Fifty years of innovation in urban stormwater management: Past achievements and current challenges

Cinquante ans d'innovation pour la gestion des eaux pluviales urbaines : réalisations passées et défis actuels

Jiri Marsalek*; **

*Water Science and Technology Directorate, Environment Canada, 867 Lakeshore Rd, Burlington, ON, Canada L7R 4A6 (jiri.marsalek@ec.gc.ca)
** Urban Water, Luleå University of Technology, 971 87 Luleå, Sweden

RÉSUMÉ
Les 50 dernières années ont permis des progrès remarquables en matière de gestion des eaux pluviales urbaines. Cette période peut être caractérisée par un taux élevé d'innovations, avec beaucoup de concepts progressifs, qu'ils soient nouvellement développés ou adaptés à partir d'autres domaines. Les recherches sur le terrain ont permis le développement de la compréhension de la génération du ruissellement sur les bassins versants urbains, la caractérisation de la qualité des eaux pluviales pour un grand nombre de constituants, les impacts environnementaux des rejets de temps de pluie sur les milieux récepteurs, ainsi que la modélisation informatique de tels processus. Cette connaissance a alors été utilisée pour développer les bonnes pratiques de gestion (les BMP) pour la réduction des impacts. En examinant les défis actuels, les recherches futures et les innovations vont probablement intégrer des motivations financières, que ce soit pour évaluer les polluants prioritaires et émergents et leur contrôle par des dispositifs législatifs, des nouvelles technologies de traitement des eaux pluviales efficaces et rentables, des outils pour la planification, la conception et la gestion des systèmes d'assainissement urbain et des méthodes pour évaluer la réponse des systèmes au changement climatique. La recherche actuelle sur les solutions alternatives bénéficierait d'études plus larges, sur des ouvrages multiples, couvrant le bassin versant dans son ensemble, sur des périodes de temps longues prenant en compte des questions de maintenance et d'analyse du cycle de vie et étendant la recherche aux questions des régions les plus mal servies. Sachant que le drainage urbain et les questions de gestion des eaux pluviales continuent à se développer, et que leur gestion exigera des évolutions, il y aura une demande continue pour une recherche visant à répondre aux besoins d'une telle dynamique.

ABSTRACT
The past 50 years brought about a remarkable progress in the development of management of urban stormwater. This period can be characterized by a high rate of innovation, with many progressive concepts either newly developed or adapted from other fields. Extensive field research supported the development of understanding of generation of stormwater runoff in urban catchments, stormwater quality characterization for a large number of constituents, environmental impacts of stormwater discharges on receiving waters, and the computer modelling of such processes. This knowledge was then used to develop best management practices (BMPs) for impact mitigation. When examining the current challenges, the future research and innovation is likely to follow financial incentives, which may be available for assessing emerging and priority pollutants and their control by policy instruments, new effective and cost-efficient stormwater treatment technologies, tools for planning, design and operation of urban drainage systems, and methods for estimating responses of stormwater management systems to a changing climate. The current research of stormwater BMPs would benefit from broader studies of multiple facilities considering whole catchments, over extended time periods factoring in maintenance issues and lifecycle costs, and extending research to the underserviced regional issues. As urban drainage and stormwater management issues keep evolving, and their management will require updating, there will be continuing demands for research targeting such dynamic needs.

KEYWORDS
Innovation, stormwater characterization, stormwater impacts on receiving waters, stormwater treatment, urban stormwater research
1 INTRODUCTION

Rapid urban development after the Second World War contributed to fast urbanization in many regions of the world. To provide drainage of such areas, urban drainage systems (UDSs) were greatly extended or new ones built. Yet these efforts and expenditures did not eliminate urban flooding or water pollution, but just transposed these problems to downstream areas, and in this process, often created new impacts of even greater magnitude. In response to such problems, water managers and researchers in many regions of the world started to examine urban stormwater runoff and the means of mitigation of its impacts. By the mid 1960s, publications on this topic started to appear regularly in the literature and addressed mostly the characterization of urban stormwater and the associated impacts. For a review of this older literature, see Porcella and Sorensen (1980).

Currently, the process of urbanization is continuing on the global scale, with more than one half of the global population living in urban areas, and the trend towards urbanization is continuing, particularly in the less developed countries (Marsalek et al. 2008). Thus, urban drainage continues to attract attention worldwide. In general, the issues of urban drainage can be examined using a systems analysis approach, of which principal objective is to define the system needs so that it will serve the needs of end-users. In more specific terms, this process generally starts with problem definition, followed by the search for alternative solutions, evaluating such solutions (including their cost vs. effectiveness), interpreting these evaluations, and finally adapting a mix of solution measures and taking action through implementation. In this context, the major innovation milestones in urban drainage and stormwater management can be described in the following chronological order: (a) Problem definition - recognition of unsustainable growth of UDSs (i.e., unsustainable environmentally and economically; growth – reflecting the size of individual elements as well as the spatial extent of the system), increasing risk of flooding, stream erosion, stormwater pollution, and other environmental impacts, with concomitant reduction in services provided, (b) Development of computer-based tools for evaluating urban drainage problem (i.e., urban rainfall/runoff models), (c) Development of problem solutions by stormwater management, including BMPs, (d) Evaluation of stormwater management measures with respect to solving drainage problems and the cost of such measures, often conducted by application of models simulating the performance of stormwater management measures, and (e) Implementation of the best solutions through master drainage plans, municipal bylaws and government policies.

