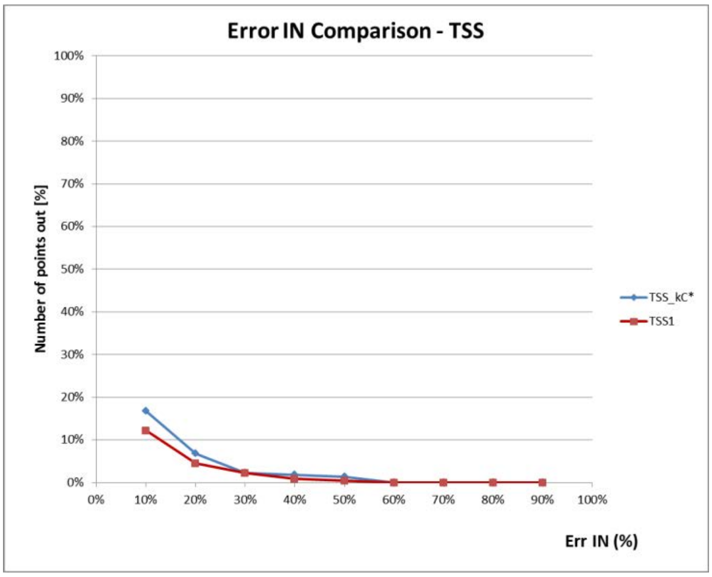


Fig. 5. 35 - Relative inlet errors for TSS, with the indication of the number of points out of each threshold.

In particular for TN (Fig. 5. 37), the difficulty in modelling for this pollutant is demonstrated by the presence of a certain number of points with errors ranging between 60% and 90%. Fortunately, in that range, the total percentage number of points is only 11%, representing an acceptable compromise for this substance.

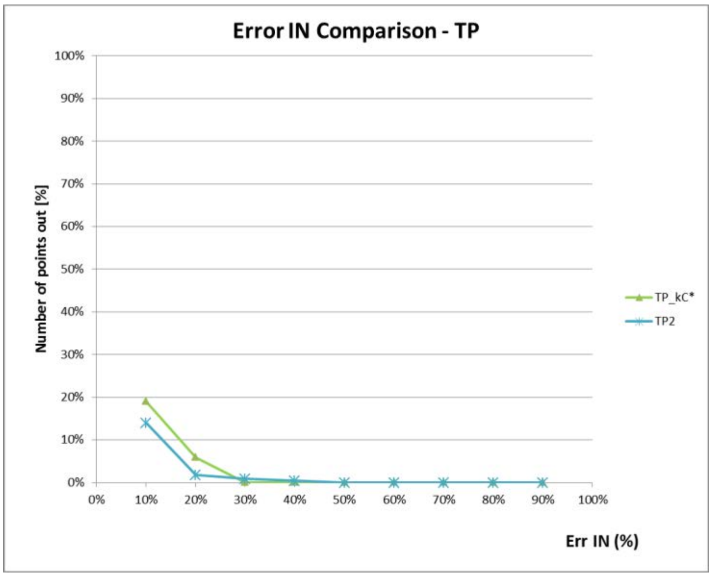


Fig. 5. 36 - Relative inlet errors for TP, with the indication of the number of points out of each threshold.

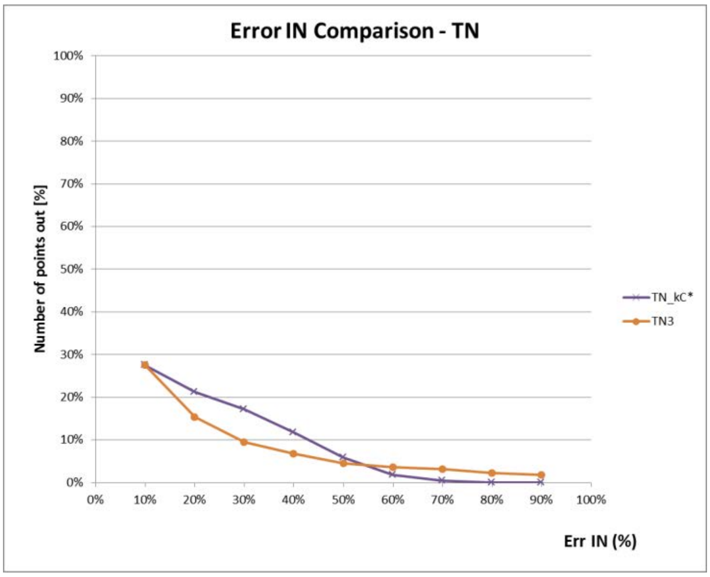


Fig. 5. 37 - Relative inlet errors for TN, with the indication of the number of points out of each threshold.

