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Key issues for sustainable urban stormwater management

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ABSTRACT

Since ancient times, it is understood that stormwater from constructed areas should be managed somehow. Waste and pollution transported by stormwater poses quantity and quality problems, affecting public health and the quality of the environment. Sanitation infrastructures in urbanized regions have different development levels and the perception of stormwater changed considerably during the centuries and especially in recent years. Still, there is an evident worldwide heterogeneity when analyzing the lack of studies on urban stormwater conducted in some Asian or African countries.

Strategies for sustainable stormwater management are needed at different decision levels (political, regional or local scale, for instance) but all of them need information and a clear understanding of the possibilities that are at stake as well as the main consequences of each decision. A sound approach to stormwater management should be flexible, based on local characteristics, and should take into consideration temporal, spatial and administrative factors and law, among other issues. Economic or technical constraints define different decision scenarios.

Best Management Practices should be seen as an opportunity for development and improvement of social, educational and environmental conditions in urbanized and surrounding areas. Therefore they require an ample perspective and the participation of different stakeholders. High-quality decision needs time and a fair overview of the problem: the purpose of this document is to contribute to sustainable stormwater management, informing on the most relevant factors that should be assessed and their interaction. A flowchart has been produced and is presented, indicating the most relevant steps, processes and information that should be taken into account in urban development.

1. Introduction

Land use modifications associated with urbanization includes removal of vegetation, replacement of pervious areas with impervious surfaces which result in changes in the characteristics of the surface runoff hydrograph (Goonetilleke et al., 2005), increasing stormwater runoff volumes and peak flows. Anthropogenic activity in urban areas generates wastes and pollutants on the catchment surfaces that may be washed out to water bodies during storms. Domestic or industrial wastewaters are also present. It is necessary to build drainage systems, in order to ensure the functionality of the constructed sites and to guarantee public health. This is an ancient concern; drainage systems, some of them quite advanced, were constructed by Romans and existed even before, in Ancient Greece (300 BC to 500 AD), Crete (from 2000 BC) and in the Mesopotamian Empire (3500–2500 BC) (Cooper, 2001; Novotny, 2003; Angelakis et al., 2005).

Urban discharges may include stormwater runoff, separate or combined sewer overflows (CSOs) and snowmelt (Burton

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and Pitt, 2002). The relative quality and quantity magnitudes of these discharges vary considerably; in the case of CSOs they carry wastewaters whose characteristics represent the combination of the different contributions. Presently, it is well known that stormwater transports large quantities of contaminants to receiving waters (e.g.: Bachoc et al., 1994; Burton and Pitt, 2002; German et al., 2005; Huang et al., 2010), thereby being the major contributor to pollution of receiving waters in many countries (Lee et al., 2007).

Stormwater presents very distinct quality and quantity characteristics from domestic sewage. It is recognized as the most important source of heavy metals whereas wastewater constitutes the main source of organic and nitrogenous pollution (German et al., 2005; Gasperi et al., 2010; Hvitved-Jacobsen et al., 2010). Biochemical Oxygen Demand (BOD_5), bacteria and nutrient concentrations are lower in stormwater than in raw sanitary wastewater (Burton and Pitt, 2002).

The sanitation infrastructures in urbanized areas have different development levels. This worldwide heterogeneity is evident when analyzing the lack of studies on urban stormwater conducted in some Asian or African countries, where people are still dealing with more basic issues (Chow et al., 2011). Historically speaking, many older towns are drained by combined sewer systems, both in Europe and in the USA; in these cases combined wet weather flow discharges may cause severe impacts on receiving waters (Gasperi et al., 2010). On the other hand, it is known that the construction of separate sewer systems in the past was not based on the flow and quality differences but mostly on economic factors (Brown, 2003; German et al., 2005).

Summarizing, it is observed that different solutions have been applied to urban sanitation management, either considering stormwater as a quantity problem to deal with either by discharging it directly to water bodies; or treating part of it in wastewater treatment plants (WWTP). Therefore specific approaches were investigated including the concern for environmental protection complying with more recent legislation requirements (for instance: the Clean Water Act, from 1987, in the USA, or the Water Framework Directive, from 2000, in the European Union countries).

Different approaches may be followed to deal with stormwater: either strategic, political decisions; source control or “end of pipe measures” (German et al., 2005). In the last decades source control was more used then the discharge into conventional combined or separated sewer systems (Martin et al., 2007). According to the focus and the country where they were first developed, these new concepts for decentralized solutions have different denominations. Some of the most common are: “Best Management Practices – BMPs (FHWA, 2000; Geosyntec Consultants, 2010); “Low Impact Development – LID” (Elliott and Trowsdale, 2007), “Water Sensitive Urban Design – WSUD”; “Sustainable Urban Drainage Systems – SUDS” (used more in the UK; Elliott and Trowsdale, 2007); “Innovative Stormwater Management” (used more in the Canada; Marsalek and Schreier, 2009), or “techniques alternatives” in France. In this document the expression BMP is adopted.

BMP can be structural, meaning built systems, such as rainwater retention, or non-structural, such as pollution prevention or street cleaning (Martin et al., 2007). This approach deals with stormwater taking into account both future needs and the protection of natural resources (Hvitved-Jacobsen et al., 2010).

The discharge of stormwater into water bodies is likely to cause impacts that depend on the characteristics of the discharge (quality and flow velocity) and on the volume and quality of the receiving water. Urban areas produce higher discharge peaks and runoff volumes; these processes increase the flow velocity and, therefore, force the streams to adjust their geomorphic properties (Tillinghast et al., 2011). The effects of stormwater downstream of the discharge can be classified as acute or chronic and as direct or indirect. They may impact the hydromorphodynamics of the water body, its quality and the aquatic ecosystem (Wanielista and Yousef, 1993; Hvitved-Jacobsen et al., 2010).

Strategies to deal with stormwater are needed at different decision levels (political, regional or local scale, for instance) but all of them will need information and a clear understanding of the possibilities that are at stake as well as the main consequences of each decision. Information on stormwater characteristics may be achieved through literature information or monitoring studies; modeling is a third alternative but it requires input data. A good methodology must consider that decisions taken with insufficient information represent costs, waste of time and the possibility of water management problems.

One of the purposes of this document is to present a comprehensive review of the most relevant information that should be considered in sustainable stormwater management, based on the authors’ view and literature revision. Another aim of the work is to make it understandable and valuable to the scientific community, to engineers and to decision-makers at different levels. It could not detail all aspects, also because research is constantly bringing up new results and there are different scenarios. For instance, the consideration of emerging organic pollutants is a recent concern in many countries (Eriksson et al., 2007; Bester et al., 2008) but is not important in countries that are dealing with basic sanitation problems (Chow et al., 2011).

2. Stormwater characterization

2.1. *Quantity and quality characteristics*

Stormwater transports different pollutants, both organic and inorganic. Hvitved-Jacobsen et al. (2010) divided them into six specific groups, presented in Table 1 which also includes analytical parameters used to measure the pollutants and other information. This is a simplified view; there is a huge amount of pollutants that were identified in stormwater and may cause relevant impacts in aquatic systems (Eriksson et al., 2007; Björklund, 2011).

Season and land use are frequently referred to as the most relevant factors affecting stormwater runoff characteristics (Burton and Pitt, 2002; Goonetilleke et al., 2005; Hathaway and Hunt, 2010). Therefore, the characterization (qualitative and quantitative) of stormwater runoff should be performed at national and regional bases, with monitoring studies, for it has been proved that site specific, climatic and other local

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Table 1 – Characterization of stormwater pollutants.