While system analysis of urban drainage may seem readily tractable, as discussed below, it suffers from some limitations, imposed by such facts as: (a) Urban drainage systems (UDSs) may be well-defined hydrologically, but not with respect to chemical inputs and interactions with other urban infrastructures, (b) the nature of UDS problems keeps evolving in time, which somewhat contradicts the long life expectancies of traditional infrastructure elements (80-100 years for concrete sewers) contributing to technological lock-in (Patouillard and Forest, 2011), and (c) UDS and drainage services involve many stakeholders whose participation increases the complexity of the implementation process. In this context, technological lock-in was defined as a process in which macro-level forces create systematic obstacles to the adoption of new technologies (Patouillard and Forest, 2011). Thus, systems analysis of urban drainage requires periodic updating, of which feasibility may be impeded by other competing urban priorities and fluctuating levels of interest of the political decision makers as well as of end-users. However, for the purpose of this overview, the systems analysis should serve rather well, particularly with respect to the past achievements.

2 PAST ACHIEVEMENTS

Description of past achievements in the management of urban stormwater follows the path of system analysis, starting with the problem definition, including the assessment of stormwater impacts on receiving waters, tools for assessing UDS problems, stormwater management measures, framework for stormwater management implementation, and documentation of recent research by the special issue of Water Research on urban drainage.

2.1 Problem definition: stormwater quantity and quality

Urban drainage impacts on the living environment represent a sub-group of broader environmental impacts of urbanization on the atmosphere, surface waters, wetlands, soil, groundwater and biota (Marsalek et al. 2008). In discussions of UDSs, the problem is usually viewed more narrowly and encompasses the issues of surface runoff and flooding, stream erosion, water pollution caused by chemicals, solids, microbiological organisms, and discharges of waste heat, and the associated
impairment of beneficial uses and impacts on biota, in the form of loss of abundance and biodiversity. Combined physical impacts of urban developments, on both surface waters and groundwater, were described by Leopold (1968) and more recently by Chocat (1997) who noted that urban development leads to increased ground imperviousness, higher runoff volumes and peaks, reduced groundwater recharge, increased soil erosion and sediment yields, and increased flood frequency. More recently, elevated temperatures of urban runoff and their effects on the receiving waters were also reported (Schueler, 1987). Reduced groundwater recharge then leads to lower baseflows and depressed water tables. In both cases, there is a loss of beneficial water uses and decrease in biodiversity (Marsalek et al., 2008). There has not been much research done on these issues lately; they are considered as relatively well understood and readily addressed using the available models (Fletcher et al., 2013). On the other hand, the issues of stormwater quality have attracted and continue to attract much more attention.

Since the mid 1960s papers on urban stormwater quality have started to appear regularly in the literature and reported concentrations of such constituents as TSS, COD, BOD, TP, PO₄-P, TN, TKN, trace metals (typically Cd, Cu, Cr, Hg, Ni, Pb and Zn), older organochlorine pesticides (e.g., endrin, methoxychlor, lindane), PCBs, and faecal indicator bacteria (faecal coliform, E. coli, streptococci). The understanding of urban stormwater quality developed in these early studies was summarized by Shaheen (1975).

More efforts followed the initial “discovery” period in the form of numerous investigations of urban stormwater quality in a number of countries during the 1970s and early 1980s, with the objective of advancing the understanding of stormwater quality impacts on the receiving environments. The most extensive among these efforts was the US NURP (Nationwide Urban Runoff Program) program summarizing data from 81 sites monitored in 28 projects located across the USA (US EPA, 1983). NURP findings confirmed concerns about runoff quantity contributing to flooding and erosion/sedimentation, but the main effort focused on stormwater quality issues (manifested by impairment of beneficial uses, violations of water criteria, and local public perception) and the general means of remediation. Similar but less extensive activities were conducted in other countries as well, e.g., France (Hemain et al., 1990), Germany (Fuchs et al., 2004), and UK (Ellis, 1991). In 1999, Duncan (1999) referred to more than 600 references in a statistical overview of worldwide urban stormwater quality data. Some of the work related to the earlier or new databases on stormwater quality continued, e.g. in the USA, as reported by Smullen and Cave (2002) (a follow up on the NURP) and a new database from the stormwater NPDES program (National Pollutant Discharge Elimination)(Pitt et al., 2004). In general, the worldwide efforts in researching stormwater quality can be credited with producing a general understanding of stormwater quality with respect to conventional and some priority pollutants (i.e., inorganics), and thereby producing arguments for conducting research on stormwater pollution assessment and its mitigation by control measures.