Finally, the best results achieved are confirmed by the graphs of concentration measured and predicted with time for TSS (Fig. 5. 38), TP (Fig. 5. 39) and TN (Fig. 5. 40). Despite of the high Nash-Sutcliffe coefficients, the Shape 1 (TSS) shows relatively good graphical results just for Porous Asphalt and Hydrapave, while these are less exciting for Permapave. The model predicts rather the concentration correspondent to the peak flows, while a general overestimation of other concentration values remains.

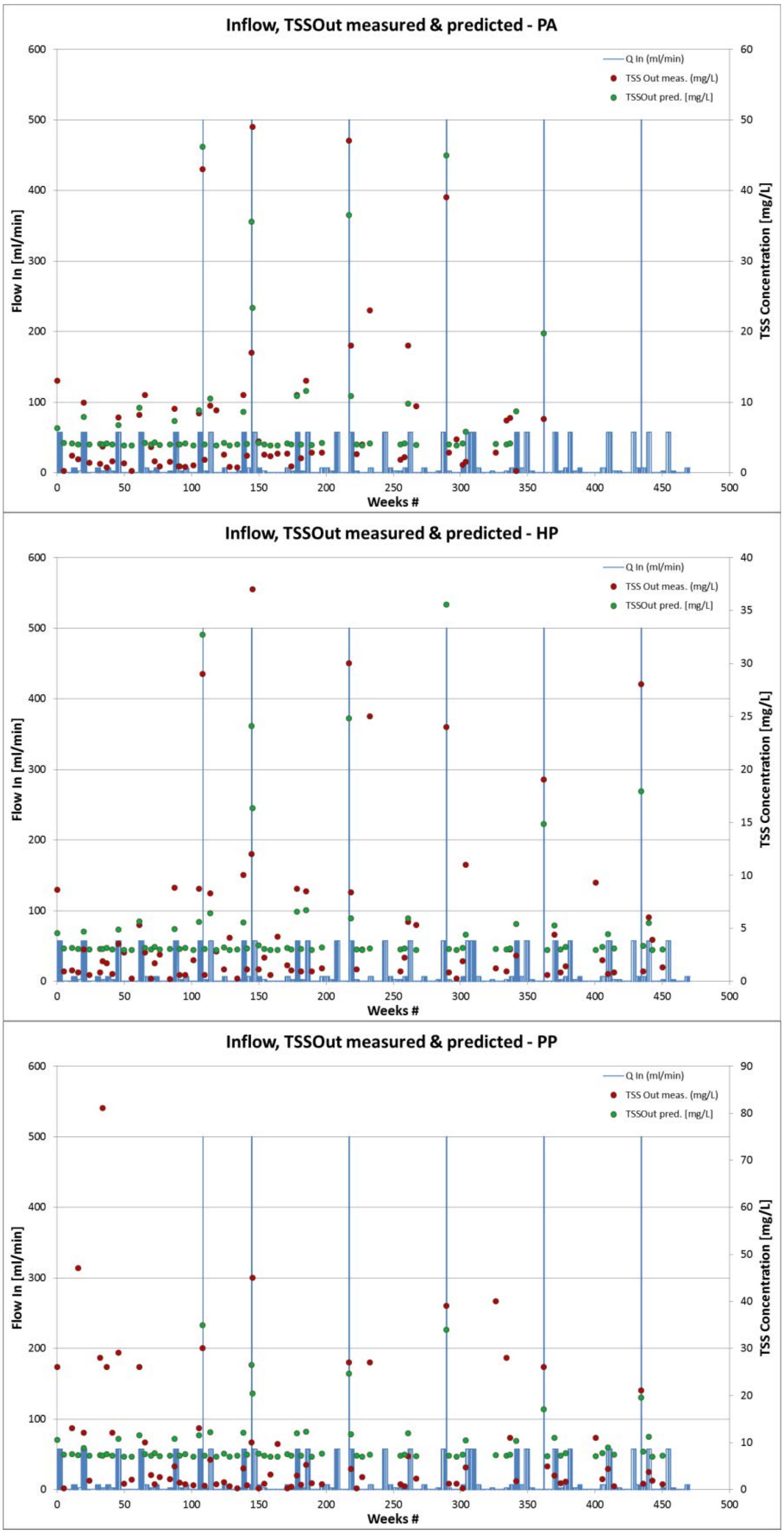


Fig. 5. 38 - Graphs of measured and predicted TSS concentration for Porous Asphalt (PA), HydraPave (HP) and Permapave (PP) with the proposed Shape 1.

