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Urban drainage system planning and design – challenges with climate change and urbanization: a review

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ABSTRACT

Urban drainage systems are in general failing in their functions mainly due to non-stationary climate and rapid urbanization. As these systems are becoming less efficient, issues such as sewer overflows and increase in urban flooding leading to surge in pollutant loads to receiving water bodies are becoming pervasive rapidly. A comprehensive investigation is required to understand these factors impacting the functioning of urban drainage, which vary spatially and temporally and are more complex when weaving together. It is necessary to establish a cost-effective, integrated planning and design framework for every local area by incorporating fit for purpose alternatives. Carefully selected adaptive measures are required for the provision of sustainable drainage systems to meet combined challenges of climate change and urbanization. This paper reviews challenges associated with urban drainage systems and explores limitations and potentials of different adaptation alternatives. It is hoped that the paper would provide drainage engineers, water planners, and decision makers with the state of the art information and technologies regarding adaptation options to increase drainage systems efficiency under changing climate and urbanization.

Key words | drainage system design, integrated systems, peak flow estimation, stormwater runoff, sustainable adaptation technologies, uncertainty

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INTRODUCTION

Over more than a century, urban drainage systems have been constructed in cities across the world in order to prevent the nuisance from flooding by quickly removing the runoff from urban areas. Combined stormwater and wastewater drainage systems were also provided with the similar objective in some parts of the world. The history of drainage system construction dates back to the early third millennium BC during the Indus civilization (Mays 2001). Ancient practices initiated by Romans with surface water systems included open channels in public areas for the purpose of runoff drainage. These practices further developed to underground combined sewer systems which were designed to remove sanitary waste and urban surface runoff.

In the late 18th century, a progressive attention was provided to wet-weather flow management, intending to transfer the increased runoff further away from urban area, which required larger stormwater collection systems (interceptors) with respect to the growing population. It resulted in higher investment cost for overall urban drainage systems.

As the combined systems transported sewage from the urban area to receiving water bodies, anthropogenic pollutants in watercourses were recognized by the middle to late 19th century. This problem was further aggravated by rapid urbanization. Consequently, treatment practices were initiated as the next major step in drainage system design. The problem also initiated a debate on the adoption of either combined or separate sewer systems. By the early 20th century, higher treatment cost required for combined systems resulted in the USA turning to the separate systems as the more cost-effective option (Methods & Durrans 2003). However, combined systems are still in use in some countries across the world. There is no general consensus on the overall better effectiveness of these two systems. A recent study has indicated that the separate system has no advantage over the combined system in terms of pollutant control (Li *et al.* 2013).

By the late 20th century, problems associated with drainage systems' failure, such as flooding, downstream erosion, deteriorating water quality, and environmental issues, were addressed by sustainable practices entailing detention/retention basin, bio-filtration trenches, porous pavement, sand filters, and water quality inlets (Watt *et al.* 2003). In particular,

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these practices intended to address the climate change effects of increase in runoff rate and volume on drainage systems. However, these approaches impose additional capital and maintenance costs to drainage systems.

Notwithstanding all advancements in the design of urban drainage systems due to new technologies and ongoing research, drainage systems are still facing breakdown in their function in the 21st century. The exacerbating problem of flooding is endangering urban areas in terms of nuisance due to local water ponding on streets, health issues resulting from possible contamination of potable water supply, and property losses and their associated economic and social impacts on the community. Also, environmental and ecological consequences of drainage systems' failure, mainly pollutant loading in watersheds, are jeopardizing availability of fresh water resources for meeting increased potable water demands. The climate change impacts are worsening some of these consequences, which would be difficult to assess due to their uncertain nature. In addition, urbanization is making uncertain impacts on drainage systems. It is still debatable as to how urbanization influences the drainage systems' efficiency. Varying pervious/impervious area ratio, detention/retention storage reduction, and rainfall increase due to urban heat island (UHI) effect are among those uncertain urbanization-induced drivers. Moreover, understanding their combined impact is complex.

The lack of our understanding on the impacts of climate change and urbanization is a strong barrier in establishing an effective integrated urban drainage implementation plan. In order to deal with the drainage system failures, it is critically important to accurately predict hydrological data affected by climate change, such as annual and extreme rainfall, antecedent soil moisture, sea level rise, and groundwater level variations during the lifetime of the drainage infrastructures. Other drivers affecting the drainage systems and their efficiencies must be recognized by monitoring and regular inspection, where the information is lacking in the initial stages of integrated planning. This would provide the design engineers with updated input data for the planning and design of drainage systems. Rather than investigating uncertain future factors, revising the design process through integrated design and planning could reveal the deficiency of the existing systems and also help engineers and decision makers to establish a place-based design framework. It is also necessary to perform a cost–benefit analysis in order to avoid costly future retrofits. To achieve these objectives, a group of professionals from different disciplines, such as geology, environmental science, engineering, and urban planning, in consultation with the stakeholders and decision makers, should collaborate, so as to derive the best adaptation option for a specific local area based on state of the art studies and technologies. Also, as stated by the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (Core Writing Team 2007), the adaptation option needs to be periodically reviewed under a changing climate. For this purpose, it is essential to expand our knowledge on possible adaption options and their local applicability. The main objective of this paper is to review challenges facing drainage systems and corresponding adaptation options in order to provide the engineers and decision makers with state of the art information required for the provision of improved drainage systems in urban areas.