Priority pollutants were also monitored in a number of studies, but in view of low concentrations (environmentally significant in some cases) and high analytical costs, such efforts were much less extensive and conclusive. The NURP addressed the occurrence of US EPA Priority pollutants and reported generally high frequencies of detection of inorganics (Pb, Zn, Cu, Cr, As, Cd and Ni; detected in more than 43% of samples), and among the 106 organics on the list, 63 were detected, particularly the plasticiser Bis(2-ethylhexyl) phthalate (22%) and an older pesticide, α-Hexachlorocyclohexane (20%). There were additional 12 organics (mostly pesticides and PAHs) occurring in more than 10% of samples. Recent studies confirmed the earlier findings with respect to trace metals and PAHs (Zghieb et al., 2012) and produced new information concerning phthalates, nonylphenols, more recently introduced pesticides, PCBs, and plasticisers (Rossi et al., 2004; Eriksson et al., 2007; Bertrand-Krajewski et al., 2008; Bressy et al., 2011; Zghieb et al., 2011; Bjorklund et al., 2012). As discussed in current challenges, the process of stormwater characterization with respect to chemical pollutants will never be complete as long as new chemicals are released into the environment and the analytical methods are refined to measure such releases at exceptionally low, though potentially significant, concentrations.

2.2 Assessment of stormwater environmental impacts on receiving waters

In general terms, stormwater impacts on many aspects of receiving waters and needs to be examined in this context. Depending on local legislation and policies, the point of focus may be the impairment or denial of beneficial uses, violation of water quality criteria, or local public perception. Impairment of beneficial uses was defined in the Great Lakes region (IJC, 1988) as a change in environmental conditions (chemical, physical or biological integrity) causing restrictions on fish and wildlife consumption, tainting of fish and wildlife flavour, degradation of fish and wildlife populations, fish
tumours or other deformities, bird or animal deformities or reproduction problems, degradation of benthos, restriction of dredging activities, eutrophication or undesirable algae, restrictions on drinking waters consumption, or taste and odour problems, beach closings, degradation of aesthetics, added costs to agriculture or industry, degradation of phytoplankton and zooplankton, and, loss of fish and wildlife habitat (Novotny et al., 2005).

Stormwater impacts on aquatic life were addressed for various types of biological communities, including algal communities, benthos and fish. Stormwater disturbs algal community richness and evenness by the presence of algal toxins (e.g., heavy metals) and interference with the supply of nutrients (Olding, 2000). The issues concerning fish populations may be addressed by assessing the fish community performance, which depends on such factors as the flow regime, physical habitat structure, biotic interactions, energy (food) sources, and chemical variables (pollution)(Yoder, 1989). Recognizing the difficulties in working with fish communities, a simpler, but more practical analysis is usually performed by focusing on benthos (a source of food for fish) and applying sediment triads, which combine field sampling of the sediment chemistry and the benthic community composition, and laboratory testing of sediment toxicity (Long and Chapman 1985). In general, the above approaches are best applicable when examining stormwater ponds and constructed wetlands, or receiving waters with dominant impacts of stormwater. In other water bodies, urban drainage may still dominate the flow regime, but with respect to pollution, there may be too much interference from other polluted discharges, including agricultural flows, and municipal wastewater and industrial effluents (Novotny et al., 2005). In those cases, the emphasis is placed on integrated monitoring and contributions of stormwater to the integrated effects may be hard to discern.

At the second level, water quality criteria violations and the resulting risks to human health and aquatic life may be assessed. Examples of such approaches were suggested by Eriksson et al. (2005) and Lundy et al. (2012). Finally, the third level (public perception) represents public complains about receiving water colour, odour, or general aesthetic appearance (US EPA, 1983).

2.3 Development of computer models for rainfall / runoff / drainage systems / receiving waters

Problem recognition contributed to the needs to address urban runoff computations for large hydrologically connected areas, with high volumes of physiographic and sewer system data. The only practical way of accomplishing such a task was to use computerized procedures, which would take into account the knowledge of hydrology, large diversity of the catchment cover, sizeable sewer systems with thousands of pipes, nodes and appurtenances, exposed to design hyetographs or historical rainfall data, and these procedures had to process the input information at short time steps, reflecting the fast hydrological response of the drainage system. The predecessors of the hydrologic modules of these models were the hydrograph methods, which were developed in Los Angeles (Hicks, 1944) and Chicago during the 1940s. The period from the early 1960s to the early 1980s was ‘a golden era’ of the development of urban rainfall/runoff models, with more than 30 models appearing in the literature. In the following years, there has been a quick consolidation in this field, with vast majority of urban rainfall / runoff / runoff control modelling being currently accomplished with several leading modelling packages, listed in the alphabetical order as, DHI MOUSE (DHI Water and Environment, 2004), Innovyze Infoworks SD CS (Innovyze, 2013), and US EPA SWMM (Rossman, 2009), notwithstanding some specialty models used for the planning and design of BMP and LID measures (Elliott and Trowsdale, 2007; Gironas et al., 2009) and the modelling of receiving waters. This consolidation resulted from the fact that the leading models are robust, offer numerous features, and have been continuously supported and refined. Furthermore, the processing of physiographic data has been simplified by using GIS support. Further model development can be expected, as new research produces new knowledge suitable for implementation in models and the improvements in computer hardware produce ever-decreasing computing times, thus allowing a greater complexity models. Undoubtedly, the introduction of computer models into urban stormwater analysis was one of the most significant breakthroughs in this field, which facilitated the use of better methods in runoff computation and sewer design, and allowed addressing more comprehensively the complex issues of runoff generation and transport, stormwater management, and mitigation of impacts on receiving waters, while maintaining high levels of productivity. For an in-depth review of urban hydrology processes, and their modelling and implications for receiving waters, see Fletcher et al. (2013).
2.4 Stormwater management measures: Best Management Practices (BMPs) and Low Impact Development (LID)