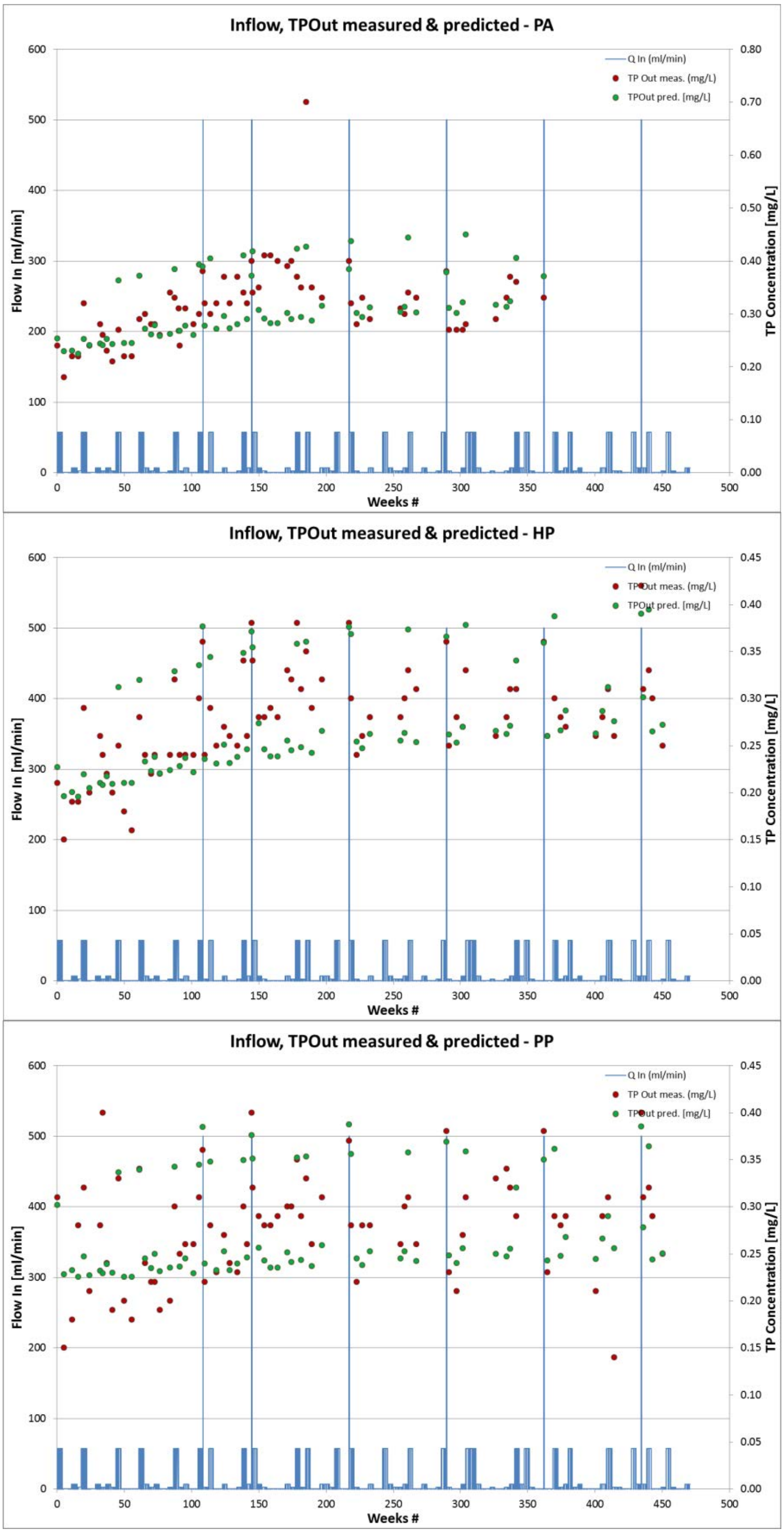


Fig. 5. 39 - Graphs of measured and predicted TP concentration for Porous Asphalt (PA), HydraPave (HP) and Permapave (PP) with the proposed Shape 2.

