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Evolution of Urban Drainage: from Cloaca Maxima to Environmental Sustainability

BY:

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Introduction

Drainage of urban settlements has been practiced for more than five thousand years, but the recognition and understanding of drainage impacts on the environment and the need for mitigation of such impacts has emerged fairly recently, during the last 40-50 years. Urban drainage was first built to improve living conditions in urban settlements by preventing water ponding and draining marshes for new development. Historical records refer to early urban drainage structures in the Mesopotamian Empire (Wolfe, 2000), but the drainage construction skills flourished somewhat later in ancient Rome and Pompeii. The best example of ancient Roman drainage achievements is the Cloaca Maxima, which was constructed in Rome around 510 BC to drain marshes and transport wastes to the Tiber River. The outfall of the Cloaca Maxima into the Tiber still exists today. Other remnants of urban drainage structures were preserved in Pompeii, where roadways were used for runoff conveyance (a concept rediscovered in the 1960s) and references to a drainage manual were found. After the decline of the Roman Empire, sanitation practices generally deteriorated, and open drains and streets were used indiscriminately for conveyance and disposal of all wastewaters.

In later times (16^{th}-18^{th} centuries), some progressive strategies for managing wastewater and stormwater emerged, with both effluents considered as valuable resources (Maneglier, 1991). For example, faeces were harvested for production of organic fertilizers, urine infiltrating into urban soils formed saltpetre that was used in making gunpowder and stormwater was collected and stored in cisterns to provide an important water source. In Venice, some city squares with permeable cover were used to collect stormwater, which percolated into underground storage reservoirs filled with sand and made watertight with clay walls and bottom preventing saltwater intrusion. During this era, neither horses nor pigeons were allowed in these squares. However, the practices of wastewater disposal were generally not hygienic and numerous epidemics of typhoid and cholera in Europe and the United States, between the 1830s and 1870s, prompted city governments to find other solutions for dealing with sewage disposal and eventually its treatment in the form of sewer systems and wastewater treatment plants (Wolfe, 2000).

In the 19^{th} century, an empirical foundation for drainage pipe sizing was laid with the development of the rational method, which is generally credited to Mulvaney (Ireland, 1851). Variations of this formula have been developed in other countries. Use of the rational method dominated engineering drainage practice until the late 1960s, and it is still widely used in some parts of the world and in certain applications (i.e., small drainage areas with simple tree-type sewer systems, no controls, no storage, no backwater, etc.). During the rational method era, the general goal of urban drainage was to collect and quickly remove stormwater from urban areas and discharge it into nearby receiving waters.

Since the 1960s, rapid developments have occurred in urban drainage practice, particularly with respect to design methods. A number of runoff hydrograph methods were developed, starting with the Chicago Hydrograph Method, followed by the Road Research Laboratory method, the Stormwater Management Model (SWMM), and many other models. The introduction of computer modelling greatly advanced this field and led to the current state where it is possible to calculate sewer network flows with the accuracy needed for proper design, analysis and operation of sewer systems. The development of water quality aspects occurred somewhat later and focused on the quality of stormwater, overflows from combined sewers, changes during transport, quality enhancement by control measures and treatment, and impacts on receiving waters. The complexity of water quality modelling is such that many challenges still exist in this field, but the available models, after calibration, are generally adequate for most of the engineering tasks.

Major changes in drainage design philosophy were introduced in the late 1980s and the early 1990s, as a result of: (a) introduction of the sustainable development concept, (b) acceptance of the ecosystem approach to water resources management, (c) improved understanding of drainage impacts on receiving waters, and, (d) acceptance of the need to consider the components of urban drainage and wastewater systems (drainage, sewage treatment plants, and receiving waters) in an integrated manner.

The discussion that follows starts with the description of urban drainage processes, followed by impacts of stormwater discharges and combined sewer overflows (CSOs) on receiving waters, impact mitigation by stormwater management and CSO storage and treatment, methods of analysis and design, environmental sustainability and emerging issues.