Pollutant group	Measurement parameter	Sources	Comments
Solids (suspended solids, SS)	TSS	Pavement wear; construction sites or rehabilitation works; atmospheric fallout; anthropogenic wastes, etc.	60–80% of SS in stormwater could be less than 30 μm diameter. Other sewer solids are present in CSO. Solids also accumulate within the sewer system and may be discharged at different times. Heavy metals and PAHs are bond to the smaller particles (e.g.: 100–250 μm)
Heavy metals	Cu, Zn, Cd, Pb, Ni and Cr	Vehicles parts and components; tire wear; fuel and lubricating oils; traffic signs and road metallic structures. Industries may also be an important source of heavy metals.	They are relevant because of toxic effects. Generally the focus is on copper (Cu), zinc (Zn); cadmium (Cd) and lead (Pb). The relevance of Pb is minor in countries using unleaded gasoline.
Biodegradable organic matter	BOD_5 and COD	Vegetation (leaves and logs) and animals such as dogs, cats and birds (either fecal contributions or dead bodies)	Organic matter (o.m.) from stormwater is less biodegradable (dominated by plant material), therefore is also less problematic for the environment than the o.m. from CSO.
Organic micropollutants	They are numerous. Among them: PAHs, PCBs, MTBEs, endocrine disrupting chemicals	e.g.: PAH: incomplete fossil fuel combustion; abrasion of tire and asphalt pavement, etc. Phthalate esters: urban construction plastic materials.	Presently, a large number of compounds (over 650 identified) are discharged in trace concentrations and sometimes there is no accurate chemical determination method available for them.
Pathogenic microorganisms	e.g.: Total coliforms; *Escherichia coli*	Contributions from cats, dogs and birds.	Stormwater sources are much different than domestic wastewater contribution in the case of CSOs.
Nutrients	Nitrogen and phosphorous (e.g.: total Kjeldahl N; $NO_2 + NO_3$; total-P; soluble-P)	Fertilizers and atmospheric fallout	Nutrients can cause not only eutrophication problems but also water discoloration, odors, toxic releases and overgrowth of plants.

(Hvitved-Jacobsen and Yousef, 1991; Wanielista and Yousef, 1993; Burton and Pitt, 2002; Björklund, 2011; Eriksson et al., 2005; Lau and Stenstrom, 2005; McCarthy et al., 2008; Hvitved-Jacobsen et al., 2010).

variables play an important role. In fact, precipitation is the phenomenon that washes and transports the pollutants and therefore the quantity of flow is characterized by the amount, frequency, intensity, duration and pattern of precipitation (Hvitved-Jacobsen and Yousef, 1991). When considering possible climatic changes, precipitation extremes will pose not only quantity problems (especially urban floods) but also water quality impacts whenever stormwater is discharged to water bodies without treatment. In the case of increased dry periods there might also be increased stormwater pollutant concentrations, probably with an enhanced first flush occurrence for some catchments, with consequences for treatment facilities and recipient water bodies.

In an integrated view of stormwater management attention should be given to, not only the water quality itself but also to erosion and flood control. Urbanization is the most anthropological factor affecting these processes. An increase of the urban area in a watershed leads to an increase of the impervious area, with higher discharge peaks and runoff volume. This will also increase the flow velocity and, therefore, forces the streams to adjust their geomorphic properties (Tillinghast et al., 2011).

Usually, stormwater is characterized by flow measurements and sample collection (of a significant number of samples for a given location) and each quality parameter/pollutant may be described by the range of concentrations (maximum, minimum and standard deviation) and the Event Mean Concentrations (EMC). EMC is calculated for each rainfall event as the total mass of pollutant divided by the total volume discharged. The Site Mean/Median Concentration (SMC) is the mean or median of all the measured EMC (Hvitved-Jacobsen and Yousef, 1991). Since these parameters result in different field and laboratory measurements, there are uncertainties associated with them (McCarthy et al., 2008). These results should be considered estimations of the real value when used for stormwater management purposes.

The pollutant annual mass load per unit of area (e.g.: g/ha/yr) is another parameter used to characterize stormwater quality. Stormwater loading rate is usually higher for high density residential areas and decreases with the following land uses: low density residential > industrial > undeveloped watershed. These observed pattern also depend on the target pollutant and type of industry(ies) (Lee and Bang, 2000; Burton and Pitt, 2002). Some studies have also observed large quantities of fecal indicator bacteria in stormwater from undeveloped basins, revealing diffuse and widespread natural sources of contamination (Schiff and Kinney, 2001; Griffith et al., 2010).

It is known that the presence (both concentration and load) of a given pollutant at the same site varies considerably between different rainfall events; the variables usually correlated with these variations are the precipitation event characteristics and the antecedent dry period. Pollutant variability within a single event is also common; the highest concentrations or the largest mass of pollutants are often transported during the initial period/volume of the stormwater event in a phenomena defined as “first flush” or “first foul flush” (Hvitved-Jacobsen et al., 2010). For instance, Chang et al. (2008) refer that the first 6–8 mm of storm volume included more than 60% of the pollutant loads from industrial parks in Taiwan. A more practical definition of the first flush as “the runoff volume required to reduce a catchment’s stormwater polluted concentrations to background levels” was proposed by Bach et al. (2010).

Nevertheless there is a lot to be said concerning the first flush: it is not a universal and constant phenomenon and depends on the characteristics of the catchment and on the climate; it may also only take place for some of the pollutants. Lee et al. (2004) observed the occurrence of seasonal first flush at the initial storm or storms of the wet season, which can be useful information for BMP management in climates with well defined rainy and dry seasons – such as the Mediterranean one.

Generally, when assessing impacts from stormwater discharges, bacteria, organic matter and suspended solids are linked to acute impacts; metals (e.g.: copper, zinc and cadmium) or organic micropollutants (e.g.: aromatic hydrocarbons) may cause mortality in living organisms if the concentration is very high (acute impact); otherwise they cause cumulative or chronic effects (Wanielista and Yousef, 1993; Hvitved-Jacobsen et al., 2010). For the purpose of environmental impact evaluation and selection of treatment processes the understanding that the pollutants are present in different forms in stormwater is also relevant: they may have a fraction associated to suspended particles (e.g.: heavy metals; PAHs; organic micropollutants), they may be present in a colloidal form (e.g.: organic matter), or in a dissolved fraction (e.g.: heavy metals) (Vollertsen et al., 2009; Hvitved-Jacobsen et al., 2010). Although there are known patterns of distribution of each pollutant among these three fractions, the chemistry of the stormwater may change the relative partition between the fractions.

2.2. *Stormwater monitoring and modeling*

Data acquisition in urban stormwater is an open issue. There is not a unique method or equipment that might be the most appropriate for all monitoring studies. The best approach for each case should take into account, among others, local constraints and the available budget and time.

Two central ideas should always be taken as guidelines in the pursuit of accuracy in data acquisition: i) little information is better than no information; ii) some reliable data is better than a lot of inaccurate information.

A monitoring program should be structured based on the local characteristics, on the budget and time available, and on the objective. The purpose of monitoring results may be to support the decision to build a treatment system; to evaluate pollutant retention efficiency of a constructed BMP, or to evaluate hydrological and water quality impacts after stormwater discharge. Fig. 1 presents a flowchart with the main processes of data acquisition in stormwater monitoring.