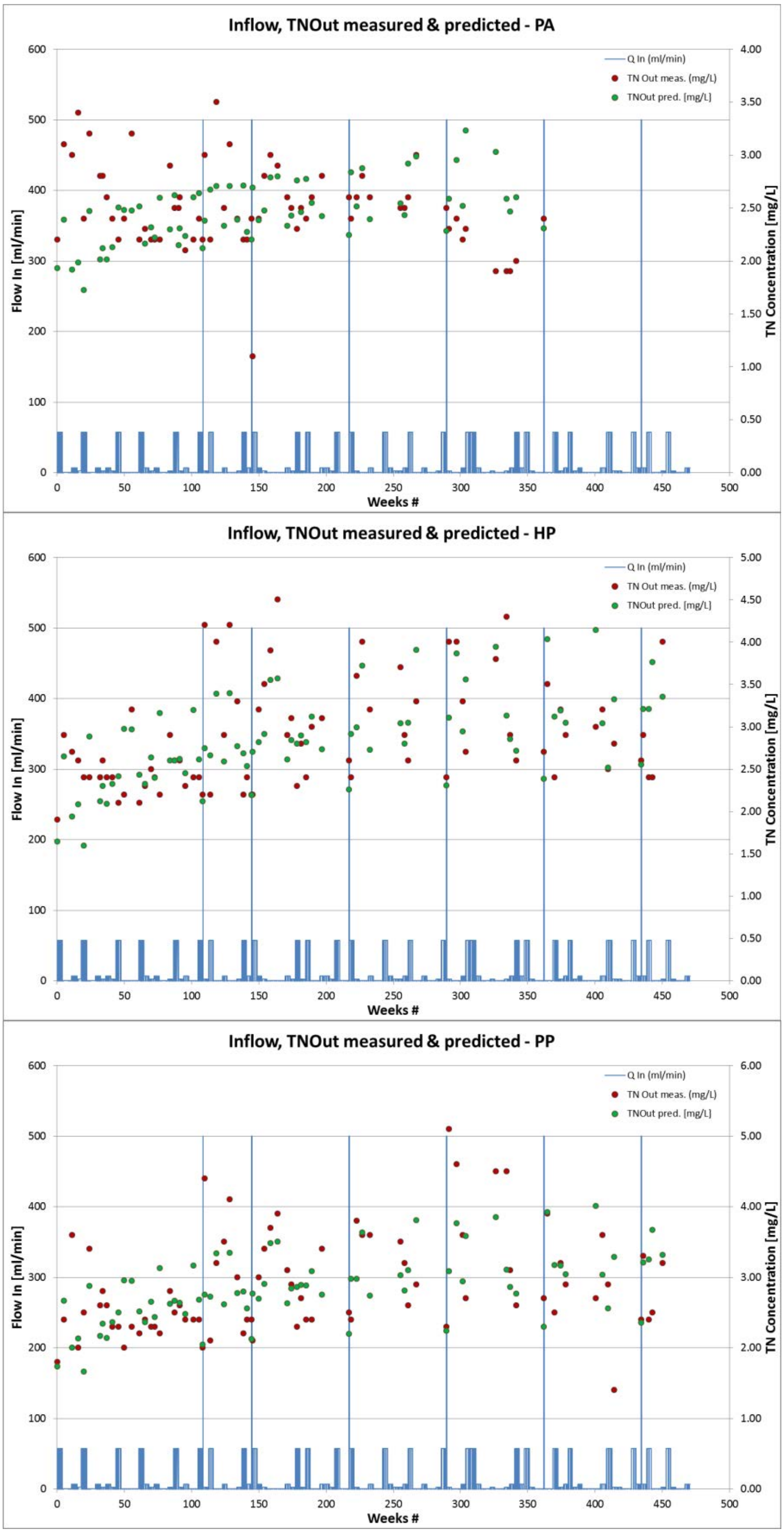


Fig. 5. 40 - Graphs of measured and predicted TN concentration for Porous Asphalt (PA), HydraPave (HP) and Permapave (PP) with the proposed Shape 3.