Urban drainage processes

One of the most fundamental concepts in hydrology is the hydrologic cycle, which is defined as a conceptual model describing the storage and circulation of water between the biosphere, atmosphere, lithosphere, and hydrosphere. The principal structure of the hydrologic cycle is preserved in urban areas, even though the cycle is greatly modified by the impacts of urbanization and the need to provide water services to the urban population, including water supply, drainage, wastewater collection and management, and beneficial uses of receiving waters (Benedini et al., 1999). Thus, the hydrological cycle becomes much more complex in urban areas (McPherson, 1973). The effects of urbanization on the hydrological cycle were described by Leopold (1968), who identified the main changes as reduced infiltration and evapotranspiration, resulting in increased runoff and reduced groundwater recharge. These processes then lead to increased flooding and receding groundwater tables. Reductions in groundwater recharge are somewhat offset by leakage from drinking water mains, exfiltration from sanitary, combined and storm sewers (Giulianelli et al., 2004), and infiltration of stormwater through various stormwater management practices.

Urbanization leads to increased catchment imperviousness and fast hydraulic transport in man-made channels and conduits. Consequently, it affects surface runoff generation in urban areas in three ways: (a) increasing the runoff volume, (b) increasing the speed of runoff leading to higher flow peaks, and (c) reducing the catchment response time allowing higher rainfall intensities to generate local runoff peaks. Riordan et al. (1978) reported that urban development increased runoff peaks 1.5 to 10 times for return periods of 2 years, and 1.1-3 times for return periods of 100 years. Thus, urban drainage design aims to control these flow increases and provide hydraulic conveyance for the residual flows.

In urban areas served by combined sewers, high influxes of stormwater into sewers lead to combined sewer overflows (CSOs), whenever the combined flow rate exceeds some threshold (typically 1.5 to 6 times the dry weather flow)(Marsalek et al., 1993). CSOs represent a mix of stormwater with sanitary sewage, plus the sludge scoured from the bottom of sewers. Some uncertainty can be introduced into the CSO characterization by commercial or industrial wastewater discharged into municipal sewers; those sources are not so well known. The degree of CSO pollution can be rather high, often exceeding the pollution of sanitary sewage, particularly during the first flush (Berretta et al., 2004; Del Giudice et al., 2000). The composition of CSOs has been studied in many countries (e.g., Barco et al., 2004; Marsalek et al., 1993) and is well understood for conventional chemicals (see Table 1). However, new concerns about CSO pollution remain, particularly in connection with the new chemicals of concern, including endocrine disrupters, pharmaceuticals, personal care products and antibiotics. While the attenuation of these chemicals in wastewater treated in sewage treatment plants is being studied and a great deal of knowledge is being generated, not much has been published on these chemicals in CSOs, particularly their attenuation by simple treatment processes applied to CSOs, often just settling, which is equivalent to primary treatment. Thus, the management and treatment of CSOs remains to be one of the great challenges in the integrated management of urban pollution.

Urban runoff affects sediment, chemical and heat fluxes in urban areas. Disturbance of land cover during development greatly increases soil erosion, with export of sediment and suspended solids from urban catchments. This increase may be temporary; after consolidation of surfaces (reestablishment of vegetation) the export rates decrease to the range of 0.1 to 1 t/ha/y (Marsalek, 1992), with Pagliara (2003) reporting a value of 0.25 t/ha/y for a catchment in Italy. Besides sediment, urban runoff also transports various chemicals. By now, more than 600 chemical substances have been identified in urban runoff, and this number is growing. The list of pollution sources in urban areas is also extensive and includes atmospheric wet and dry deposition (from local and remote sources), catchment land use activities (residential, commercial and industrial sources, open land - parks, traffic, road maintenance, spills, pets), and surface attrition/corrosion/ elution (road wear and tear, corrosion of structures, and elution of chemicals from construction materials, sediment deposits and soils). The sediment and chemicals which accumulate on urban surfaces (Maglionico and Pollicino, 2004) are washed off during rainfall (Del Giudice et al., 2000). Concentrations of selected constituents in urban runoff are listed in Table 1, which combines data from a compilation of worldwide data by Duncan (1999) and the U.S. NURP program (U.S. EPA, 1983). With small exceptions, the numbers of samples used in calculating the values in Table 1 were greater than 100.