HISTORY OF URBAN DRAINAGE DESIGN APPROACHES

An urban drainage system is generally defined as a runoff collection and transportation system, which is responsible for quickly removing stormwater runoff only from urban areas to prevent any flooding. Such systems are known as separate drainage systems and are widely used in Australia and North America (Vymazal 2010). However, combined sewer systems, which transport urban runoff as well as municipal wastewater, are still working in some part of the world (Europe, Asia, and Africa). These systems have similar function to the urban drainage systems in terms of runoff removal. The first step in the design of drainage systems is to estimate design discharge resulting from stormwater runoff. Pipe sizing is generally performed based on the preselected slope considering velocity constraints and then using the peak flow discharge. Traditionally, estimating peak flow discharge is based on empirical formulas, which were developed for site-specific conditions and, therefore, resulted in poor estimation (e.g. Adams, McMath, and Talbot in Methods & Durrans (2003)). These formulas evolved to conceptual methods (e.g. rational method) in the second half of the 19th century (Methods & Durrans 2003). Also, some modifications had been made regarding pipe resistance description following the recognition of the dependency of traditional Hazen–Williams and Maning equations on Reynolds numbers (Carter *et al*. 1963; Liou 1998). This could limit the accuracy of these equations for conditions different from those for which the equations had been developed. The Darcy–Weisbach equation was then recommended as the substitute for traditional equations (Brown 2002). However, this recommendation was ignored during the last decades because of the cumbersome approach presented by the American Society of Civil Engineers (ASCE) Task Force (Fenton 2010). This problem was addressed by developing a Reynolds number-dependent formula interpolating between the smooth boundary and fully rough flow formulas (Yen 1992).

The rational method, as the widely known equilibrium-based method, was developed in 1851 by Mulvaney for peak flow estimation in small to medium watersheds with no significant storage. It takes into account the steady state condition to estimate peak runoff discharge resulting from a rainfall event of specific recurrence interval, which is usually in the range of 2–10 years and occasionally up to 25 years (Watt *et al.* 2003). The rational method has been the most common method because it is simple, and also because urban drainage design typically requires peak discharge data only (Methods & Durrans 2003). The Rational approach has been formulated as below:

$$Q = 0.278\,CiA \qquad (1)$$

where Q = runoff rate (m^3/s); C = runoff coefficient; i = average rainfall intensity (mm/hour); and A = drainage area (km^2). The unit conversion factor of 0.278 should be recalculated when using different units for rainfall intensity and drainage area.

Rainfall intensity is typically derived from intensity–duration–frequency (IDF) curves, also referred to as intensity–frequency–duration (IFD) in Australia, which traditionally derive from statistical analysis of rainfall records. A 'storm/design duration' has to be assumed to utilize these curves. The critical condition, needed to perform design of drainage systems, is achieved by assuming the storm/design duration to be equal to the 'time of concentration', which is the smallest time for which the entire basin is contributing runoff to the basin outlet (Methods & Durrans 2003). Also, runoff coefficient varies spatially based on infiltration characteristics of the catchment's surfaces and the impact of other runoff losses (QUDM 2013). Some tables are available to provide recommended runoff coefficients for different land uses (Methods & Durrans 2003). For a basin having a combination of various pervious and impervious surfaces, a composite runoff coefficient is required to be derived. It must also account for any land use changes indicated in the local urban development plan (QUDM 2013). The selection of a runoff coefficient is highly dependent on the judgment of the designers and engineers.

It is important to consider the limitations and restrictions of the rational method while applying it in the design procedure. The assumption of considering the time of concentration as the storm duration is not logical for large basins; thus the applicability of the rational method is limited to small drainage basins. Also, the application of the rational method would require a steady state climate, where spatial and temporal distribution of the storm intensity must be constant, which would not be the case in large catchments. It is also highlighted in the literature that physical features of the catchments could limit the applicability of the rational method (QUDM 2013). Small catchments are defined variably by different local authorities for the application of the rational method. The upper limits of 25 and 500 km^2 for 'small' and 'medium' watersheds, respectively, are suggested for Australian watersheds (Goyen *et al.* 2014), while ASCE suggested an upper limit of 0.8 km^2 (80 ha) for American watersheds (WEF & ASCE 1992) for the application of the rational method. However, depending upon the local characteristics, the upper limit can reduce to 0.04 km^2 (4 ha) in some cases (Methods & Durrans 2003). A small drainage basin would translate to a small time of concentration, which necessitates an accurate means to estimate short duration rainfall intensity. As a solution, equations were developed to provide better estimation of short duration rainfall (1 hour or less) (Froehlich 2010).

The conventional rational formulation is a poor estimation method as it assumes a constant runoff coefficient through a deterministic manner. Alternatively, probabilistic interpretation of the rational method was first developed by Homer & Flynt (1936), which considers varying runoff coefficient from storm to storm. The probabilistic method has been utilized extensively in Australia and has shown to be a more advantageous and favorable method than the conventional rational method (Pilgrim *et al.* 1989). The current design procedure in Australia has been derived based on the following formulation (Pilgrim 2001):

$$Q(Y) = 0.278C(Y)I(t_c, Y)A \qquad (2)$$

where t_c = time of concentration (hour); Y = average recurrence interval (ARI) of y years selected by a frequency analysis of observed flood data available at the site; $I(t_c, Y)$ = average rainfall intensity of selected ARI; $Q(Y)$ = peak flow of selected ARI; and $C(Y)$ = runoff coefficient for selected ARI.