Excellent are the results achieved for the Shape 2 (TP) with all pavement types. The formulation predicts good concentration values both for low and peak flows, with a generally good fitting of the measured values. Maybe a slight improvement would be desirable for intermediate flow values (flows C, D), whose predicted concentrations are sometime underestimated.

The Shape 3 still reveals problems in modelling of Total Nitrogen. For Porous Asphalt, particularly, an initial underestimation of concentration values is present, leaving space later to an overestimation in the final part of the simulation. The situation is clearly better for Hydrapave and Permapave simulations, where the formula generally predict an 'intermediate' value for concentrations, while ignores some positive and negative outliers.

In conclusion, notwithstanding some residual problem, the analysis carried out confirm the reliability of the new proposed formulas, which allow to estimate the concentrations of the main pollutants (TSS, TP, TN) to the output section of the porous pavements.

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Chapter 6: Conclusions and further research

6.1 Conclusions

Climate changes have become increasingly sudden and abrupt nowadays, raising the concern of researchers and scientists on how to decelerate or reverse this negative tendency. All recent studies conducted up to now agree on an increase in extreme events, both for droughts as well as precipitations. In regards to the latter, rainfall have become more intense and frequent, even with short duration. Thus, for its heavy impact, these events are called ‘extreme rainfall events’ and, often, they can have dangerous consequences in urban areas such as flash floods or damages to infrastructures (roads, buildings, etc…).

Therefore, modern cities have to face and manage such new complex environmental conditions moving towards a more sustainable approach. It is necessary to rethink the design of our cities, making them more ‘sensitive’ to water management. An answer to this need comes from the widespread application of sustainable urban drainage measures connected together within the ‘Blue-Green Corridors’ concept. It consists to create a network of blue and green components (made of traditional low impact development – LIDs – or best management practices – BMPs) interconnected to the sewage system, in order to achieve the minimisation of water pollutants concentrations and the reduction of stormwater runoff and the relative urban flooding risk.

Main objective of this thesis has been the qualitative and quantitative assessment of SUDS implementation in urban areas through the overland flow network enhancement and the reduction of the relative water pollution.

First step was to retrieve the overland flow network to enhance, subsequently, through the use of various BMPs. Major advances in survey technologies give us today the capability to obtain topographic maps from high quality data at relative cheap price. Then, this data can be used for hydrological and hydraulic purposes, after a prior error removal has been performed. A case study for the Liguori Channel (LC), situated in Cosenza (Italy), has been carried out in order to evaluate how DTM resolutions and presence of buildings affect the delineation of ponds, namely potential flooded areas. To achieve this aim, three different DEMs of the study area, generated from different sources, were used: two contour-based DTMs with contour interval respectively of 30 m (*DTM 30*) and 20 m (*DTM 20*), and one LiDAR-based DEM, with horizontal resolution of 1 m (*LIDAR DTM*). Elaborations carried out brought to the conclusion that reliability of major system strongly depends by quality of data used with particular attention to DEM's resolution, because overland flow paths are influenced by urban characteristics. Presence of buildings generally improves delineation of ponds, diminishing total accumulated water volume, even if number of depressions tend to increase with higher resolutions (lower cell size). Moreover, downsampling or upsampling operations do not improve DEMs accuracy as demonstrated by entropy calculation leading, instead, to an increment of errors. Based on that, the original LiDAR data with overlapped buildings has been used to generate the overland flow network because the operation does not affect the data accuracy while buildings help to minimise the number of individuated ponds and the relative storage volume.