Table 1. Quality of urban runoff and combined sewer overflows (after Duncan (1999), Marsalek et al. (1993) and U.S. EPA (1983))

Chemical Constituent	Units	Urban Stormwater		Typical CSO data (Marsalek et al., 1993)
		Mean of Duncan's dataset (1999)	U.S. NURP median site (U.S. EPA, 1983)	
Total Suspended Solids	mg/L	150	100	50-430
Total Phosphorus	mg/L	0.35	0.33	2.2-10
Total Nitrogen	mg/L	2.6	-	8-12
Chemical Oxygen Demand	mg/L	80	65	150-400
Biochemical Oxygen Demand	mg/L	14	9	45-90
Oil and Grease	mg/L	8.7	-	-
Total Lead (Pb)	mg/L	0.140	0.144	0.01-0.10
Total Zinc (Zn)	mg/L	0.240	0.160	0.06-0.40
Total Copper (Cu)	mg/L	0.050	0.034	-
Faecal Coliforms	#/100 mL	8,000	-	10^4-10^7

While the chemical and microbiological characterization data on CSOs and stormwater seem to be fairly extensive, many challenges remain. In water quality analyses and for design of mitigation measures, one needs to know not only the total constituent concentrations, but also their partitioning to water or solids, and speciation, which affects both potential toxicity and mobility. These difficulties led to an alternative description of stormwater and CSO quality by other factors, such as toxicity. An example of toxicity data for stormwater (about 300 data points) and CSO (about 200 data points) samples is shown in Fig. 1 (after Marsalek et al., 1999).

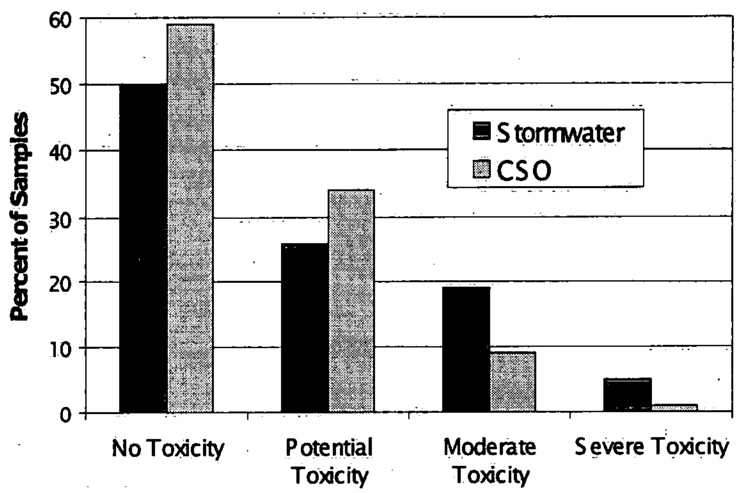

Fig.1. Toxicity data for 15 sites in Southern Ontario (8 stormwater and 7 CSO sites)

Challenges with microbiological data are also substantial. In typical studies, indicator bacteria are observed and enumerated (typically *E. coli*), though the actual interest is in pathogens. Research indicates that typical *E.coli* counts in recreational waters include bacteria from three general sources – humans, wildlife (mostly birds) and domestic pets. In general, bacteria from animals pose lower health risks to humans, but only during the last several years the technology of microbial source tracking has evolved to the point where bacterial sources can be differentiated. This will lead to substantial changes in monitoring of bacteria in the future and interpretation of such data, particularly in connection with the safe use of recreational waters.

Finally, urban runoff also conveys waste heat from impervious surfaces, which may be particularly hot in summer. This heat flux then affects the thermal regime of receiving waters

Stormwater and CSO impacts on receiving waters

Urban drainage impacts on receiving waters need to be considered in the context of time scales, spatial scales and the types of receiving water bodies. With respect to time scales, acute and cumulative impacts are recognized (Harremoes, 1988). Acute impacts are exerted instantaneously and represent those caused for example by flow (flooding), biodegradable matter (impact on dissolved oxygen levels), toxic chemicals (acute toxicity) and faecal bacteria (impacts on recreation). For pollutants causing acute impacts, frequency and duration of the occurrence of pollutant concentrations are of interest. Transport dynamics in the receiving waters, including effluent mixing and dispersion, and pollutant decay, are important phenomena influencing the resulting ambient concentrations in the receiving waters. Cumulative impacts generally result from a gradual build-up of pollutants in the receiving waters and become apparent only after such accumulations exceed some critical threshold value. Examples of such impacts are those exerted by nutrients and toxicants released from accumulated sediment. For pollutants causing cumulative impacts, fine time scale dynamics is not important and the main interest concerns the loads integrated over extended time periods (Harremoes, 1988).