As another renowned conceptual method, the Soil Conservation Service Curve Number (SCS-CN) method, applicable for small watersheds, was introduced in the 1950s by the US Soil Conservation Service, intending to determine the direct runoff volume from effective precipitation depth. It takes into account initial abstraction, consisting of interception, infiltration, and depression storage, and retention capacity of the catchment, which refers to continuing infiltration following the runoff initiation (Methods & Durrans 2003). The method has been formulated as documented below in Equation (3) (Methods & Durrans 2003):

$$P_e = \frac{(P - I_a)^2}{(P - I_a) + S}\ ; \qquad S = \frac{1000}{\text{CN}} - 10 \tag{3}$$

which is valid for $P > I_a$; $P = 0$ otherwise. Here, $P_e =$ depth of effective precipitation (runoff in mm); $S =$ maximum possible retention after runoff begins (mm); $P =$ total rainfall depth in storm (mm); CN = runoff curve number; and $I_a =$ equivalent depth of initial abstractions (mm). An extensive graphical and tabular solution to this method has been presented in Technical Release 55 (SCS 1986). CN could be derived from available curve number tables based on antecedent moisture condition (for preceding 5 days) (Liu & Li 2008), soil group and cover type/land use. Apparently, the CN parameter reflects human activities and urbanization impacts. So, it should be revised and updated with respect to the urban development plan, reflecting the change in development density. CN value was also found to be inversely variable with drainage area (Simanton *et al.* 1996). A composite CN estimation is required for an area of different land uses, which can be calculated as an area-weighted average of individual curve numbers (Methods & Durrans 2003).

The SCS-CN method became popular due to its simplicity and easy application. It also accounts for most of the watershed characteristics associated with runoff production and incorporates them in the CN parameter. Moreover, it provides better details in describing physical characteristics of the watershed, which led to its applicability to bigger watersheds than those in the rational method (Maidment 1992). It also accounts for the antecedent conditions, which are neglected in the rational method. Conversely, the CN values need to be accurately assessed for each locale (Liu & Li 2008; Wood *et al.* 2010). It could depend on rainfall depth in some locations (Soulis *et al.* 2009). Furthermore, it does not consider the spatial and temporal variability of the antecedent condition and continuing losses, which could make it a less reliable predictive method (Ponce & Hawkins 1996). Many studies have been conducted to amend the incorporation of antecedent conditions into the SCS-CN method (Michel *et al.* 2005; Jain *et al.* 2006; Mishra *et al.* 2008).

Comparing the rational and SCS-CN methods, it was shown that the SCS-CN method could be utilized for surface runoff estimation while the rational method could estimate the peak runoff rate only (Varanou *et al.* 2002). Besides the rational and SCS-CN methods, there are some other methods to estimate peak flow discharge, which have their own advantages and disadvantages (Wood *et al.* 2010). However, there is no consensus on which method is more appropriate for a specific location. It highly depends on local characteristics, data requirement of the method and the engineering judgment. Also, these methods need to account for climate change and urbanization impacts simultaneously. For instance, increasing rainfall intensity could be the dominant factor in a more urbanized area, which has higher impervious/pervious ratio, than in a less urbanized area. In the latter case, the land use change could be the dominant factor.

UNDERSTANDING ISSUES WITH CONVENTIONAL DESIGN APPROACHES

For many years the conventional design method has been used for the design of drainage systems. However more accurate pipe sizing methods for circular and non-circular pipes have been developed (Swamee *et al.* 1987; Sharma & Swamee 2008). The conventional approach does not just translate to a conventional rainfall-runoff modeling for designing drainage system components, but also implements conventional management methods which ignore the interaction between drainage systems, the environment, and the society. Regardless of all improvement in drainage systems design and planning methods, growing problem implied a deficiency in the conventional approach. Various case studies investigated the causes and effects of urban drainage failures in different locations and reported that the climate change and urbanization were the most critical factors impacting on the performance of conventional drainage systems (Nie *et al.* 2009; Eckart *et al.* 2012; Pedersen *et al.* 2012; Huong & Pathirana 2013).

Global climate change could affect the drainage systems in many ways. It places a strong barrier to the provision of reliable hydrological input data for the design process. Extreme rainfall events could result in urban flooding exceeding the capacity of the drainage system, which is the most important impact of climate change on drainage systems. Also, high variation in rainfall between wet and dry seasons could cause hydraulic deterioration of the drainage systems due to sedimentation. Urbanization is another driver that has attracted attention relatively recently (Barron *et al.* 2013; Huong & Pathirana 2013). Urban growth results in population and land use changes. It could not only aggravate the flood risk due to higher rate of impervious area and UHI effect, which results in increase in rainfall (Mote *et al.* 2007), but also decrease the storage area for detention/retention basins, and consequently affect the stormwater harvesting, which is an inseparable part of contemporary drainage systems planning.