A theoretical basis for stormwater quantity management (i.e., reduction and control of flow volumes and rates) is relatively simple and has been known in catchment hydrology for quite some time. It is based on two concepts: the hydrological equation (describing the attenuation of inflows by storage) and manipulation of rainfall abstractions. The former concept has been used in dam reservoir design for flood management, but in the urban environment, storage may take many shapes and forms, ranging from roof storage (e.g., on green roofs), to street surface storage (enhanced by inlet flow restrictors), to classical stormwater ponds. Typical rainfall abstractions in urban areas include surface depression storage, infiltration on pervious parts of the catchment (into soils – natural or engineered, pervious and permeable pavements), and evapotranspiration which is characterized by relatively slow process rates compared to the other abstractions (WEF and ASCE, 1992). In actual applications, both concepts are applied, but generally not to the same extent. Storage by itself redistributes flows, but generally does not affect flow volumes and distribution of runoff into various water balance compartments, as further discussed below (Burns et al., 2012).

Stormwater quality control measures are more complex than those for quantity control only and are still evolving. Firstly, quality controls need to be considered as closely related to quantity controls. Indeed, if stormwater volumes and flows are reduced by quantity controls, then the corresponding fluxes of stormwater pollutants are prevented, which is one of the fundamental axioms of modern stormwater management – preventing problems and exerting control as close to the source as possible (WEF and ASCE, 1998). The early stormwater quality controls focused on passive treatment in stormwater management facilities, with emphasis on settling or filtration of total suspended solids (TSS), the next generation of BMPs also included some forms of biological treatment and targeted not just TSS, but also other pollutants, including trace metals, nutrients, and faecal indicator bacteria. Conventional BMPs included stormwater management ponds (dry or wet), various forms of storage (roofs, super pipes), infiltration trenches and basins, porous pavement, water quality inlets, constructed wetlands, grassed swales or grassed filter strips, and sand filters (Schueler, 1987). To large extent, the treatment oriented BMPs were adopted with modifications from other fields, particularly wastewater treatment, in which various forms of settling (plain, or with lamellas, or chemically aided, or ballasted), treatment by infiltration into the soil, sand filtration, and treatment wetlands have been used for long time (Metcalf and Eddy, 2003). In that sense, these older methods can be seen as “low hanging fruit” options that were readily available to the early adopters. The process of searching for innovative stormwater management and/or treatment is still continuing (Clark and Pitt, 2012), but some of the innovative approaches (technological devices) may be becoming too expensive to gain broad acceptance.

Stormwater environmental technologies represent devices or structures which provide stormwater treatment by application of various unit processes. This is a fairly dynamic evolving field driven largely by the competition to serve a potentially large market for such devices. However, this field is not without its own challenges, largely caused by the ever-increasing complexity of these technologies, resulting in increasing costs, including the heavy demands on maintenance (some of these devices, e.g., inserts into catch basin, may require weekly maintenance). Furthermore, there is confusion about the actual life-cycle costs and benefits of these devices, which is partly attributable to ambiguous information on their performance in treating stormwater (e.g., not specifying the characteristics of the treated medium and presenting treatment performance for fine sand, rather than clay and silt encountered in practice). Finally, with the increasing complexity of stormwater treatment devices, the requirements on their maintenance greatly increase. This aspect of stormwater management is still somewhat being neglected, partly because of maintenance underfunding. Capital investments into the municipal infrastructure produce much higher visibility than sewer or BMP maintenance.

In recent literature, a distinction has been drawn between the conventional BMPs and the measures promoted more recently under such headings as LID (low impact development), SUDS (sustainable urban drainage systems), WSUD (water sensitive urban design), and others (Burns et al., 2012). When drawing a distinction between these new approaches and the “conventional” BMPs, the BMPs were sometimes presented as more or less end-of-the pipe measures, but this perception may be biased. Some of this criticism may apply to the older facilities (from the 1960s and 1970s), which were primarily designed for reducing post-development runoff peaks. More recently, the stormwater management objectives were expanded to include preservation of groundwater and baseflow characteristics, prevention of undesirable and costly geomorphic changes in watercourses, prevention of flood risk potential, protection of water quality, and maintenance of appropriate abundance and
diversity of aquatic life and opportunities for human beneficial uses (MOE, 2003). Thus, the difference between BMP and LID applications is more in the design approach taken, i.e., the design criteria followed, rather than the measures themselves. Furthermore, the BMPs were never meant to represent “the structural measures” only, but rather all the measures including non-structural measures focusing on such source controls as land use planning and development (Field et al. 1977).

LID and similar approaches follow a goal of pursuing a comprehensive, landscape-based approach to sustainable urban development encompassing strategies to maintain existing natural systems, hydrology and ecology (Davis et al., 2009). In that respect, they are similar McHarg’s “design with nature”, which was introduced more than 40 years ago (McHarg 1969). LID source controls target runoff generation and the associated pollution generation, good stewardship with respect to pollution sources and their exposure to rainwater, but without limitations on the nature of treatment processes. The modelling of LID measures creates special requirements on modelling urban catchment processes, with more importance assigned to groundwater/baseflow components and exfiltration from LID facilities. Elliott and Trowsdale (2007) reviewed 10 models used in LID modelling and noted that several leading models provided practically all the features required for successful LID design.