Stormwater runoff and CSO impacts also depend on the magnitude of discharges and the type and physical characteristics of the receiving waters. While all receiving waters can tolerate some pollution loads, problems arise when this capacity is exceeded. Impacts are most serious in small urban creeks, in which the dilution of stormwater and CSO discharges from many dispersed outfalls is minimal. In rivers, stormwater and CSO pollutant impacts are generally reduced because of dilution and the self-purification capacity of the stream. Pollutant transport in the receiving waters further increases the spatial scope of stormwater and CSO impacts. Stormwater and CSOs also impact on lakes and reservoirs depending on the size of such water bodies (Capodaglio et al., 2003). The most impacted are small impoundments in urban areas; in the case of large water bodies, the impacted zone may be limited to the near-shore waters; however, these may also be key recreational areas.

Stormwater and CSO discharges, often in combination with other stressors, cause combined impacts which are best measured by the performance of a biological community, such as fish. The community assessment should be conducted in conjunction with the assessment of physical and water quality factors (Horner et al., 1994), and it reflects the combined effects of such factors as flow regime, habitat structure (geomorphology), biotic interactions, energy sources and chemical variables, most of which are further discussed below.

Urban drainage contributes to physical impacts on receiving waters through increased flows, erosion (Pagliara and Chiavaccini, 2004), temperature, and densimetric stratification. Increased flows may lead to flooding, sediment and habitat washout (Borchardt and Statzner, 1990), and morphological changes (Schueler, 1987), accompanied by ecological impacts on food web, critical species and ecosystem development. Fishing is the most affected primary beneficial water use (Lijklema et al., 1993). Changes in the receiving water sediment regime (erosion and sediment deposition) contribute to loss of habitats and damages caused by high concentrations of suspended solids (e.g., siltation of spawning grounds). Ecological impacts include those related to critical species and dispersal and migration; and, practically all beneficial water uses are affected (water supply, bathing, recreation, fishing, industrial water supply and irrigation (Lijklema et al., 1993). In summer months, stormwater runoff temperatures may exceed those in the receiving waters by up to 10° C (Schueler, 1987; Van Buren et al., 2000) and contribute to long-term changes in the receiving water thermal regime, with a conjunctive loss of cold-water fishery. The ecological impacts of thermal enhancement include those related to energy dynamics, food web, genetic diversity, and dispersal and migration. The most impacted beneficial water use is fishing (Lijklema et al., 1993). Finally, in areas, where road salt is used in winter road maintenance, water bodies receiving stormwater discharges may become densimetrically stratified (Marsalek, 1997), which impedes vertical mixing and oxygenation of bottom layers, with the concomitant loss of biodiversity (Crowther and Hynes, 1977). The affected beneficial water uses include water supply, fishing, and irrigation (Lijklema et al., 1993).

Urban runoff and CSO effluents with relatively low contaminant levels cause biological damage in two ways - chronic impacts resulting from cumulative water quality stress and by pollutant accumulation in aquatic sediment and the resulting impacts on the organisms that inhabit or spend considerable time in or on the streambed or reservoir/lake bottom (Horner et al., 1994). Several types of chemical impacts are discussed below.

Depletion of dissolved oxygen and the concomitant biomass accumulation are typically caused by discharges of oxygen demanding substances, characterized by elevated concentrations of BOD, COD and ammonia. Oxygen demanding substances are conveyed in relatively high concentrations by CSOs (Harremoes, 1988); stormwater sources are much less important. Environmental impacts occur as short-term impacts caused by dissolved BOD/COD and ammonia, and intermediate-term impacts, which are caused by the sediment oxygen demand (Hvitved-Jacobsen, 1982). Ecological impacts include the loss of biodiversity and critical species; the affected water uses are water supply, bathing, fishing and industrial water supply (Lijklema et al., 1993).

Nutrient enrichment in and eutrophication of receiving waters is typically caused by total nitrogen and total phosphorus found in both CSOs and stormwater, with CSOs generally carrying much higher concentrations (see Table 1). Eutrophication degrades lake ecosystems in a number of ways, including reduced food supplies for herbivores, reduced water clarity, and at the end of the algal bloom, decomposition which causes high oxygen demands leading to oxygen deficiency, particularly in the bottom layers. Ecological impacts include those on energy dynamics, food web, critical species, and ecosystem development. The affected water uses include water supply, bathing, recreation, fishing, industrial water supply, and irrigation (Lijklema et al., 1993).