Each event has specific conditions behind, such as the intensity and the amount of precipitation or the pollutants accumulated in the drainage areas; all these variables conjugate and create inimitable conditions. This event-based nature of the pollution leads to one of the causes of the variability of the phenomena (Hvitved-Jacobsen et al., 2010).

The monitoring program should be focused on the main changes of the stormwater quantity and quality characteristics. They are mostly related with seasonal variability, therefore several events, representing different seasons should be characterized. Monitoring programs should also account for the variability during each event. This is why collecting only one sample during the event is not representative of the average conditions (Wanielista and Yousef, 1993). Several samples should be collected at different times in order to learn the changes along the event. Quite a number of authors emphasize the importance of considering statistically independent rainfall events in stormwater monitoring studies (Hvitved-Jacobsen and Yousef, 1991).

Hydrological data monitoring is essential to characterize a stormwater event or to calibrate the simulation model. A well-defined program should pay attention to the appropriate equipment, to the monitoring procedures and to the selection of the sites. Maheepalaa et al. (2001) presented some guidelines on these issues. It was recommended, for instance, resolutions of 0.5 mm for the rain gauges and time steps of 2 min for the flow meters. The cost of the equipment was also investigated. It was found that it is possible to obtain good agreement between measurements of flow meters with indirect measurement of the flow (through rating curves). This would avoid the need of expensive flow meters.

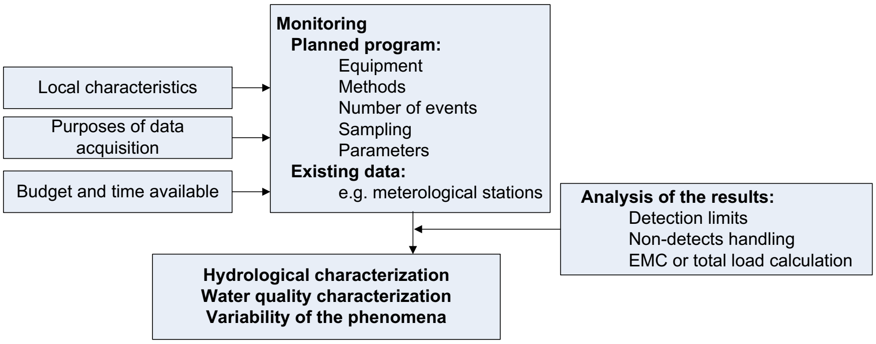

Fig. 1 – Monitoring stormwater processes.

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According to the purposes of the data acquisition and the available budget, two different approaches may be used: i) to analyze a flow weighted composite sample made of all the single samples taken along the event or ii) to analyze each single sample. The second choice is more expensive, but allows the evaluation of the occurrence of first flush and pollutants concentration variations. For most studies, as pointed out by Wanielista and Yousef (1993), there is no need to get a continuous record of the precise changes due to the number of the variables and the consequent cost.

The majority of the monitoring studies include rain gauges, flow meters and automatic or manual methods for sample collection. The monitoring equipment should be chosen in order to obtain the accuracy needed for the specific study. It may be done with different levels of resources; using a complete set of automatic equipment or alternative methods that include equipment and manual recording/sampling. The precision of the information obtained with the equipment should be evaluated and the data should be used with due consideration of the inherent uncertainties contained within these measurements (Bertrand-Krajewski, 2007; McCarthy et al., 2008; Huang et al., 2010).

Meteorological stations near the study area can be consulted to obtain data concerning not only precipitation, but also air temperature, humidity, evaporation, sun radiation and wind speed and direction. They can also be used to schedule the monitoring program; e.g.: stormwater sampling.

Detection limits, within the possibilities of each analytical method, should be carefully discussed with the laboratory. They should be consistent with the expected pollutant minimum concentrations that can be obtained from the revision of similar studies in the literature or reference books (e.g.: Hvitved-Jacobsen and Yousef, 1991; Burton and Pitt, 2002; Hvitved-Jacobsen et al., 2010) or by using prediction models. Otherwise, having results below the detection limit may frustrate the objectives of the monitoring program, even if there are approaches to deal with non-detects, from not considering them at all to more or less complex replacement processes (Helsel, 1990; Zhang et al., 2004).

After gathering the stormwater quality and hydrological data the analysis of the results is the final step that should be performed carefully as well. It is common that studies of the kind use different approaches, although the principles behind each measurement and data analysis are common; e.g.: Dimova et al. (2005), Nanbakhsh et al. (2007), Chang et al. (2008), Vollertsen et al. (2009), Gasperi et al. (2010), Maniquiz et al. (2010).

Three estimators for storm and annual mass emissions have been evaluated by Leecaster et al. (2002). They found that single storms were most efficiently characterized by taking 12 samples following a flow-interval schedule and using a volume-weighted estimator for mass emissions.

For water resources management purposes or decision concerning the need for treatment of stormwater, there is the need for models able to predict stormwater quality whenever there is few or no monitoring data. Such models are based on the establishment of relationships between pollutant concentrations and site characteristics. The most relevant variables are: traffic flows, rainfall totals, rainfall intensity, rainfall duration, antecedent dry periods, drainage area, and land use (Barbosa and Fernandes, 2009; Brezonik and Stadelmann, 2002; Chow et al., 2011). The relative influence of each variable is site specific; for instance, Chow et al. (2011) concluded that in a tropical climate stormwater quality is mainly influenced by storm size. Usually when modeling stormwater runoff, flow simulation results tend to be more accurate than water quality parameters estimation (Chang et al., 2008).

For practical applications, water quality modeling requires the selection and monitoring of the key parameters, the model simplification and the assumption of literature data for other model parameters, which increases the uncertainty already associated with the data (David and Matos, 2002; Rauch et al., 2002).

Several studies demonstrated that modeling approaches may be suitable and effective methods for evaluating stormwater strategies impact on receiving waters (German et al., 2005; Elliott and Trowsdale, 2007). According to Chen and Adams (2007) the types of models for estimation of urban stormwater runoff may be classified in three categories, namely: Design storm event approach; Continuous simulation approach and Derived probability distribution approach.

Deterministic stormwater hydraulic modeling is in a consolidated stage of knowledge and success in practical applications and, although the general mechanisms are known, the parameter variation cannot be universally described (Harremoës, 2002). Most models use buildup and wash off equations for runoff, algorithms for solid transport in the sewers, proportional relationships between the suspended solids and their attached pollutants and pollutant decay or transformation equations.

There are a number of references in the literature of studies aiming at establishing prediction tools for estimation of stormwater/road runoff pollutants. One of the key issues is the prediction of the first flush, which has been showed to vary to a large extent, even in the same catchment. Deletic (1998) considers that a generalized equation based on climate, rainfall and runoff characteristics may not be sufficient for predicting the first flush loading.

3. Relevant factors affecting stormwater management

3.1. *Geophysical factors*

Geophysical characteristics of the study area will affect the quantity and the quality of the stormwater. It influences the choice of the practice for the stormwater management and disposal. Within geophysical constraints one may consider climate, hydrology, land, soils and topography.

The climate and the hydrology of the catchment will affect primarily the quantity of water and, therefore, its quality. In a multiple regression analysis, Brezonik and Stadelmann (2002) confirmed that the drainage area and the rainfall amount and intensity were the most important variables for estimating event loads.

The geophysical constraint denominated by “land” includes its use, the drainage area and the space available for the implementation of stormwater solutions.

The role of the land use in urban stormwater quality management was investigated in Goonetilleke et al. (2005).