2.5 Framework for stormwater management implementation

Understanding of technical-scientific issues of urban stormwater management and their verbalization has greatly advanced during the last two decades. Various stakeholders can describe rainfall/runoff processes, stormwater management and impacts on receiving waters exceptionally well, but generally within the limits of their experience and without a deeper understanding of quantitative aspects of such processes, or other limitations. In this process, there is a tendency for propagation of “idola fori”, or “false notions which are now in possession of the human understanding, and have taken deep root therein, not only so beset men's minds that truth can hardly find entrance, but even after entrance is obtained, they will again in the very instauration of the sciences meet and trouble us, unless men being forewarned of the danger fortify themselves as far as may be against their assaults” (Sir Francis Bacon (1561-1626), an English philosopher, in Novum Organum, as cited in Wikipedia (http://en.wikipedia.org/wiki/Idola_fori; visited on Feb. 18, 2013). Such notions may include thoughts that “pavements should be peeled off” from urban areas (i.e., ignoring the need to provide ground support for traffic and the fact that one can design pervious pavements with reduced runoff), all stormwater is a “resource” under all circumstances (this would include catastrophic rainfalls, e.g. the 2005 Mumbai rain event that recorded 944 mm of rainfall in 24 h), exaggerated performance of some environmental technologies, and so on. These notions need to be corrected through public education and scientific studies.

At the same time, there is a need for realization that the city’s performance in meeting end-users needs, including drainage, does not depend just on hard infrastructure (roads, sewers, treatment plants), but also on the availability and quality of knowledge communication and social infrastructure, where the latter infrastructure includes information and communication technologies and contributes to urban competitiveness. These concepts were introduced into urban planning as “smart” or “intelligent” cities, or “liveable (or livable)” cities, and do bear some consequences for urban drainage development (socio-economic factors). Furthermore, liveable cities feature attractive built and natural environments. It is of interest to note how these concepts are viewed by the economists. The Economist magazine (2013) suggested that these concepts (exemplified by “smart cities”) follow a “hype cycle” (coined by Gartner, Inc., Wikipedia, http://en.wikipedia.org/wiki/Hype_cycle; visited on March 13, 2013) characterized by a period of “inflated expectations”, reaching some peak, followed by rapidly reduced visibility leading to the “trough of disillusionment”, and then following a slope of enlightenment to some “plateau of productivity”. Naturally this is just a discussion model, which is based on past stories of technology triggers, and their eventual stabilization at some plateau of productivity, which is hard to predict. The Economist magazine suggested that perhaps later this year (2013), or next year (2014), we may start seeing some benefits of the smart cities concept (Economist, 2013).

While various explanations for different rates of uptake of modern stormwater management have been offered (Patouillard and Forest 2011), the author is of the opinion that that economic aspects dominate in: (a) In “green-field” developments, where such stormwater management may be required by regulations, mostly because the funds and space are available, and (b) in high-value retrofits, where again funding is available, and the drainage design may be motivated by the need to meet the drainage restrictions placed on the land, or marketing considerations. In the former case, the level of uptake of modern stormwater management depends on the rate of growth of the city; e.g., in Calgary (Alberta, Canada), where the sustained growth has been 12% annually, within 6 years, half of the city would have modern drainage, but in the case of a city with a negative growth (e.g., Windsor, Ontario;-
1%), the gains will be minimal. In the former case, it is relatively easy to work with principal stakeholders and ensure the implementation of modern drainage. Other factors include the local precipitation regime, and geological and terrain conditions.

2.6 Special issue of Water Research (2012)

When taking stock of the current status of urban drainage, it is of interest to examine the topics addressed in a recently published (Dec. 2012) special issue of Water Research on Stormwater in urban Areas (Rauch et al., 2012). The issue contains 25 papers dealing with urban stormwater and prepared by a multitude of authors from about a dozen of countries, according to the listed affiliations. Scanning of the paper contents indicates that about 36% of papers dealt with stormwater characterization, 40% with stormwater treatment, 16% with impacts, and the remaining 8% with benefits of stormwater treatment facilities and adaptation of drainage to a changing climate. Obviously the interest in knowing better the characteristics of stormwater is continuing and the papers focused on studying less well-known constituents in stormwater (priority pollutants, pathogens) or methods for developing stormwater characteristics (including treatability) (Metadier and Krajewski, 2012; Vezzaro et al., 2012) and stormwater from a specific land use (highway runoff) (Kayhanian et al., 2012). The other major section of papers dealt with stormwater treatment by existing best management practices and, besides addressing removal processes for various chemicals, it also dealt with operational issues including important factors for sustaining performance and maintenance. It was interesting to observe that the traditional terminology (BMPs) prevailed in these papers, rather than LID, SUDS, WSUD, etc. Impact papers dealt with impacts of various chemicals (priority or conventional), and receiving environments of various scales. Finally, benefits in the form of ecological services were examined and issues of drainage adaptation to climate change.

3 CURRENT CHALLENGES

Developing a comprehensive list of current and future challenges in such a broad field as urban drainage is a daunting task, particularly for a single author. Thus, the list of ideas compiled here is recognized as subjective and incomplete, and simply reflecting the author's experience in the field. Nevertheless, it could serve as a starting point for initiating discussions on this topic and eventually developing a much broader outlook on the future of urban drainage, effectively updating the earlier outlook provided by Chocat et al. (2007). With these qualifications, the author would like to address here future innovations, evaluation of urban drainage problem definition (sources of pollution, priority pollutants and climate change impacts), BMP research issues (models vs. prototype, generalization of results from single facilities, and study duration), and measuring the research accomplishments.