Later on, a series of available in-situ runoff treatment devices has been analysed. The study has been conducted in order to choose the right practices to implement into a typical European city layout. Advantages and drawbacks of each one has been analysed, aiming to link them together with the previously generated overland flow network, in order to create a network of blue-green elements, thus, emphasising the performance of all practices. Green roofs and porous pavements has been chosen to be easily retrofitted into a urban high density context. Particularly for permeable pavers, the loss of hydraulic conductivity due to sediment accumulation into the filter layer over time has been studied and subsequently modelled, in order to improve the available software modelling algorithms. Promote the adoption of BMPs and LID practices to protect and preserve natural environment, has forced the software houses to update their models including new modules for the qualitative and quantitative assessment of stormwater runoff. Then, new information on the performances of BMPs practices has been collected and many software (such as EPA SWMM) has been updated to incorporate these new technologies. An analysis of different alternatives for the simulation of BMPs and LID practices has been carried out. Currently, this kind of analysis is performed by the majority of the models, even if at different level of detail. Anyway, not all stormwater management practices are implemented in all software then, the use of a particular model can lead to limitations of simulation capabilities. Another aspect is the malfunctioning or maintenance issues associated with BMPs. Reduced removal efficiencies are likely without regular maintenance, and effects of clogging or other reduction in performance should be included in any modelling procedure. The proposed review has shown that a comprehensive model that can be used in all circumstances and for all aims still does not exist. Overall, even the well-known and widely adopted models (such as USEPA SWMM or eWater-CRC MUSIC) need to be enhanced, especially as regards the water quality modelling of LID practices.

After the description of properties and characteristics of each practice and a background on the modelling software available and their working concepts, two applications were presented and discussed. The first was an example of Blue-Green Corridors implementation in an highly urbanized catchment. The overland flow network of a catchment subarea has been retrofitted through the hypothetical implementation of a certain percentage of green roof and porous pavements. Different simulations were performed, using in input the historical annual rainfall series (between 2008 and 2011) and considering three scenarios: a first scenario with no LID implemented (baseline scenario), a second scenario with green roof and porous pavement implemented, but without considering the clogging phenomenon and a third scenario with LID implemented and subjected to performance decay due to clogging. Within SWMM, the clogging phenomenon is taken into account through a parameter called '*clogging factor*' that considers the possible decay of LID performance due to the fine material carried by infiltration waters. The same simulations were repeated, also, considering a single time series composed by 4 years of precipitations (2008-2011), namely performing a continuous simulation. The yearly simulation shown a percentage volume reduction into the network of around 35% on average each year, a Total Suspended Solids mass reduction of around 30% on average, while the relative concentration underwent an increment of around 15%. The latter result was explained looking at the SWMM runoff quality algorithm, that takes into account of the reduction of pollutants only in terms of reduction of surface runoff. A further indication of the weird results achievable with SWMM for LID modelling comes from the long-term simulations. In fact, when the continuous simulation is considered, the volumes of the clogged LID are even higher, sometimes, than the volumes occurring without any BMP implemented. During the first two simulated years the trend is similar to what it has been found during the annual simulation where volumes for the scenario 'LIDs with clogging' range always between the other two cases, without and with LIDs. The efficiency tends to decrease during time, from 50% when simulation starts to almost 0% at the end of the second year, continuing then to swing around zero per cent for the remaining part of the simulation.