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They studied three different places with similar geological, topographical and climate variables but with different forms of land developments and housing density. The results show a significant impact of the urbanization on water environments due to the increase of runoff (replacement of previously pervious area with impervious surfaces) and the degradation of water quality (introduction of pollutants from various anthropogenic activities).

The drainage area is an important constraint not only for the water quantity but also for its quality. As an example, Lee and Bang (2000), after investigating nine different watersheds, found that the pollutant concentration peak can be correlated to the watershed area. The land topography influence is significant for hydraulic reasons and for BMP that deal with pipe or open channel.

Most solutions for stormwater management and disposal are physically implemented in the field; therefore the available space can be an important constraint in high density areas. The range of the space requirements for BMP is very wide. It can go from practices that do not detain runoff (e.g. filter strips) to practices that require large areas for detention without infiltration or evapotranspiration (Geosyntec Consultants, 2010).

The soils type and thickness should be considered in stormwater management because of its influence on runoff volumes and pollutant removal (Barbosa and Hvitved-Jacobsen, 2001). The decision to improve infiltration in urban areas depends on the soil permeability, but should also be carefully evaluated based on hydrogeological studies, due to the increasing risk of groundwater contamination (Pitt et al., 1999; Fischer et al., 2003; Powell et al., 2003).

3.2. *Law and social factors*

Research should precede legislation; however requirements from legislation clearly define different boundaries for engineering solutions (Hvitved-Jacobsen et al., 2010) and represent, as well, a driving force for research and applied solutions. This has been, for instance, the result of well known legislation: the Clean Water Act (1972) in the USA, and the Water Framework Directive (2000) in Europe. This EU Directive and its 'daughter' Directives define a new approach to water management, based on risk management, on public information and consultation using georeferenced technology, and on the establishment and maintenance of monitoring, forecasting and early warning systems. Their implementation strengthens the perception by society of the challenges of stormwater management, contributing to a higher level of participation and requirement, and to change the paradigms of institutions and politicians.

To be able to handle the social dimensions appropriately, measures that are attuned to spatial planning, urban renewal, traffic, recreation, education, culture, maintenance and management of public areas have to be included in an integrated approach. Thus, planning must be carried out by the drainage department in close cooperation with other city departments and with the public participation. This is seldom problem-free due to a limited culture of cooperation in this field and often unexpected institutional barriers. Most of the public and political support emerges out of the process when practical examples are shown, as in Augustenborg, Malmõ. The benefits may increase the price of the developments and incentivate private developers (Geldof and Stahre, 2004).

The nature of environmental problems and the role of official organisations vary in urban and rural context. E.g., high bacteria counts and downtown flooding were perceived to be the most pressing issues in an urban watershed studied by Hardy and Koontz (2010), while habitat loss and invasive species were seen as the greatest threats in the rural setting. In the urban watershed the key relationships are among municipal governments, and their officials are viewed as having important roles to play. In the rural watershed, fear of government interference enhanced the trust in local organizations and in the role of social capital (trust, social networks, and norms of reciprocity).

Roy et al. (2008) identified the lack of legislative mandate and the resistance to change as two of the seven major impediments to sustainable urban stormwater management in Australia and in the USA. The lack of a national legal obligation to control or treat stormwater runoff in those countries leads to inconsistent management policies across jurisdictions. The existence of multiple layers of risk and risk aversion are the main causes for resistance to change by both practitioners and the general public. Morison and Brown (2010) highlight that BMP tend to be ignored in municipalities of lower socio-economic status, with relatively few natural environmental assets, in part due to the use of a wrong communication, with lack of relevance to the laity, and weakly linked with the variety of interests and environmental problems of such communities. The higher levels of performance with stormwater management programs have been assessed in wealthier and more educated communities, as well as in coastal areas (White and Boswell, 2006; Morison and Brown, 2010) that due to recreation activities ensure economic and quality of life interests.

The delay of action in case of discharge violations and insufficient penalties to recover the economic benefits may harm compliance with legislation (Alsharif, 2010). However, a humble attitude toward the public demands and requests will facilitate the public acceptance of less attractive measures (Geldof and Stahre, 2004). Some facilities may be socially acceptable if their appearance is understood as necessary in supporting functions valued by the community (Wagner, 2008). On the other hand, a single high profile case of failure may undermine public confidence (Hatt et al., 2006). Therefore, education programs and pilot scale applications are fundamental. More sophisticated programs, such as stormwater retrofit auctions, appealing not only to the altruism but also to the profit-seeking feature of people, may be better succeeded engaging private landholders in the retrofit of stormwater retention measures on their properties (Fletcher et al., 2010). Some studies have shown homeowner clear preferences for some management practices and the trade-offs they are willing to make between alternative BMP (e.g.: Kaplowitz and Lupi, 2012).

3.3. *Technical and economic factors*

The costs of stormwater management should be considered at an early stage of the decision process. FHWA (2000) includes in

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management considerations not only the land acquisition, the construction, operation, maintenance and monitoring costs, but also other expenses that may be forgotten, such as the ones related to the effective life duration of the facility (years) and the technical training of staff. Therefore the relevant information to be evaluated is the cost-effectiveness of each BMP (Davis and Birch, 2009); this calculation requires reliable data on costs and on the performance of several BMP of each kind.

The use of market mechanisms to encourage end-users and industry to implement BMP at site and local level is an approach that has potential for a successful application and it is being encouraged in many countries. These include: i) price instruments (stormwater fees and charges); ii) allowance markets; iii) and voluntary offset (incentive) programs, such as the stormwater retrofit auctions described in Section 3.2. Nevertheless, the selection of an appropriate market-based approach is complicated as it depends on the unique physical characteristics of the catchment, on the existing legal structure, and on the social institutions and economic aspects of the community (Parikh et al., 2005). Many of these subjects were discussed in the previous sections.

The Total Maximum Daily Load (TMDL) is an approach currently used by the USEPA to restore impaired streams by allocating allowable loads to the polluters; it does not mandate any economic consideration, due to the complexity associated with pollutant load modeling and allocation. According to Zaidi et al. (2008), the incorporation of an economic assessment at an early stage of the TMDL process may ensure a successful implementation by providing technologically and economically feasible reduction targets.

When taking a decision on stormwater management it is relevant to bear in mind that a good solution may be not operational in all contexts. The local, regional and national practice and technical know-how must be evaluated before taking a decision. If it is acknowledged that there is a relevant lack of practice for a given method/technology, then a simpler solution should be adopted and the project itself may incorporate possible upgrades of the system in future stages.

Decision-making based on an Infrastructure Asset Management (IAM) Approach is “the art of balancing performance, cost and risk in the long term” (Brown and Humphrey, 2005). Alegre et al. (2011) describe an IAM approach aiming to assist water utilities in answering the following questions: i) Who are we at present, and what service do we deliver? ii) What do we own in terms of infrastructures? iii) Where do we want to be in the long term? iv) How do we get there?

4. Stormwater management and disposal

4.1. *In-sewer stormwater control*

Sustainability is currently a driving force in the evolution of water policy in developed countries. However, flooding and public health hazards are still the major issues in developing countries, where four-fifths of the world population lives, in many cases in overcrowded cities and in regions suffering from water scarcity (Chocat et al., 2007). Climate changes are posing increasing challenges in stormwater management and political decisions. Research results based on insurance data show that flood damage costs have been rising during the last two decades (Marsalek, 2000; Luechinger and Raschky, 2009; Ntelekos et al., 2010).