3.1 Future innovations

As cities continue to grow, there is a pressure on political decision makers and managers to provide water services, including drainage, to a growing population and generally at higher levels of service, certainly in the environmental context (Marsalek et al., 2008). This is a daunting task which can be fully accomplished only by adopting innovative approaches over expanding urban areas. However, in urban drainage the diffusion of innovation may be somewhat constrained by technological lock-in, attributable to such factors as monopolistic provision of services, long design lives of drainage elements, and lack of funding. On the other hand, it is also recognized that new innovations can be spurred by incentives, as noted in the case of the private sector (The Economist, 2013).

If one examines the past innovation in urban stormwater management, much of it was the result of adopting and/or adapting relatively well-known processes from catchment hydrology (i.e., in controlling stormwater quantity) and wastewater management (in controlling stormwater quality). Thus, we have picked all the low-hanging fruit that was accessible to us. This leads to a question, how much innovation we can expect in urban drainage in the near future and where will this innovation come from. The answer to this question will differ depending on who is posing the question – the end-user (i.e., an urban dweller), the UDS operator (a municipality or utility), technology vendor, designer (a consulting company), or researcher. The issue of concerns about future innovation is by no means unique to urban drainage; it has been addressed in many fields, including computer processing, and in that case the Economist magazine (2013) questioned whether the past pace of innovation can be sustained.

The author would like to suggest that with respect to innovation in urban drainage, we may be facing a near-future period during which the innovation concerning the basic drainage elements (i.e., sewer infrastructure with appurtenances, traditional BMPs) will change rather slowly (limited incentives), but
other aspects of UDSs, including those involving the private enterprise and requiring research (e.g., UDS problem definition updating, software for planning, design and operation of UDSs, environmental technologies) will keep evolving, because of the inherent incentives. Such a tendency seems particularly clear in the case of environmental technologies, where there has been proliferation of devices and structures serving to treat stormwater, or to protect or enhance its quality (Clark and Pitt, 2012). However, the complexity of innovative products and their total costs (i.e., the initial investment plus the operating costs) keep increasing, which is sometimes overlooked. For example, inserts into sewer inlets/catch basins for improving stormwater quality have been proposed, but require weekly maintenance. The costs of such innovations may become rather high because of the servicing costs, and the environmental and economic efficiency of such measures (i.e., measured in dollars per kg of solids, or litter removed) needs to be questioned and assessed. Furthermore, the associated maintenance costs could overwhelm the existing public works departments and their typical allocations of resources.

Finally, a further concern in the diffusion of innovation in stormwater management is the ambiguous terminology (i.e., terminology which is either doubtful or uncertain, or capable of being understood in more than one sense). This concern has been voiced during the last decade, but there is no improvement in sight. The current state reflects the process of evolution of stormwater treatment in many jurisdictions, without any consolidation of terminology, and as pointed out by Minton (2007), this ambiguity led to different design methods developed for essentially identical processes/devices. In spite of recognition of this situation and a general agreement among stormwater professionals that the situation should be corrected, it is not happening, partly because the experts may be able to navigate among these ambiguous terms, and partly that this ambiguity was introduced by the proponents of stormwater management designs or technologies, who wished to distinguish their products/approaches from those already on the market and in that process wished to imply some superior features of their approaches. A substantive contribution to introducing a clear terminology has been made by Minton (2007), who proposed to group SW treatment systems into the following five families: Basins, swales, filters, infiltrators and screens, and subdivided each family into sub-families, unit operations, and systems representing specific products or facilities.

### 3.2 Evolution of urban drainage problem definition

While the understanding of common impacts of urbanization on various environmental compartments is at a fairly advanced level, several specific issues are currently of concern and will stimulate further research: (a) Building materials as in-situ sources of pollutants, (b) Priority pollutants from local or remote sources, and (c) Future precipitation regimes and their potential modifications by climate change, with implications for quantity and quality of urban stormwater.

#### 3.2.1 Building materials as an in-situ source of pollution

Building materials have been identified as sources of pollutants in urban stormwater more than 30 years ago, certainly in the case of trace metals released by metal roofing materials (Malmqvist and Svensson, 1978). The past 15-20 years brought about a greatly expanded research on this topic, with the list of pollutants identified expanding from metals to such chemicals, as plasticizers or biocides used in industrial paints on building facades (e.g., DCMU, Terbutryn and Carbendazim). There are continuing concerns about this in-situ source of stormwater pollution and the limited control options available to the drainage professionals to address it, particularly for the existing buildings (Burkhardt et al., 2012). Building or road pavement materials may also exert positive effects on runoff (washoff), as documented by the use of self-cleaning concrete with embedded TiO₂ particles, e.g. for pervious concrete (Burton, 2011). This photocatalyst, oxidizes air pollutants, including nitrogen oxide and volatile organic compounds, and thereby removes pollutants at street level.