Because of the SWMM results not very accurate, lastly, the research has been focused on improving the qualitative simulation algorithms for porous pavements. Data collected into an experimental laboratory rig of three different and widely used permeable pavement types has been analysed. The investigated systems were: monolithic porous asphalt (PA), modular Hydrapave (HP), and monolithic Permapave (PP). The system has been subjected to a semi-synthetic hyetograph, made of five different rain intensities (wetting regime) plus several drying periods, simulating 26 years of operation under Melbourne climate in 1 year of laboratory experiment. The pollutant analysed were: Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN). A correlation analysis has been performed, which allowed to find the key variables influencing the process: flows (wet conditions), twelve hours cumulated flows (historical conditions) and cumulative input volumes and masses (clogging conditions). The achieved results have shown that the 'k-C* model', notwithstanding its wide popularity and tested applicability on various other treatment practices, does not show satisfying results when applied to porous pavements, especially about heavy metal and total nitrogen modelling. The predictive power of this model (and other proposed new shapes) has been assessed through the calculation of the Nash–Sutcliffe model efficiency coefficient, widely adopted in the Anglo-Saxon world to evaluate behaviour and performance of the hydrologic models. Consequently, a series of attempts has been done in order to modify the k-C* model or create a new empirical model able to successfully considering the clogging phenomenon during the prediction of the pollutants behaviour. The performed research has allowed to find three new formulations, one for each pollutant, able to correctly predict the pollutant concentration at the outlet of any porous pavement type. Two formulations (Shape 1 for TSS and Shape 2 for TP) represent a variation of the k-C* model, where the third one (Shape 3 for TN) is a totally new equation. Every formula contains the two previously identified key variables: the cumulative flow every 12 hours before the sampling time and the cumulative inflow volume. The goodness of fit is confirmed by the Nash-Sutcliffe coefficients that result always higher than the correspondent values for the k-C* model. In particular, the highest efficiency has been obtained for the first formulation (TSS), but even for the shape 2 (TP) the coefficients are quite satisfactory. The lowest values were retrieved for shape 3 (TN), probably because of the complex nitrogen chemistry, due to the several oxidation states that nitrogen can assume. The reliability of the three formulation has been further verified through an error analysis. For all models the percentage relative error to the measured inlet concentration and the percentage relative error to the measured outlet concentration have been calculated. Furthermore, a range of error thresholds between 10% and 90% has been considered. Then, for each error value, the percentage of points with an error greater than the threshold has been determined. The analysis shown how, for each error threshold, the percentage of points with a greater error was lower for the new proposed shapes instead of the k-C* model. This trend was confirmed for all the three pollutants, where the best performance were achieved for TN. Furthermore, it was possible to see that errors were relatively small, ranging between 10% and 40% in terms of relative outlet error while, considering the relative inlet error, percentage of errors were even smaller, ranging between ±20% for TSS and TP and ±40% for TN.

In conclusion, the analysis carried out have confirmed the reliability of the new proposed shapes, which allow to estimate the concentrations of the main pollutants (TSS, TP, TN) at the output section of a porous pavement.

6.2 Possible future developments

This research has greatly contributed to increase the knowledge about the implementation of best management practices in urban environments. Useful information were given about their modelling and the relative achievable performance. In particular, the porous pavements behaviour has been modelled, furnishing new equations able to predict in a better way their long-term working. Despite the remarkable achievements presented in this work, there is still space for improvements. Relatively to the overland flow network delineation, in this thesis only buildings has been considered as obstacles for runoff. In the reality, into the urban environment there are many other objects that can divert the flow direction such as walls, fences, underpasses or railway embankments that should be considered during the flow path delineation. Another issue regarding the overland flow paths is that, currently, they have been modelled with an open circular cross-section while the accurate determination of the real cross section (possible through the use of a detailed DEM) can significantly affect prediction of water depth and flow velocity, then, of likely inundated areas. Still remains important to use an error free DEM, in which the spurious ponds has been removed. In this work spurious depressions has been partially removed through the over imposition of the buildings and the detailed knowledge of the study area. However, no new procedure has been developed to help in distinguish automatically between real and spurious features.

Further investigations might be performed about the blue-green corridors simulations. Current simulations have been performed with EPA SWMM, but thesis results have confirmed the partial inadequacy of this software to properly simulate the behaviour of these practices. Major issues were identified about the qualitative algorithm used, especially about the porous pavements modelling. However, it should be interesting to compare SWMM results with those ones retrieved by other hydraulic simulation software such as eWATER CRC Music or CHI PC SWMM, in order to estimate the magnitude of error observed. Similarly, it might be worthwhile to repeat the annual and the continuous simulations in SWMM after the new pollutant modelling shapes have been included. Indeed the proposed shapes, that consider the clogging phenomenon while predicting the permeable pavers pollutant outlet concentrations, have been tested only singularly, without verifying their functioning when inserted into a complex blue-green network.

Finally, the three new proposed shapes have been validated only with Australian laboratory data. Because of the climate, similar but not the same to the Mediterranean one, a further validation is strongly suggested. It would be advisable to use porous pavements data coming from an Italian field installation. This could lead to a confirmation of the achieved results, extending the applicability of the three formulations and certifying their universal validity.