The construction of combined or separate sewer systems has been the major decision on flood control in urban areas for centuries. In the last decades, some developed countries have used detention inside the sewer system to reduce floods and combined sewer overflows discharges. This requires the construction of underground storage structures and, in some cases, the use of the potential storage capacity through real time control systems. The sustainability of this traditional approach has long been considered unfeasible and, consequently, a wide range of other source control measures have been increasingly used aiming to reduce runoff and pollutant loads entering into the sewers.

Based on the extrapolation of the current trends, Chocat et al. (2007) discuss three potential scenarios for the future in the framework of the most developed countries: the green, the technocratic and the privatization scenarios. The authors point out the risks of a rapid change for a “green scenario” resulting mainly from political decisions based at ecological appearance, eco-radicalism or short-term interests in the transfer of responsibilities from local authorities to end-users. On the opposite side, centralized systems using impressive technologies (such as automation, robotics, real-time control, third generation of communication, bio- and nano-technologies) are also attractive to decision makers that want to be in line with advanced technological progress. However such technologies tend to be very expensive, requiring top engineering. In addition they do not lead to changes in individual and corporate behavior, thus leaving people mentally unprepared for rare but probably dramatic failures.

4.2. *Stormwater source control*

The use of source control in stormwater management aims to reduce the excessive runoff and the pollutants loads that enter into the drainage system. The advantage is that these measures are usually more cost effective than the construction and maintenance of treatment systems. Nevertheless this statement may not be universal and a preliminary cost-benefit analysis of source control and other stormwater management strategies should be made before the decision is taken.

Source control measures could be non-structural such as alternative layouts of roads and buildings, minimizing imperviousness and maximizing the use of soils and vegetation; contaminant reduction and educational programmes to reduce stormwater pollution (FHWA, 2000). On the other hand, structural measures include the construction near the source of the stormwater of systems such as infiltration and rainwater re-use facilities or green roofs (Schroll et al., 2011).

Methods such as street sweeping meant to remove pollutants from the streets before they are washed out by rain events, are considered a source control measure, although is recognized that their implementation at a large scale is difficult (German et al., 2005).

There are enough evidences that source control measures have been efficient for reduction of the environmental impacts from stormwater runoff (Hvitved-Jacobsen et al., 2010). However, Chocat et al. (2007) point out three risks resulting from a too fast and wide-scale implementation of decentralized solutions: the limited knowledge about their potential harmless effects of a cumulative and long-term nature; the temptation of local authorities to use such solutions as a convenient way to free themselves from the costly obligation of maintaining water infrastructures; and the difficulties and costs associated to the operation of coexisting centralized and decentralized systems.

4.3. *Stormwater treatment*

Structural BMP consist in systems constructed to treat stormwater at the origin or near the discharge into the receiving waters, or into the urban rain sewer system (Wanielista and Yousef, 1993; FHWA, 1996; Dickie et al., 2010; Hvitved-Jacobsen et al., 2010). They operate by trapping and detaining stormwater runoff until unwanted pollutants settle out or are filtered. Common examples of these systems are: detention or retention ponds, wet ponds, infiltration trenches, infiltration basins, sand filters, grassed swales and constructed wetlands.

The decision to treat stormwater requires a previous assessment of its quantity and quality characteristics, the selection of the required treatment level and volume control and a good understanding of the local conditions available for the construction of the system. It must be evaluated, as well, the importance of secondary objectives, such as to integrate the treatment facility in an amenity or recreational/education area. These issues should be characterized in a small report before making a decision on a type of treatment system – or combination of systems.

When the local scenario is well defined it is possible to select the treatment system(s) more suitable to the conditions and the objectives of the treatment. The concept of best management decision imposes the need for a correct balance between a sound project with reasonable construction and maintenance costs, able to reduce the pollution to the required level (Barbosa and Fernandes, 2009). Several publications or sites (Wanielista and Yousef, 1993; FHWA, 1996; FHWA, 2000; Government of South Australia, 2002; US EPA, 2008; Dickie et al., 2010; Geosyntec Consultants, 2010; Hvitved-Jacobsen et al., 2010) describe the fundamentals of each type of treatment or system, project and design requirements/guidelines, maintenance and monitoring activities, etc. On the other hand, quite a lot of papers published in international conferences or in journals investigated the performance of specific treatment operations and systems (Barbosa and Hvitved-Jacobsen, 2001; Dimova et al., 2005; Maniquiz et al., 2010). Scholes et al. (2008) present very good and systematic information concerning the relative performance of different BMP in the removal of five common stormwater pollutants.

There are simpler and more advanced systems that integrated different methods or operations, in order to improve the treatment efficiency and retain both particulate, colloidal and dissolved pollutants (e.g.: Vollertsen et al., 2009). For instance, a solution to enhance treatment by infiltration may be the purchase of commercial aggregate materials (Nanbakhsh et al., 2007; Sommer and Sieker, 2005). Higher surface loads have been obtained by addition of appropriate chemicals and/or equipping the structures with lamella settlers (Rietsch et al., 2003). More complex systems usually are more expensive and require more maintenance and monitoring efforts.

In combined sewer systems, storage tanks are frequently designed to ensure a pre-treatment by settling to the overflow discharges. Recent upgrades of stormwater sedimentation tanks are showing that high-rate clarification is a promising cost-effective method for wet weather pollution abatement in combined systems (Averill et al., 2001; Capodaglio, 2003; Ding et al., 1999; Marsalek et al., 2003; David and Matos, 2005).

It is noteworthy this possibility to integrated strategies for pollutant control within the urban rain drainage system, such as sediment traps or commercial products and manufactured technologies that may be placed at specific points of the sewer system (e.g.: in gutters, Sommer and Sieker, 2005; FHWA, 2000).

The risk of failure or not achieving the target efficiencies is also something to be faced and evaluated. Another issue of practical importance is the costs associated with project, construction and maintenance of a BMP; several of them are difficult to estimate and may be increased by unexpected occurrences during operation (FHWA, 2000).

Barbosa and Fernandes (2009) recommend that the project of a treatment system should give some indications concerning monitoring the efficiency and prepare devices or structures needed for the monitoring actions. This purpose is especially important for any structural BMP that do not present an open inlet and/or outlet, as is the case of infiltration systems. Several authors advice each country to evaluate its practice in stormwater management and to produce guidelines with respect to design construction, operation and maintenance of treatment systems and for evaluation of costs and benefits from different options, taking into account the views of different stakeholders (Hatt et al., 2006; Martin et al., 2007; Barbosa and Fernandes, 2009). Among the guidelines there should be the obligation to have an ID of each system including design, operation activities and the results from monitoring, together with the comparison of the system performance with the project target treatment efficiency.

5. Steps toward a sustainable decision

The transition to more sustainable stormwater management is a slow process, and each country should find out its place in this process, learning from more developed regions/countries but always taking sustainable steps forward. Marsalek and Schreier (2009) recommend using a range of combinations of innovative measures, rather than focusing on single innovations, in order to provide more reliable solutions, incorporating the different site and catchment characteristics.