Toxic impacts may be caused by elevated levels of ammonia (in CSOs), and chlorides, metals, and trace organic contaminants mostly associated with stormwater discharges. Acute toxicity was observed most frequently in winter highway runoff (Marsalek et al., 1999), the cumulative impacts resulting from a gradual build up of contaminants over long time periods are also of concern. Indications of the chemical abundance of these substances are not adequate to describe these impacts; the bioavailable fraction, whose presence varies and depends on the sources as well as ambient conditions, are the most important descriptors (Marsalek et al., 1999). Ecological impacts of ammonia and trace organic contaminants include those on food web, biodiversity, and critical species; in the case of metals, such a list could be further expanded for adverse impacts on the ecosystem development. In the short term, the only beneficial water use impacted is fishing (Lijklema et al., 1993); in the long term, the receiving water ecosystem is downgraded.

Microbiological pollution effects on human health and biomass are primarily associated with CSOs, and to a lesser degree, with stormwater. The effects on public health are related to swimming beaches (Marsalek and Rochfort, 2004), the effects on biomass include contamination of shell fish and closure of harvesting areas. Both stormwater and CSOs convey high loads of faecal bacteria (see Table 1), which are typically described by concentrations and fluxes of indicator bacteria, such as *Escherichia coli.* Whenever the local guideline is exceeded, public beaches are posted or closed to public use, with concomitant impacts on the local economy. Urban runoff, in the form of CSOs or stormwater, is a significant source of faecal pollution bacteria and pathogens. Major sources of such pollution include pet populations, urban wildlife (particularly birds), cross-connections between storm and sanitary sewers, lack of sanitation, deficient solid waste collection and disposal, accumulation of sediments in sewers and receiving waters, rodent habitation in sewers, land wash and growth of bacteria in nutrient rich standing waters (Olivieri et al., 1989). Ecological impacts of microbiological pollution include those on energy dynamics, food web, and ecosystem development. The impacted beneficial water uses include water supply, bathing, and fishing (Lijklema et al., 1993).

Impact Mitigation Measures

Concerns about the environmental and human health effects of stormwater and CSO discharges led to the development of various control and treatment strategies, which differ for each of these two sources and are therefore discussed below separately. Stormwater is generally managed by applying best management practices (BMPs); the abatement of CSO pollution is achieved by reducing stormwater inflow, and storing and treating the overflows.

Stormwater management is applied in the form of policies and source controls, and BMPs which are applied at the lot, community or watershed levels. Policies and source controls are generally highly cost-effective non-structural measures that are considered in all stormwater management plans. These measures include public awareness, education and participation; urban development planning considering minimization of runoff impacts; material use, exposure and disposal controls minimizing contact between rainfall/runoff and various chemicals; spill prevention and cleanup, prevention/elimination of illegal dumping and illicit connections, and maintenance of street and stormwater facilities (Camp Dresser & McKee et al., 1993).

Lot-level BMPs typically represent minor measures implemented at the lot level mainly in the form of source controls. Such measures include enhanced rooftop detention, green roofs, flow restrictions at catch basins to enhance local storage/detention, reduced lot grading to slow down runoff flow and enhance infiltration, redirecting roof leader discharges to ponding areas or soakaway pits, and sump pumping of foundation drains (MOE, 2003). More effective infiltration of stormwater is achieved in small-scale infiltration facilities in the form of wells (pits), trenches, basins, perforated pipes and drainage structures, and porous pavement. Such structures serve to reduce the volume and rate of runoff, reduce pollutant transport/export and recharge groundwater. The use of infiltration is generally feasible in small residential areas with a low risk of groundwater contamination, soils with good percolation rates, and deeper groundwater or bedrock. Septic tanks and building foundations have to be avoided. The main difficulties with infiltration applications include potential contamination of ground water and uncertain longevity of these structures. Biofiltration by grass filters and swales reduces runoff volume by infiltration and enhances runoff quality by such processes as settling, filtration, adsorption and bio-uptake. Vegetated filter strips and swales are feasible in low density developments with small contributing areas (< 2 ha), diffuse runoff, suitable soils (good sorption), and low groundwater tables (Schueler, 1987).