It should be noted that climate change and urbanization (CC & Ur) impacts are woven together and could not be considered in isolation from one another. As shown by a recent case study, these combined effects could result in reduction in groundwater level and consequently land subsidence in the long term (Gu *et al.* 2011). It could not only increase the potential for flooding, but also cause underground pipe fractures and structural deterioration of drainage systems, necessitating costly retrofitting practices to repair or prevent the damage. As another consequence of combined CC & Ur, discharging stormwater overflows from surfaces of urban areas into water bodies is endangering public health, especially if the water bodies are used for recreational purposes (Ellis & Hvitved-Jacobsen 1996).

Despite many studies investigating how climate change and/or urbanization impacts incorporate into the design of combined drainage systems, few regional case studies were conducted considering both kinds of impacts simultaneously (Semadeni-Davies *et al.* 2008; Astaraie-Imani *et al.* 2012; Huong & Pathirana 2013). The combined effect of climate change and urbanization could make a catastrophic situation in a coastal city in terms of flooding, by making an 80% increase in maximum inundation depth of a previous rainfall event in 2009 (Huong & Pathirana 2013). Also, there could be an increase in the volume of combined sewer overflow by 200% over design flow due to urbanization alone and by 450% due to the combined impact of urbanization and climate change (Semadeni-Davies *et al.* 2008). Urbanization within a context of climate change could also result in growing pollutant loading in receiving water bodies (Astaraie-Imani *et al.* 2012). It is obvious that without considering both kinds of drivers together, developing a planning and design framework for a drainage system, which is unable to adapt to future changes, would fail. In this case, both climate scenarios and urbanization storylines need to be tailored to the future changes in each location. However, using an analysis method, considering combined effect of climate change and urbanization, could result in additional uncertainties in final outcomes, due to complex interaction between drivers, which would require caution when applying this approach (Huong & Pathirana 2013).

APPROACHES TO ADDRESS DRAINAGE SYSTEMS CHALLENGES

Subsequent to recognizing the challenges associated with drainage systems, finding solutions to address these challenges is also required for the improved management. The solutions should protect the drainage systems against the future changes and mitigate the adverse effects of CC & Ur.

As the first attempt to reduce the climate change effects, mitigation strategies were initiated to reduce the anthropogenic greenhouse gas emission, which was recognized as the most important cause of climate change. However, mitigation strategies alone could not prevent the climate change effects completely (Harvey *et al.* 1997). As a result, the need for adaptation strategies was raised. Adaptation strategies were supposed to provide less vulnerable infrastructure to the future uncertain climate. Without adaptation options, the performance efficiency of the drainage systems would decrease drastically over time resulting finally in systems' failure. Adaptation options are defined by the following characteristics as highlighted in the mainstream climate change adaptation handbook for practitioners (Huxtable & Yen 2009):

- oriented towards longer term livelihood security;
- a continuous process;
- results are sustained;
- uses resources efficiently and sustainably;
- involves planning;
- combines old and new strategies and knowledge;
- focused on finding alternatives.

In comparison, mitigation strategies are responsible for reducing the causes of the climate change while adaptation options address the effects of climate change. It is important for decision makers and design engineers to understand the interaction between mitigation and adaptation strategies in order to plan for a combined synergic strategy, which could provide more sustainable drainage design options (McEvoy *et al.* 2006). Various adaptive measures, proposed in recent studies, have been categorized in the following sections.

Sustainable development technologies and their management

It is a global consensus that the conventional urban water management approach is not dealing with the current and future sustainability issues (Wong & Brown 2009). With increasing attention to the concept of minimizing the adverse impact of development practices on the environment, sustainable management concepts, such as sustainable urban drainage systems (SUDS) in Europe, low impact development (LID), best management practice (BMP) in the United States, and water sensitive urban design (WSUD) in Australia, have emerged during the last 40 years (Fryd *et al.* 2012). The use of different terminologies to describe the same concept of sustainable practices over the globe is due to different local cultural and political contexts (Fletcher *et al.* 2014). The idea underpinning the sustainable adaptation strategies is to provide more natural means to preserve the water cycle and the environment against potential threats of climate change and/or urbanization. These practices aim to provide decentralized components for infiltration, detention, and evaporation of stormwater runoff to decrease the stormwater flow entering water bodies and minimize the risk of water bodies being polluted.

Sustainable management principles include policies, source controls and 'end of pipe' practices. Policies and regulations are being adopted through a sustainable management strategy which includes increasing public awareness and public participation, and applying flow and land use restrictions to enhance local detention and prevention of illegal dumping of contaminant wastes (SMPDM 2003; Strickland 2012). As another management principle, source controls aim to minimize production of excessive urban runoff and pollutant loads at or near their source. Green infrastructure (GI), with the purpose of increasing infiltration and water reuse, is a kind of source control including infiltration trenches, sumps and drywells, vegetated swales, porous pavement, rain gardens, and green and blue roofs (Arthur & Wright 2005; Arnbjerg-Nielsen & Fleischer 2009; Beecham 2011; SSCDG 2012). These innovations should be utilized with caution, given that they have uncertain longevity; and there is always a risk of contaminating shallow groundwater (Marsalek 2005). In addition to GIs, some filtration structures are proposed in stormwater management manuals to provide a primary level of treatment by sedimentation and skimming floatables. These systems include storage vault system, gravel bed system, perforated pipe system, stormwater chamber system, sedimentation basins, gross pollutant traps, water quality inlets, and bioretention/infiltration systems (Alcazar *et al.* 2008; DPLG 2009; Strickland 2012). These tools can be provided alone or in combination based on the local requirements.