It is common that the evaluation of national practices ends up emphasizing the importance of developing well established guidelines concerning construction, operation and maintenance of stormwater sustainable solutions (e.g.: Hatt et al., 2006; Barbosa and Fernandes, 2009; Marsalek and Schreier, 2009). Several countries or states have already produced their own guidelines for this purpose (Government

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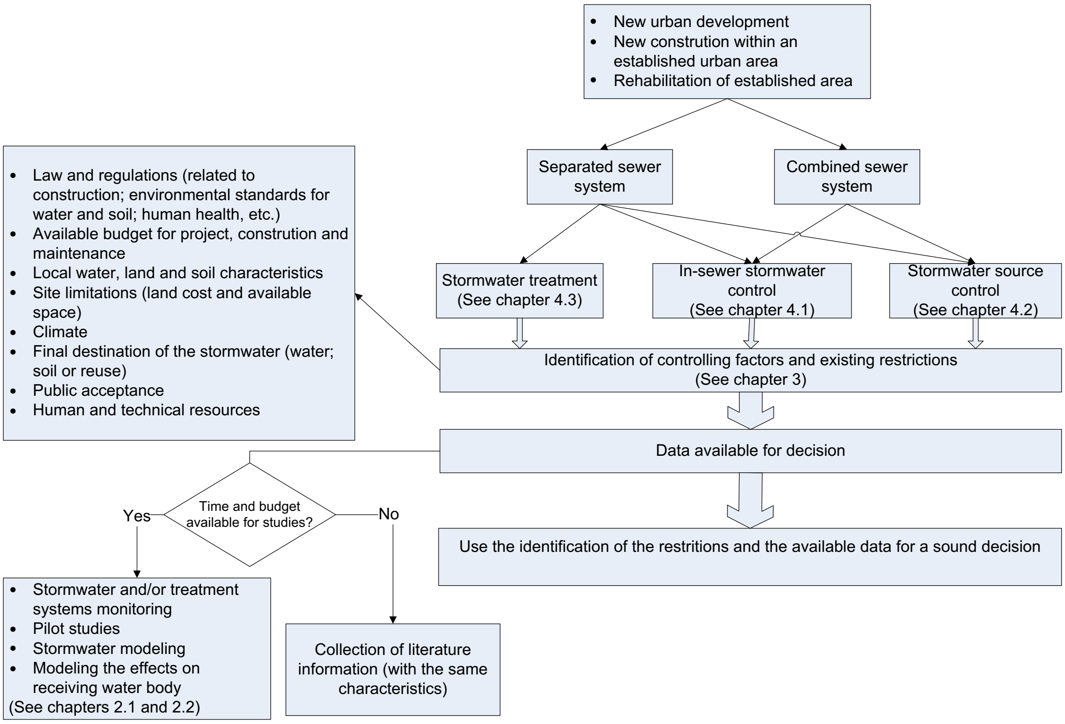

Fig. 2 – Stormwater management decision support flowchart.

of South Australia, 2002; Dickie et al., 2010; Geosyntec Consultants, 2010); these and other existing documents are of most use for the ones enrolled in stormwater management.

Fig. 2 summarizes in a flowchart the steps and the most relevant processes and information that should be taken into account in urban development when the objective is to contribute to sustainable stormwater management.

There are more advanced tools that may be used, such as GIS based decision support systems combined or not with other methods developed to assess decision makers (Burton and Pitt, 2002; Viavattene et al., 2008; SWITCH, 2009). Another possibility is to use models for stormwater and BMP; there are several of them, presenting different possibilities but also limitations. Elliott and Trowsdale (2007) evaluated ten stormwater models, focusing on their role for predicting at least some water quality and flow effects from BMP application, and concluded that there is considerable scope for improvement.

All the different options have advantages and shortcomings; one crucial fact is that the more sophisticated the tool for stormwater management is, the more experienced and specialized the user should be, in order to overcome difficulties and analyze the outputs with a critical eye.

6. Final remarks

The approach to sustainable stormwater management must be flexible and multidisciplinary, and consider law, economic, social and environmental aspects, among many others. Best Management Practices (BMP) should also be seen as an opportunity for development and improvement of social, educational and environmental conditions in urbanized and nearby areas; therefore it requires a wide perspective and the participation of different stakeholders.

Economic or technical constraints define different decision scenarios; noteworthy is that innovative and high technological solutions are not necessarily the best or most effective ones: their cost and risk of failure may undermine them when compared to more traditional BMP. Therefore a good decision is not unique; it depends on the place, on the occasion it is made and on the available information. The contribution that science and research are continuously providing is precious, enabling a better understanding of stormwater characteristics and its effects on ecosystems and water resources.

In addition to some limited knowledge about the potential harmless long-term effects of most recent alternative solutions, constraints in properly designing and implementing stormwater managing strategies may arise from current data gaps on the mobilization of organic compounds by stormwater. Such data gaps are of particular concern in the context of recent climate changes.

It is crucial to understand that a high-quality decision needs both time and a fair overview of the problem: this document would like to contribute to sustainable stormwater management, informing on the most relevant factors that should be assessed and their interaction.

REFERENCES

Alegre, H., Covas, D., Coelho, S.T., Almeida, M.C., Cardoso, M.A., 2011. An integrated approach for infrastructure asset management of urban water systems. In: Proceedings of IWA

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4th Leading Edge Conf. on Strategic Asset Management, Mülheim An Der Ruhr, Germany.

Alsharif, K., 2010. Construction and stormwater pollution: policy, violations, and penalties. Land Use Policy 27 (2), 612–616.

Angelakis, A.N., Koutsoyiannis, D., Tchobanoglous, G., 2005. Urban wastewater and stormwater technologies in ancient Greece. Water Research 39 (1), 210–220.

Averill, D., Chessie, P., Henry, D., Fok, S., Marsalek, J., Seto, P., 2001. Field experiences with chemically-aided settling of combined sewer overflows. In: Proceedings of the 4th Int. Conf. Novatech, vol. 1, pp. 237–244.

Bach, P.M., McCarthy, D.T., Deletic, A., 2010. Redefining the stormwater first flush phenomenon. Water Research 44 (8), 2487–2498.

Bachoc, A., Tabuchi, J.P., Chebbo, G., Philippe, J.P., 1994. Urban stormwater pollution: quantity, origin and nature (in French). La Houille Blanche 1–2, 21–33.

Barbosa, A.E., Fernandes, J.N., 2009. Assessment of treatment systems for highway runoff pollution control. Water Science and Technology 59 (9), 1733–1742.

Barbosa, A.E., Hvitved-Jacobsen, T., 2001. Infiltration pond design for highway runoff treatment in semiarid climates. Journal of Environmental Engineering, ASCE 127 (11), 1014–1022.

Bertrand-Krajewski, J.-L., 2007. Stormwater pollutant loads modelling: epistemological aspects and case studies on the influence of field data sets on calibration and verification. Water Science and Technology 55 (4), 1–17.

Bester, K., Scholes, L., Wahlberg, C., McArdell, C.S., 2008. Sources and mass flows of xenobiotics in urban water cycles – an overview on current knowledge and data gaps. Water, Air & Soil Pollution: Focus 8 (5–6), 407–423.

Björklund, K., 2011. Sources and fluxes of organic contaminants in urban runoff. Thesis for the degree of Doctor in Philosophy, Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden, 63 pp.

Brezonik, P.L., Stadelmann, T.H., 2002. Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota. Water Research 36 (7), 1743–1757.

Brown, R.B., 2003. Institutionalization of Integrated Urban Stormwater Management: Multiple-Case Analysis of Local Management Reform across Metropolitan Sydney. Doctor of Philosophy thesis. School of Civil and Environmental Engineering, University of New South Wales.

Brown, R.E., Humphrey, B.G., 2005. Asset management for transmission and distribution. IEEE Power and Energy Magazine 3 (3), 39–45.

Burton Jr., G.A., Pitt, R.E., 2002. Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. Lewis Publishers, 911 pp.

Capodaglio, A.G., 2003. Improving sewage treatment plant performance in wet weather. In: Nato ARW on Enhancing Urban Environment by Environmental Upgrading and Restoration. NATO Science Series, IV, vol. 43, pp. 155–166.