Water quality inlets, which were originally developed as small three-chamber storage tanks installed at inlets to the sewer system, were mostly replaced by oil/grit separators sometimes designed as in-line devices. They provide some stormwater treatment by sedimentation and skimming of floatables (and oil). Filtration is also applied in stormwater treatment, either at the inlet (Papiri et al., 2003), or as sand filtration or bio-filtration. Sand filters were found effective in removing pollutants, but attention must be paid to preventing clogging (e.g., by pre-treatment) and backwashing may be required. Good filter designs may serve up to 5 ha, use a sand layer of 0.5 m, operate with a hydraulic head 0.6 - 1.0 m (higher heads compact sand), and should be equipped with a collector for the filtrate and an overflow/bypass structure (Urbonas, 1999). Biofilters (i.e., with a coarse medium with biofilm on granular surfaces) were also tested and show good promise for removal of dissolved heavy metals and nutrients (Anderson et al., 1997).

Community level BMPs include larger-scale infiltration facilities, stormwater ponds and basins, and constructed wetlands. At the community level, infiltration facilities are built as trenches or basins. Trenches are generally designed for contributing areas of less than 2 ha, and draw-down times of 24-48 hours; infiltration basins were recommended (in Ontario) for contributing areas up to 5 ha, and soils with percolation rates > 60 mm/h (MOE, 2003).
Stormwater management ponds are used widely in urban areas to provide various types of controls, including flow control (reduction of flow peaks), sedimentation (removing sand, and some silt and clay), and removal of dissolved pollutants by aquatic plants (Van Buren, 1994). These BMPs require a fair amount of land, but also serve for aesthetic and recreational purposes. They are well suited for areas with community acceptance, contributing areas > 5 ha, low slopes, and sites without shallow groundwater or bedrock. Poorly performing ponds may need to be redesigned and retrofitted with additional measures as shown in Fig. 2 (Watt et al., 2004).

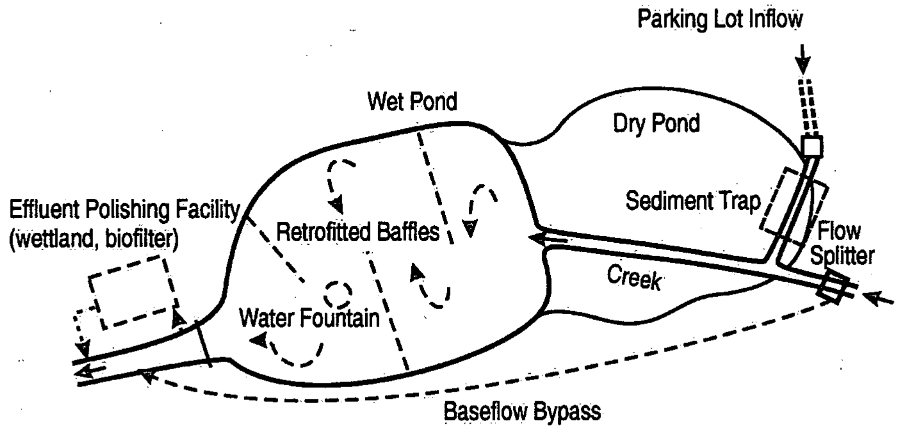

Fig. 2. Retrofit options for an on-stream stormwater pond (sediment trap, baseflow bypass, retrofitted baffles, water fountain removal, effluent polishing)

There are some concerns about pond operation - safety, poorly designed or maintained facilities that become a nuisance, heating up of pond water, and breeding of mosquitoes (Schueler, 1987). Regular maintenance of ponds is required, including the removal of accumulated sediments. Extended detention (dry) basins provide stormwater settling in areas where it is difficult to maintain wet facilities. They are widely applicable and are designed for drawdown times of 24-40 hours. Aesthetics of dry ponds with deposited sediment is questionable; but the land which they occupy often serves dual purpose, e.g. as a play field and stormwater storage (Camp Dresser & McKee et al., 1993; Schueler, 1987)

Constructed wetlands provide stormwater detention and treatment by such processes as filtration, infiltration, and biosorption, and remove both particulate and dissolved pollutants (Rochfort et al., 1997). They are widely applicable in drainage design, serving areas > 2 ha with available sites, tight soils, low evapotranspiration and presence of baseflow. The problems associated with this BMP include thermal enhancement, seasonal variations in performance, poor performance during winter months, and complicated maintenance (MOE, 2003).