'End of pipe' facilities such as wetlands or retention ponds aim to remove already formed contaminants and mitigate the worst feature of what is pouring out into watercourses. However, novel sustainable drainage systems shift towards optimizing resource utilization (Balkema *et al.* 2002).

In a move towards sustainable urban water management, retrofitting and maintenance practices are also implemented to enhance the performance of existing drainage systems. However, the replacement of pipes is sometimes required, given that the current variable-intensity storm does not match the design storm used for existing systems' design and there are no other practical options suitable due to local conditions. The applicability of these practices should be locally investigated and economically justified. It is the responsibility of engineers to perform cost–benefit analysis to find out whether replacing the components, rectifying them or a beneficial combination of both is the most efficient and operative alternative for a specific urban catchment. Some studies have investigated the applicability of retrofitting/upgrading solutions. Implementing off-line storage facilities in order to reduce the risk of flooding using sustainable construction technologies has been investigated by Dae-Hyun Koo and colleagues (Koo *et al.* 2012). Other retrofitting options, such as disconnecting impervious surfaces (e.g. roof area) and increasing depression storages, could decrease the peak runoff entering drainage systems (Waters *et al.* 2003). Disconnecting the roof area translates to redirecting roof runoff to a rainwater harvesting system, which stores water for later use (e.g. garden watering and toilet flushing), and/or making stored rainwater traverse a pervious surface to be filtered and/or infiltrated into the soil.

In spite of increasing attention towards sustainable practices for stormwater management, there are some difficulties in establishing these approaches. It requires not only technical and financial analysis of drainage systems under CC & Ur, but also the knowledge of social response and public participation in the planning process. This information could help stormwater planners to identify which technical departments of the city must collaborate in the development of local stormwater management plans. Through an efficient management model, the departments of drainage and city environment cooperate in order to develop a sustainable stormwater management plan. Other city technical departments, such as department of street and traffic, recreation, real estate, and city planning, along with media, local developers, and the community also provide critical contributions to the stormwater planning (Geldof & Starhe 2006).

Considering social dimensions and interdisciplinary collaboration of scientists, developing a sustainable framework is a complex process due to the involvement of multiple stakeholders with conflicting interests. Moreover, identifying sustainable solutions is not a typical linear problem-solving process. Instead, it is a continuous improvement process with a collective learning between disciplines involved in sustainable urban drainage planning. This complexity of sustainable solutions has resulted in little experience with implementing sustainable retrofits to large-scale urban areas and cities. For instance, outcomes from the studies of existing small-scale systems by Danish scientists indicated that these systems were not well-designed to be implemented into large-scale urban areas as they did not provide hydrological connectivity, which is a core principle of sustainable planning (Backhaus & Fryd 2012). However, large scale retrofits could be established by continuing research and experiments on different case areas and carefully reflecting the results in the design process.

Some national agencies and municipal councils across the world have updated their local stormwater management manuals in accordance with new requirements to include sustainable practices appropriate for each municipality (SMPDM 2003; DPLG 2009; Strickland 2012; QUDM 2013). Also, some algorithms have been proposed for selecting the best sustainable practices applicable in specific urban areas (Montalto *et al*. 2007; Karamouz *et al*. 2010).

Integrated urban water management strategies

During the last 25 years, the idea of integrated urban water management (IUWM) arose from questioning the efficiency of conventional centralized urban drainage systems facing prospective climate change impacts (Mitchell 2006). The main concern of the IUWM paradigm is to maximize the overall system efficiency, accounting for the changing climate and growing urban population. In particular, it studies how all aspects and components of a drainage system interact with each other. Through an integrated perspective, solutions for drainage system problems should address the entire drainage system rather than its individual components. Otherwise, the solution would not be a long-term alternative considering future changes. The need for integrated analysis of the urban drainage systems was signified by previous studies and adopted policies (Kallis & Butler 2001; Rauch *et al*. 2002a).

Integrated drainage modeling consists of separate approaches to analyze individual components of the combined drainage system through an integrated manner. The integrated models mainly aim to deal with water quality issues with water bodies, which are increasing due to climate change and urbanization. For the purpose of developing an integrated model, three distinct commercial pieces of software used for simulating individual physical systems, namely, sewer system, wastewater treatment plant, and receiving watercourse, were linked to generate and facilitate integrated drainage simulation (Mannina *et al*. 2006). ICS, WEST, SIMBA, and SYNOPSYS are among some integrated urban drainage models simulating water quality and quantity (Clifforde *et al*. 1999; Butler & Schütze 2005; Rauch *et al*. 2002b). The readers are suggested to investigate the suitability of integrated models based on their needs. Notwithstanding accurate simulation using integrated models, they have not been commonly used due to great difficulty with their applications. The individual models are not developed as a part of an integrated urban drainage model and thus operate as independent components. These models are not basically developed for working together in a single modeling framework (Mannina *et al*. 2006). In fact, integrating the sub-system models into a single model is a complex process with high parameterization and requiring expensive computational effort. For this reason, integrated models need to be formulated and optimized in a consistent way, incorporating sub-system models jointly (Rauch *et al*. 2002a).