#### 3.2.2 Priority pollutants

A high number of priority pollutants have been identified by various international and national environmental agencies, starting with the US EPA list of 129 Priority Pollutants studied in the NURP program (USEPA 1983) and followed recently in a number of studies initiated under the EU Water Framework Directive (Birch, 2012; Bertrand-Krajewski et al., 2008). Experience from NURP shows that such data are generally used for assessing the pathways and fate of priority pollutants, but it is highly unlikely that their control would be added to the mandate of municipal or drainage engineers; it is more probable that such pollutants will be controlled by policy instruments (source controls), as was the case of phasing lead out of gasoline (OECD and UNEP, 1999). In a related example from urban drainage, this action was equivalent to across-the-board removal of 97% of Pb from highway runoff (Marsalek and Viklander, 2011). Furthermore, municipal “ownership” of the priority pollutants problem
would create municipal liabilities – i.e., responsibility for deposition and storage of priority pollutants in municipal stormwater management facilities, and the exceptionally high costs of their removal and disposal. The latter problem has been noted for stormwater pond sediment disposal and would apply to other BMPs as well. While the marginally polluted stormwater sediments can be disposed off for as little as CAD $20/m³ (i.e., the sediment of quality allowing on-land disposal at a public site, located about 7 km from the pond), for severely contaminated sediments disposals at special containment facilities may be up to two orders of magnitude higher (Karlsson et al., 2010). Controls of priority pollutants are likely to arise from international action at high level, as was the case of phasing lead out of gasoline through a series of international agreements.

3.2.3 Climate change impacts on urban drainage

Climate change impacts on urban drainage have been addressed during the past decade in many publications and much of that effort has been synthesized in Willems et al. (2012) and, with respect to adaptation, in Gersonius et al. (2012). In spite of this progress, the problem of producing quantitative assessments of climate change impacts on urban drainage remains to be challenging and further complicated by the dynamic nature of urban catchments, which keep changing as well. In projecting climate changes, the main challenges arise from the fact that global or regional climate model outputs need to be downscaled to scales of few kilometres and time resolution in minutes. Under such circumstances, the downscaled results may be highly uncertain and dependent on the downsampling process itself (Willems et al., 2012). In this uncertain environment, the infrastructure managers need to make decisions with consequences projected 80-100 years into the future. Perhaps a first important step would be to develop uniform procedures which municipalities could apply, while maintaining design flexibility allowing further adjustments in the future. So far, most of the attention focused on flooding aspects, but the assessment of performance of the stormwater quality infrastructure in a changing climate is also of interest. This performance will be impacted by the anticipated changes in stormwater quantity and quality regimes, and likely changes in pollution sources and their controls.

3.3 Stormwater management measures: research challenges

Achievements in developing stormwater quantity and quality management measures are indisputable. However, there are some limitations of the current research which will require further study. Among those, one could list strong reliance on laboratory rather than field studies, focus on small installations, relatively short durations of studies (ignoring issues of performance deterioration in time and the need for maintenance), and a “case study” nature of research work. Further discussion follows.

3.3.1 Model vs. prototype studies

Researchers who have worked in the field fully appreciate the challenges of such a work, including the difficulties in controlling experimental conditions and coping with the risk of vandalism. On the other hand, laboratory studies (typically on small elements of the prototype) eliminate practically all such challenges. However, to produce realistic results, lab studies on small elements (or even field studies on such elements) have to mimic fully the actual field conditions. Essential needs are establishing the mass balance of water, chemicals and solids in such tests, and mimicking fully the boundary conditions. The mass balance determines the ultimate fate of mass entering the facility (particularly the chemicals) and boundary conditions (e.g., outflow from filters into water or soils, rather than into free atmosphere) change the unit area treatment rates and possibly even the chemical reactions. Furthermore, field facilities (permeable/porous facilities) are prone to the development of macro-pores (or soil cracks) which greatly affect the infiltration/percolation rates, development of preferential flows, and also suffer from deficiencies occurring during construction. This has been noted for research facilities, and there is no reason why the same problem would not apply to common field installations.

Compared to the lab studies, the field installations are exposed to different atmospheric, chemical and biological influences, such as the nature of rainfall events providing hydraulic loads of the test facility (distribution of rainfall depth and intensities, and rainwater quality), atmospheric deposition of chemicals or chemical applications or influx in field installations (e.g., chloride input in cold climate), solids input (e.g., from applications of sand and grit in winter road maintenance, subject to grinding by vehicle tires), and naturally occurring bioturbation of soils or benthic sediments by biota. In would be desirable to demonstrate that the results from small element (lab) studies describe adequately the performance of full-scale facilities.

3.3.2 Spatial scaling: A single facility vs. catchment

Spatial issues are perceived here as resulting from studying a single facility vs. the whole catchment.
The literature on BMP and LID measures contains numerous studies essentially investigating mass balance of specific singular facilities and indicating inflows and outflows of water, chemicals and solids. Such studies have been most useful in developing a basic understanding of operation of such facilities. However, from the water management point of view, the interest is much broader – how a set of such measures (often including various types of measures) protects the entire catchment and its water resources (Roy et al., 2008). The issue is more complex than a simple assumption of additive properties of these facilities, because the control measures within catchments should be designed as integrated systems, rather than individual dispersed measures. Thus, looking for evidence that urban BMPs / LID provide water protection at the catchment level is a legitimate question, even though highly challenging (i.e., to find comparable watersheds with different uptakes of stormwater management).