Chang, C., Wen, C., Lee, C., 2008. Use of intercepted runoff depth for stormwater runoff management in industrial parks in Taiwan. Water Resources Management 22 (11), 1609–1623.

Chen, J., Adams, B., 2007. Development of analytical models for estimation of urban stormwater runoff. Journal of Hydrology 336 (3–4), 458–469.

Chocat, B., Ashley, R., Marsalek, J., Matos, M.R., Rauch, W., Schilling, W., Urbonas, B., 2007. Toward the sustainable management of urban storm-water. Indoor and Built Environment 16 (3), 273–285.

Chow, M.F., Yusop, Z., Mohamed, M., 2011. Quality and first flush analysis of stormwater runoff from a tropical commercial catchment. Water Science and Technology 63 (6), 1211–1216.

Cooper, P.F., 2001. Historical aspects of wastewater treatment. In: Lens, P., Zeeman, G., Lettinga, G. (Eds.), Decentralized Sanitation and Reuse: Concepts, Systems and Implementation. IWA Publishing, pp. 11–38.

David, L.M., Matos, R.S., 2002. Wet weather water quality modelling of a Portuguese urban catchment: difficulties and benefits. Water Science and Technology 45 (3), 131–140.

David, L.M., Matos, J.S., 2005. CSO emissions to bathing waters in Portugal. How to reduce in densely urbanised areas? Water Science and Technology 52 (9), 183–190.

Davis, B.S., Birch, G.F., 2009. Catchment-wide assessment of the cost-effectiveness of stormwater remediation measures in urban areas. Environmental Science & Policy 12, 84–91.

Deletic, A., 1998. The first flush load of urban surface runoff. Water Research 32 (8), 2462–2470.

Dickie, S., Ions, L., McKay, G., Shaffer, P., 2010. Planning for SuDS – Making It Happen (C687). CIRIA, 112 pp.

Dimova, G., Woods, B., Kellagher, R., 21–26 August 2005. A critical appraisal of retention pond sizing criteria for water quality treatment. In: Proceedings of the 10th International Conference on Urban Drainage, Copenhagen/Denmark, p. 8.

Ding, Y., Dresnack, R., Chan, P., 1999. Assessment of High-Rate Sedimentation Processes: Microcarrier Weighted Coagulation Jar Tests. Internal Report. Department of Civil and Environmental Engineering. New Jersey Institute of Technology, Newark, New Jersey.

Elliott, A.H., Trowsdale, S.A., 2007. A review of models for low impact urban stormwater drainage. Environmental Modelling & Software 22 (3), 394–405.

Eriksson, E., Baun, A., Mikkelsen, P.S., Ledin, A., 2005. Chemical hazard identification and assessment tool for evaluation of stormwater priority pollutants. Water Science and Technology 51 (2), 47–55.

Eriksson, E., Baun, A., Mikkelsen, P.S., Ledin, A., 2007. Risk assessment of xenobiotics in stormwater discharged to Harrestrup Å, Denmark. Desalination 215 (7), 187–197.

FHWA, 1996. Evaluation and Management of Highway Runoff Water Quality. Federal Highway Administration n.° FHWA-PD-96-032. U.S. Department of Transportation, Washington, 457 pp.

FHWA, 2000. Stormwater Best Management Practices in an Ultra-urban Setting: Selection and Monitoring. Federal Highway Administration n. FHWA-EP-00–002. U.S. Department of Transportation, Washington, 287 pp.

Fischer, D., Charles, E.G., Baehr, A.L., 2003. Effects of stormwater infiltration on quality of groundwater beneath retention and detention basins. Journal of Environmental Engineering 129 (5), 464–471.

Fletcher, T.D., Walsh, C.J., Bos, D., Nemes, V., RossRakesh, S., Prosser, T., Hatt, B., Birch, R., 2010. Evaluating the multiple benefits of an allotment-scale stormwater retrofit auction. In: Proceedings of Novatech 2010.

Gasperi, J., Gromairea, M., Kafia, M., Moillerona, R., Chebboa, G., 2010. Contributions of wastewater, runoff and sewer deposit erosion to wet weather pollutant loads in combined sewer systems. Water Research 44 (20), 5875–5886.

Geldof, G.D., Stahre, P., 2004. The Interaction between Water and Society. A new approach to stormwater management. In: Nato ARW on Enhancing Urban Environment by Environmental Upgrading and Restoration. NATO Science Series, IV, vol. 43, pp. 381–394.

Geosyntec Consultants, 2010. Stormwater BMP Guidance Tool- A Stormwater Best Management Practices Guide for Orleans and Jefferson Parishes, Prepared for Bayou Land and Louisiana, 142 pp.

German, J., Vikström, M., Svensson, G., Gustafsson, L.-G., 2005. Integrated stormwater strategies to reduce impact on receiving waters. In: Proceedings of the 10th International

Conference on Urban Drainage, Copenhagen/Denmark, 21–26 August, 2005.

Goonetilleke, A., Thomas, E., Ginnc, S., Gilbert, D., 2005. Understanding the role of land use in urban stormwater quality management. Journal of Environmental Management 74, 31–42.

Government of South Australia, 2002. Guidelines for Urban Stormwater Management, Produced by Patawalonga Catchment Water Management Board - Torrens Catchment Water Management Board and Planning SA, 153 pp.

Griffith, J.F., Schiff, K.C., Lyon, G.S., Fuhrman, J.A., 2010. Microbiological water quality at non-human influenced reference beaches in southern California during wet weather. Marine Pollution Bulletin 60 (4), 500–508.

Hardy, S.D., Koontz, T.M., 2010. Collaborative watershed partnerships in urban and rural areas: different pathways to success? Landscape and Urban Planning 95 (3), 79–90.

Harremoës, P., 2002. Integrated urban drainage, status and perspectives. Water Science and Technology 45 (3), 1–10.

Hathaway, J.M., Hunt, W.F., 2010. Evaluation of first flush for indicator bacteria and total suspended solids in urban stormwater runoff. Water, Air & Soil Pollution 217 (1–4), 135–147.

Hatt, B.E., Deletic, A., Fletcher, T.D., 2006. Integrated treatment and recycling of stormwater: a review of Australian practice. Journal of Environmental Management 79 (1), 102–113.

Helsel, D.R., 1990. Less than obvious: statistical treatment of data below the detection limit. Environmental Science and Technology 24 (12), 1766–1774.

Huang, J., Tu, Z., Du, P., Lin, J., Li, Q., 2010. Uncertainties in stormwater runoff data collection from a small urban catchment, Southeast China. Journal of Environmental Sciences 22 (11), 1703–1709.

Hvitved-Jacobsen, T., Yousef, Y.A., 1991. Highway runoff quality, environmental impacts and control. In: Hamilton, Ronald S., Harrison, Roy M. (Eds.), 1991. Highway Pollution, Studies in Environmental Science, vol. 44. Elsevier, pp. 165–207.

Hvitved-Jacobsen, T., Vollertsen, J., Nielsen, A.H., 2010. Urban and Highway Stormwater Pollution. Taylor & Francis Inc, 347 pp.

Kaplowitz, M.D., Lupi, F., 2012. Stakeholder preferences for best management practices for non-point source pollution and stormwater control. Landscape and Urban Planning 104, 364–372.

Lau, S., Stenstrom, M.K., 2005. Metals and PAHs adsorbed to street particles. Water Research 39 (17), 4083–4092.