Integration was also defined and implemented as an approach which accounts for financial, social, environmental, and institutional concerns. In fact, for establishing an integrated framework, a comprehensive cost–benefit analysis must be carried out, considering direct costs of data provision, design and construction, social impacts, maintenance, and upgrading, as well as indirect costs associated with long-term consequences of future changes which could necessitate larger financial investment for adaptation in some locations (Arnbjerg-Nielsen & Fleischer 2009). Furthermore, a large number of scientists from different disciplines must closely work together with stakeholders and decision makers on an ongoing basis in order to develop an integral framework (Wong & Brown 2009; Fryd *et al*. 2012). For instance, SWITCH, an EU Sixth Framework research project, is a global project which gathered professionals and stakeholders involved with water management problems across the world in order to find sustainable solutions (Eckart *et al*. 2012). Obviously, integrated strategies which incorporate two or more of the aforementioned concerns give better understanding to decision makers for establishing holistic adaptation strategies and policies based on local opportunities and restrictions (Seggelke *et al*. 2005; Kirono *et al*. 2014).

Uncertainty reduction techniques

Uncertainty associated with climate projections is an important issue which must be dealt with while establishing an adaptation strategy. As uncertainties result in unreliable hydrological input data for planning and design of urban drainage systems, utilizing techniques to reduce these uncertainties is a must. There are three sources of uncertainty associated with the climate projections (Allen *et al.* 2004):

1. scenario uncertainty, which represents uncertainties in anthropogenic greenhouse gas emission scenarios;
2. natural variability, including internally and externally driven natural climate change;
3. response uncertainty or model uncertainty, which reflects our lack of knowledge associated with the response of multi-parameter climate systems to the external forces.

As suggested by Ed Hawkins and Rowan Sutton, the relative importance of different sources of uncertainty associated with climate predictions depends on the prediction lead time as well as spatial and temporal averaging scale. For a temporal scale of two decades or less and regional spatial scale, the dominant source of uncertainty is attributed to model uncertainty and natural variability. Conversely, uncertainty due to scenario uncertainty and model uncertainty is significant for temporal scale of many decades in regional spatial scale (Hawkins & Sutton 2009).

As a great source of uncertainty associated with climate predictions, general circulation models (GCMs) have been used for many years to predict climate change under different emission scenarios (Alley *et al.* 2007). The most common problem with these models is that the spatial scale of their outputs is too coarse comparing with local hydrological process scales. This scale problem could result in significant uncertainty in climate projections functioning as input for urban drainage design procedure. As a solution, downscaling methods, aiming to bring the spatial scale of GCMs (typically $300 \times 400\ \text{km}^2$) down to the order of data requirement for regional hydrological models, have been developed. The first kind of downscaling method is dynamic downscaling in which a regional climate model settles inside the GCM grid-squares to bring spatial resolution down to the order of about 50×50 to $10 \times 10\ \text{km}^2$ (Olsson *et al.* 2009). However, this computationally expensive method does not provide adequate fine resolution for urban hydrological assessment (Leith 2005; Chen *et al.* 2011). To overcome these deficiencies, statistical downscaling (SD) methods were proposed based on a statistical relationship between GCM output and regional observations (Rummukainen 1997). SD methods were found to be much easier to apply with less computational effort (Chen *et al.* 2011). They include transfer functions, regression methods, weather typing schemes, weather generators, and resampling techniques (Wilby & Wigley 1997; Onof & Arnbjerg-Nielsen 2009). As another popular downscaling method, the delta change factor method adjusts the observed time series by considering the difference between current and future GCM simulations (Hay *et al.* 2000; Olsson *et al.* 2009).

In addition to spatial downscaling, the temporal resolution of typical daily climate models need to be finer as many changes in precipitation happen at sub-daily time scales, which could not be captured accurately by these typical models. For this reason, some algorithms were presented to disaggregate the daily climate data into sub-daily time-scale for climate models (Pui *et al.* 2012; Westra *et al.* 2013). There are also some studies which have used the mixed spatio-temporal downscaling methods to better predict climate changes (Segond *et al.* 2006; Nguyen *et al.* 2007).

All of these downscaling methods provide means to incorporate climate change impacts into urban drainage design procedure in order to reduce uncertainty associated with hydrological input data. Availability of a wide range of downscaling methods implies that the choice of downscaling method significantly affects the climate change impact studies and thus must be considered as another source of uncertainty in climate change predictions (Chen *et al.* 2011).

Apart from climate prediction, other uncertainties could be associated with urban drainage models. For this reason, drainage models are required to be evaluated in terms of uncertainties and model sensitivities. The results are of paramount importance for establishing a more reliable planning and design framework. This evaluation is even more important when a complex integrated model has to be assessed. As a solution, model calibration and uncertainty analysis techniques have been presented in order to identify the reliability of a particular parameter set as a simulator of the system (Beven & Binley 1992). However, such practices are limited in use. Uncertainty analysis techniques commonly used in urban drainage modeling include generalized likelihood uncertainty estimation (GLUE), the shuffled complex evolution metropolis algorithm (SCEM-UA), a multi-algorithm, genetically adaptive multi-objective (AMALGAM) method, and a Bayesian approach based on a simplified Markov Chain Monte Carlo method (Dotto *et al.* 2012). Moreover, uncertainty analysis should be considered as a dynamic concomitant of the modeling process that imposes restrictions throughout the modeling study rather than through a post-assessment approach (Refsgaard *et al.* 2007).