A closely related issue concerns the fact that most field studies of urban stormwater BMPs are done at a single facility, generally because of the costs or lack of choices. While such studies may offer insight into field processes, there are usually so many experimental variables that often these studies represent case studies, rather than research studies. Thus, there is a need to look at larger groups (samples) of BMP facilities and attempt to develop more general findings (Moore and Hunt, 2012). While compilation of databases of BMP facilities performance is most helpful (International Stormwater BMP Database, 2013), such efforts may be impaired by challenges in undertaking QA/QC on the data submitted. Formation of task groups mining such databases and addressing specific BMPs with the objective of developing robust criteria for their design in various conditions would be most useful.

3.3.3 Study duration

One of the missing points in the UDSs research is studying BMP performance over sufficiently long time periods, which would cover gradual deterioration of performance due to deposition of sediment, reduction in filtration capacity by clogging (Le Coustumer et al., 2012; Sansalone et al., 2012), and reduction of sorption spaces, recognizing that there may be even changes in the rainfall regime due to a changing climate. Recognizing high costs of facility monitoring, it may be impractical to monitor such facilities (or sites) continuously, but in that case periodic revisiting of the facility would be desirable. The other factor which may speak against this approach is the dynamic nature of the urban areas (and the climate), but still the author believes that it would be a worthwhile activity. Alternatively, we need quick, inexpensive procedures for assessing the performance and maintenance needs status of BMPs, and procedures for triggering the maintenance action (Yong et al., 2013). Such procedures should reach beyond the cost-benefit analysis, by including environmental risks associated with accumulations of contaminants in stormwater management facilities.

3.3.4 Pollutant source control by policy instruments

There is number of examples of environmental research which resulted in adoption of policies that contributed to the successful development of source control policies. Primary examples of such success stories include phasing lead out of gasoline and substitution of low copper content in automobile brake pads. The author believes that there are opportunities for more advances in this field, by focusing on the pollution source management process. This requires collaboration between the researchers and science policy communities, by identifying sources of contaminants in urban stormwater, assessing the associated environmental risks, engaging in advocacy and argument in support of source controls, adopting source control decisions and actions, and finally, providing feedback and revision of environmental regulations. When dealing with low-level diffuse contaminants, source control policies are the most cost-effective management control tools deserving further promotion and development (Marsalek and Viklander, 2011).

3.4 Measuring the research accomplishments

The volume of peer reviewed journal publications identifying with urban drainage research has been steadily growing for some time, but the rate of growth has greatly increased during the last decade. This is partly caused by the continuing interest in the urban environment and the resulting availability of funding and opportunities for engagement of graduate students, and partly by the pressure on researchers to publish, preferably in journals with high impact factors, and obtain citations for such publications. The author believes that this system may work well for natural sciences and be appropriate for some aspects of urban drainage, but its usefulness for assessing the benefits to the end-users (i.e., urban dwellers) can be questioned. For many publications, it may be challenging to identify how they serve the end-users and their needs. The review process generally does not ask about the real or perceived applicability of the paper findings, but simply the adherence to the scientific method, and other formal requirements, including high probability of securing paper citations for the
journal. The widening gap between the end users (e.g., municipal engineers) and authors of journal papers has increased to the point, where some research programs institute “knowledge translation” projects, which provide a communication bridge between the science producers (usually university professors, whose scientific performance is measured by publications) and the end users of the produced knowledge, representing urban drainage professionals working for government agencies, or the private sector (consultants, utilities). Furthermore, the papers with lower citation potential (e.g., addressing specific climate regions) are less welcome in publication media.

The business model of publication of peer reviewed journal papers is unusual in the fact that in the process of publication of research results, which may represent a costly product (i.e., the funds required to produce the research results), the quality control (i.e., the review process) relies greatly on help of volunteers, some of whom are even competitors (i.e., colleagues working in the same field) striving to publish in the same journal. There are no obvious and immediate solutions to this problem; the publication process can not afford the additional costs of “professional” reviewers, but the potential bias in the system should be reduced by a careful selection of reviewers, who understand and accept their responsibility for unbiased quality control. Furthermore, some prolific authors ‘do not have time’ for reviewing papers of others (Dixon and Loosdrecht, 2012), which reduces the quality of the reviewer population. Additional challenges to this publication process are likely to be caused by proliferating on-line journals, which offer free access to papers by the general public, but are also in a conflict of interests, because their operation depends directly on the publication fees paid by the authors. In time, these on-line journals may provide real competition for traditional journals.

4 CONCLUSIONS

In spite of the remarkable progress in the development of urban drainage and stormwater management during the past 50 years, demands on innovation and research will continue in the near future, because of the dynamic nature of urban areas and their inhabitants. Requirements on urban drainage systems and stormwater management are continually changing, as a result of the dynamic nature of urban areas, changes in precipitation and temperature over urban areas due to climate change, changing releases of pollutants, and changing objectives for operation of urban drainage systems, resulting from changing expectations of the urban population.

LIST OF REFERENCES


Hydrology, Melbourne, Australia, Report 99/3.


Moore, T. L.C. and Hunt, W.F. (2012). Ecosystem service provision by stormwater wetlands and ponds – A
means for evaluation? Wat. Res. 46(20), 6811-6823.