Lee, J., Bang, K., 2000. Characterization of urban stormwater runoff. Water Research 34 (6), 1773–1780.

Lee, H., Lau, S., Kayhanian, M., Stenstrom, M.K., 2004. Seasonal first flush phenomenon of urban stormwater discharges. Water Research 38 (19), 4153–4163.

Lee, H., Swamikannub, X., Radulescub, D., Kimc, S., Stenstrom, M.K., 2007. Design of stormwater monitoring programs. Water Research 41 (18), 4186–4196.

Leecaster, M., Schiff, K., Tiefenthaler, L., 2002. Assessment of efficient sampling designs for urban stormwater monitoring. Water Research 36 (6), 1556–1564.

Luechinger, S., Raschky, P.A., 2009. Valuing flood disasters using the life satisfaction approach. Journal of Public Economics 93 (3–4), 620–633.

Maheepalaa, U., Takyib, A., Perera, B., 2001. Hydrological data monitoring for urban stormwater drainage systems. Journal of Hydrology 245 (1–4), 32–47.

Maniquiz, M.C., Lee, S., Kim, L., 2010. Long-term monitoring of infiltration trench for nonpoint source pollution control. Water, Air & Soil Pollution 212 (1–4), 13–26.

Marsalek, J., 2000. Overview of flood issues in contemporary water management. In: Marsalek, J., Watt, W.E., Zeman, E., Sieker, F. (Eds.), Flood Issues in Contemporary Water Management. NATO Science Series: Series, vol. 2. Environmental security, Kluwer Academic Publishers, Dordrecht, pp. 1–16.

Marsalek, J., Schreier, H., 2009. Innovation in stormwater management in Canada: the way forward. Overview of the Theme Issue. Water Quality Research Journal of Canada 44 (1), v–x.

Marsalek, J., He, C., Rochfort, Q., Exall, Wood, K., Krishnappan, B.G., Seto, P., Chessie, P., 2003. Upgrading the North Toronto combined sewer overflow storage and treatment facility. In: Nato ARW on Enhancing Urban Environment by Environmental Upgrading and Restoration. NATO Science Series, IV, vol. 43, pp. 93–103.

Martin, C., Ruperd, Y., Legret, M., 2007. Urban stormwater drainage management: the development of multicriteria decision aid approach for best management practices. European Journal of Operational Research 181 (1), 338–349.

McCarthy, D.T., Deletic, A., Mitchell, V.G., Fletcher, T.D., Diaper, C., 2008. Uncertainties in stormwater *E. coli* levels. Water Research 42 (6–7), 1812–1824.

Morison, P.J., Brown, R.R., 2010. Understanding the nature of publics and local policy commitment to Water Sensitive Urban Design. Landscape and Urban Planning 99, 83–92.

Nanbakhsh, H., Kazemi-Yazdi, S., Scholz, M., 2007. Design comparison of experimental storm water detention systems treating concentrated road runoff. Science of the Total Environment 380, 220–228.

Novotny, V., 2003. Water Quality: Diffuse Pollution and Watershed Management. John Wiley & Sons, Inc., 864 pp.

Ntelekos, A.A., Oppenheimer, M., Smith, J.A., Miller, A.J., 2010. Urbanization, climate change and flood policy in the United States. Climatic Change 103 (3–4), 597–616.

Parikh, P., Taylor, M.A., Hoagland, T., Thurston, H., Shuster, W., 2005. Application of market mechanisms and incentives to reduce stormwater runoff. An integrated hydrologic, economic and legal approach. Environmental Science & Policy 8 (2), 133–144.

Pitt, R., Clark, S., Field, R., 1999. Groundwater contamination potential from stormwater infiltration practices. Urban Water 1 (3), 217–236.

Powell, K.L., Taylor, R.G., Cronin, A.A., Barrett, M.H., Pedley, S., Sellwood, J., Trowsdale, S.A., 2003. Microbial contamination of two urban sandstone aquifers in the UK. Water Research 37 (2), 339–352.

Rauch, W., Bertrand-Krajewski, J.-L., Krebs, P., Mark, O., Schilling, W., Schütze, M., Vanrolleghem, P.A., 2002. Deterministic modelling of integrated urban drainage systems. Water Science and Technology 45 (3), 81–94.

Rietsch, B., Buer, T., Dettmar, J., 8–13 September 2003. Design of stormwater structures with special regard to sedimentation processes. In: Proceedings of the 9th Int. Conf. on Urban Drainage, Portland, Oregon. USA.ASCE/IWA/EWRI/IAHR (CD ROM).

Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Thurston, H.W., Brown, R.R., 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. Environmental Management 42, 344–359.

Schiff, K., Kinney, P., 2001. Tracking sources of bacterial contamination in stormwater discharges from Mission Bay, California. Water Environment Research 73 (5), 534–542.

Scholes, L., Revitt, D.M., Ellis, J.B., 2008. A systematic approach for the comparative assessment of stormwater pollutant removal potentials. Journal of Environmental Management 88 (3), 467–478.

Schroll, E., Lambrinos, J., Righetti, T., Sandrock, D., 2011. The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. Ecological Engineering 37 (4), 595–600.

Sommer, H., Sieker, H., 21–26 August 2005. Reduction of load from street-runoff by an inlet-filtration-system filled with adsorptive material. In: Proceedings of the 10th International Conference on Urban Drainage, Copenhagen, Denmark, p. 8.

SWITCH, 2009. A GIS Data Integration Tool for Assessing Stormwater Management Options: User Guide, Deliverable 2.3.2a, 30 pp. http://www.switchurbanwater.eu/outputs/pdfs/W2-3_GEN_MAN_D2.3.2a_GIS_data_integration_tool_user_guide.pdf.

Tillinghast, E., Hunt, W., Jennings, G., 2011. Stormwater control measure (SCM) design standards to limit stream erosion for Piedmont North Carolina. Journal of Hydrology 411 (3–4), 185–196.

US EPA, 2008. National Pollutant Discharge Elimination System, National Menu of Stormwater Best Management Practices. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm.

Viavattene, C., Scholes, L., Revitt, D.M., Ellis, J.B., 2008. A GIS based decision support system for the implementation of Stormwater Best Management Practices. In: Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, p. 9.

Vollertsen, J., Lange, K.H., Pedersen, J., Hallager, P., Brink-Kjær, A., Laustsen, A., Bundesen, V.W., Brix, H., Arias, C., Nielsen, A.H., Nielsen, N.H., Wium-Andersen, T., Hvitved-Jacobsen, T., 2009. Advanced stormwater treatment – comparison of technologies. In: Proceedings of the 11th Nordic/Nordiwa Wastewater Conference, pp. 44–53.

Wagner, M.M., 2008. Acceptance by knowing? The social context of urban Riparian Buffers as a stormwater best management practice. Society and Natural Resources 21, 908–920.

Wanielista, M.P., Yousef, Y.A., 1993. Stormwater Management. John Wiley & Sons, Inc., 579 pp.

White, S.S., Boswell, M.R., 2006. Planning for water quality: implementation of the NPDES Phase II stormwater program in California and Kansas. Journal of Environmental Planning and Management 49 (1), 141–160.

Zaidi, A.Z., de Monsabert, S.M., El-Farhan, R., 2008. How to include economic analysis in TMDL allocation. Journal of Water Resources Planning and Management 134 (3), 214–223.

Zhang, Z., Lennox, W.C., Panu, U.S., 2004. Effect of percent non-detects on estimation bias in censored distributions. Journal of Hydrology 297 (1–4), 74–94.

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