As another solution to address the future uncertainties, management strategies are also suggested in recent studies. The concept of flexible design, aiming to adapt to the uncertain future, was studied in order to make the adaptation option more flexible to future changes (Eckart *et al.* 2012). However, the identification and measuring methods of flexibility for urban drainage systems need to be enhanced. Additionally, engineers could utilize uncertainty-management methods which intend to apply long-term climate information rather than expecting climate scientists to provide them with certain climate projections (Hallegatte 2009).

Updating design procedure

Over the years, drainage design procedure has evolved from hydraulic sizing of drainage components entailing, pipes, inlets, gutters, and culverts to an integrated sustainable design procedure which additionally includes sizing of stormwater detention facilities. This evolution occurred as the conventional design procedure was unable to provide effective structures when facing upcoming changes. These evolutions could be regarded as adaptation measures. Adapting design procedure to the uncertain future climate not only requires defining a new criterion, like an increase in pipe diameter based on the climate change projections, but also tailoring the statistical analysis to the changing climate. In this regard, a few studies applied changes to design criteria to avoid costly rehabilitation and maintenance practices in the near future. Among these, a new approach to define a design return period was proposed using a linear relationship between return period and time (Mailhot & Duchesne 2009). This approach intends to address varying occurrence probability of extreme events in a context of climate change. However, it took into account the simplest hypothesis in the context of climate change, in which the entire rainfall distribution of the extreme event shifted over time. There is still considerable room for studies accounting for how rainfall distribution of extreme events fluctuates over time and location. Furthermore, this linear relationship is the simplest assumption, which needs to be promoted to a nonlinear estimation in order to meet the requirements of a more adaptive design plan.

The planning and design framework could also be updated by analyzing available rainfall records, so as to calibrate design inputs such as lag time and time of concentration (McEnroe & Young 2012). In this way, more reliable input data would be provided for the design of drainage systems. Furthermore, using updated IDF curves, extracted from recent rainfall data and state of the art scientific findings, could update the design process. In Canada, updated municipal IDF curves were released in 2009 based on observational data from 1961 to 2002 (Simonovic & Peck 2009). The Bureau of Meteorology, Australia, released new IFD curves in 2013 (Australian Government 2013). In the United States there is a different system of mapping the rainfall statistics. Similarly, latest maps for American watersheds are available for download from the US National Weather Service website.

Long-term continuous simulation for system design

Drainage system design procedures employed a design storm approach assuming, typically, that runoff generated in the design event is unaffected by antecedent channel flow conditions or by flood water held in temporary storage following a previous event (Engineers Australia 1999). Integrated stormwater management approaches may implement storages for flow management that can impact the design event. Argue (2004) referred to Kuczera *et al.* (2003) stating that, in the case of the design storm approach, the specification of average initial conditions is problematic and the design storm approach can be seriously biased. Continuous simulation has been recognized as the best remedy to overcome these issues.

Unlike event-based simulation, continuous models do not assume the loss from the rainfall event, including initial and continuing losses. They simulate total flow during a rainfall event using a loss model considering baseflow discharge between flood events (Boughton & Droop 2003). Also, continuous models determine the temporal distribution of outflow. It has been shown that using continuous simulation is preferable to the event-based method, as the event-based method underestimates the design flood due to inaccurate modeling of antecedent soil moisture (Grimaldi *et al.* 2012; Pathiraja *et al.* 2012).

Many studies have been undertaken to investigate advantages and deficiencies of continuous models (Boughton & Droop 2003). Notwithstanding its deficiencies, continuous simulation is attracting more attention nowadays, mainly because of computer advancements. This method is typically used to examine the performance of drainage systems rather than for practical design purposes. A continuous rainfall-runoff model serves to estimate runoff rate considering the possible losses subsequent to a particular rainfall event. It takes into account both wet and dry periods of a watershed at daily, hourly and occasionally sub-hourly time steps (Boughton & Droop 2003). Some among many continuous models applicable for urban catchments are Storm Water Management Model (SWMM), Quality–Quantity Simulator (QQS), Storage, Treatment, Overflow, Runoff Model (STORM), Hydrological Simulation Program–Fortran

(HSPF), King Country Runoff Time Series (KCRTS), and Distributed Routing Rainfall-Runoff Model (DRRRM-QUAL or DR3M–QUAL) (Jackson *et al.* 2001; Zoppou 2001). The Australian water balance model (AWBM), as a continuous model for Australian watersheds, has been investigated mainly from the early 1990s. However, it was used widely in water management studies rather than for design flood estimation (Boughton 2004)

Despite many advantages of continuous simulation, it is not yet a well-accepted approach for the design flood estimation in urban drainage design. As continuous simulation requires large model run time and computational effort, it must be used for major projects for which the large computational effort could be justified. However, subsequent to rapid computer advancement, the combination of the stochastic weather generator method with continuous simulation could result in generating flood statistics with ARI ranges from 100 to 100,000 years in the temporal scale of minutes. It is a major development in design flood estimation that has occurred recently (Boughton & Droop 2003). Alternatively, a combination of event-based and continuous simulation method was presented as a comprehensive and efficient watershed model (Borah *et al.* 2007).

As stated, continuous simulation has proven to be a model with less uncertainty due to considering a long record of rainfall events. But the studies linking the continuous simulation with urban drainage design process are relatively rare. Among those few, Lucas (2009) proposed an approach for improving the design of a bio-retention/infiltration urban retrofit by presenting a vertical routing approach using the power of continuous simulation. Also, an analytical probabilistic approach which provides a reasonable approximation of continuous simulation results with less computational efforts has been presented for flood control detention facilities (Guo & Adams 1999; Grossi & Bacchi 2008). There is a huge opportunity in continuous simulation being implemented in the design of urban drainage systems. However, more research is required to develop cost-effective continuous models.

DISCUSSION

A broad literature review has been performed to identify urban drainage systems' challenges due to rapid urbanization and climate change. Proposed solutions to address these challenges have also been categorized. Solutions should not only consider designing drainage system components to be adapted to the changing climate and continuing urbanization, but also establish an integrated planning and design framework which works sustainably. For this to occur, it is of paramount importance to recognize deficiencies and weaknesses of current drainage systems under climate change and urbanization. Also engineers and decision makers need to be provided with state of the art knowledge and technologies regarding adaptation options.

The first step toward establishing an integrated, sustainable planning and design framework is to quantify the effects of climate change and urbanization, which may vary locally. Many climate change impact assessment studies have been performed so far. However, a limited number of studies focused on urban catchments (Arnbjerg-Nielsen 2012; Willems *et al.* 2012). Also, urbanization impacts in urban areas have been rarely assessed. There is a lack of case studies assessing the performance of drainage systems under combination of climate change and urbanization-induced drivers, which is not well perceived at this stage.

Modifying the conventional design approach along with updating local design manuals is an important step toward establishing a sustainable design and planning framework. Thus, adjusting drainage design criteria, to suit uncertain future changes, is highly demanded. In other words, the effects of climate change and urbanization are required to be incorporated into the design procedure in order to avoid further maintenance cost and retrofitting practices. Also, a continuous simulation approach could be preferable for the design of drainage systems over the design storm method as the underlying assumption in the design storm method, stating the design event is unaffected by antecedent conditions, is unrealistic. Such a situation will be further inflated by climate change and urbanization impacts.

Also, it is important to provide more reliable (i.e. less uncertain) hydrological input data for the design process. This could be gained through incorporating a cost-effective continuous rainfall-runoff model in the planning and design procedure. It is also of critical importance to narrow uncertainties related to climate predictions and drainage models by utilizing downscaling methods, drainage model uncertainty analysis techniques, and uncertainty-management strategies. To address climate change uncertainties, a case-specific framework has recently been developed so as to identify robust adaptation measures which are insensitive to climate change uncertainties (Dessai & Hulme 2007). Developing similar frameworks considering local decision-making contexts should be investigated.

Possible adaptation options for a specific local area are required to be assessed, from technical, financial, social, environmental, and institutional considerations, in order to investigate a sustainable option which also satisfies the cost–benefit analysis. Selecting sustainable practices among various options, such as GI, filtration structures, and retrofitting and maintenance practices, is highly influenced by the implementation cost and the net benefit of the practice over the catchment. The best selection could be made through using local and municipal stormwater management manuals together with informed engineering judgment. Based on a recent study, the best sustainable solution to mitigate the adverse effects of future drivers was found to implement dynamic adaptation options within a continuous learning context (Mikovits *et al.* 2013).

Promoting uptake of sustainable practices as well as investigating mainstream implementation of adaptation strategies into all vulnerable sectors is also of significant importance in the way towards establishing a sustainable planning and design framework. As sustainable development is a new area with a wide knowledge gap in design and implementation, there are constraints and impediments in adopting sustainable practices. The gaps need to be locally identified and addressed by the stakeholders to promote their adaptation in local developments (Sharma *et al.* 2012). At this stage, more case studies of implementing sustainable practices in large-scale urban areas are required in order to provide sustainable drainage infrastructure and better understand their effectiveness.

The other important factor is the necessity of close collaboration of different disciplines, together with stakeholders and decision makers, for developing an integral sustainable design framework. This interdisciplinary research environment provides decision makers with a comprehensive overview to establish a cost-effective and efficient planning and design framework for urban drainage systems.

CONCLUSION

Urbanization and climate change are the two major issues impacting the performance of conventional drainage systems. The combined impact of these issues should be considered due to their complex nature. Climate change would impact the availability of reliable hydrological data, and associated extreme events would result in urban flooding. The high variation in rainfall between dry and wet seasons would increase sedimentation in existing systems. Similarly, urbanization would increase the risk of flooding and reduce storage areas for detention/retention systems. The pollutant loading into receiving water bodies will also increase due to urbanization, which would also impact the water bodies' flora and fauna.

Sustainable management approaches, including policies, source control measures, and end-of-pipe solutions, can be implemented as mitigation and adaptation strategies to address climate change and urbanization impacts. It is also important to employ an appropriate uncertainty analysis technique to reduce the uncertainty associated with climate projections and drainage system modeling.

These management efforts can be further strengthened if mitigation and adaptation strategies are incorporated into integrated urban water management approaches considering economic, social, and environmental aspects. The implementation and management of such approaches, being new, have significant impediments due to knowledge gaps and involvement of various stakeholders with conflicting interests.

Complexities of climate change together with urbanization impacts, which vary spatially and temporally, necessitate careful scrutiny of possible adaptation measures in each location. In such a context, future urban drainage studies should focus on identifying factors impacting on specific locations as well as developing location-based adaptation options and practical implementation methods with minimum investment cost and maximum system efficiency.

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