Watershed-wide planning of stormwater management recognizes the cumulative impacts, protects specific features and resources, supports land use decisions, improves source-control BMPs, and assists in BMP siting (i.e., local vs. regional facilities). Site resources to be protected in watershed-wide stormwater management include wetlands (provide habitat, water storage and treatment), floodplains (provide flood conveyance, habitat, and recreation opportunities), riparian (forested) buffers (contribute to moderating stream temperatures and dissolved oxygen variation, protect stream banks and wildlife habitat), meadows (function as buffers), and soils (impact on water quality) (DDNR&EC and EMCBC, 1997).

For all stormwater management measures, good guidance is available for their design, performance and maintenance (Camp, Dresser & McKee et al., 1993; MOEE, 2003; Schueler, 1987; WEF and ASCE, 1992). Also, there is a great volume of data available on BMP performance (more than 220 facilities) in the ASCE BMP database (Strecker et al., 2004). The cost data for various stormwater BMPs are somewhat limited. The selection of BMPs is empirically based, generally starting with application of source controls (policies) followed up by "structural" BMPs. The selection process starts with establishing the performance goals, listing solution alternatives in the form of treatment trains, eliminating unfeasible measures, ranking the remaining measures with respect to benefit/cost ratios, and finally selecting the most effective combination of BMPs (Camp, Dresser & McKee et al., 1993; Schueler 1987).

Recognizing that CSOs are caused by excessive inflows of stormwater into the combined sewer system, all measures reducing generation of stormwater also help to abate CSOs. Such helpful measures include many source controls, infiltration measures (pits, trenches, basins, porous structures) and porous pavements. The mitigation of actual overflows is accomplished by various forms of flow storage (Bornatici et al., 2004; Calomino et al., 2004) and treatment (Zukovs and Marsalek, 2004); flow storage serves to balance CSO discharges, which may be returned to the treatment plant after the storm, once flows have subsided below the plant capacity (Paoletti and Sanfilippo, 2004).

CSO storage capacity can be created in a number of ways; by maximizing the utilization of storage available in the existing system (e.g. through centrally controlled operation of dynamic flow regulators in real time (Schilling, 1989)), as newly constructed storage on-line or off-line (on-line storage include oversized pipes or tanks; off-line storage includes underground storage tanks or storage and conveyance tunnels), or even in the receiving waters by implementing flow balancing systems formed by suspending plastic curtains from floating pontoons, in a protected embayment in the receiving waters (WPCF, 1989). Stored flows are returned to the wastewater treatment plant, which must be redesigned/upgraded for these increased flows. Without such an upgrading, the plant may become overloaded, its treatment effectiveness impaired and the benefits of storage would be defeated. Some storage facilities are designed for enhanced treatment by sedimentation, which can be further improved by installing lamellar plates and applying chemical coagulants/flocculants (Averill et al., 1999).

CSO treatment takes place either at the central plant, together with municipal sewage, or may be done in satellite plants dedicated to this purpose. Various processes have been proposed or implemented for the treatment of CSOs, including preliminary treatment (screening, degritting), physical or physical-chemical treatment (retention treatment basins, chemically enhanced high-rate sedimentation, hydrodynamic separation, continuous deflective separation, screening, filtration, dissolved air flotation, ballasted flocculation/ settling, and disinfection by chlorination/dechlorination, or UV irradiation) (Zukovs and Marsalek, 2004; WPCF, 1989).

Treatment technologies are available to achieve almost any level of CSO treatment, but proper cost/benefit considerations are crucial for achieving the optimal level of abatement, within given fiscal constrains. Reductions in the required treatment capacities are obtained by balancing inflows by storage (Marsalek et al., 1993). From the maintenance point of view, the operators (municipalities) prefer simple treatment systems, with more or less automatic operation, and minimum maintenance requirements. The most cost-effective CSO abatement schemes are designed as systems dealing with the entire urban area or watershed (and all system components), and combine various source controls, storage and treatment measures, allowing flexible degrees of control and treatment, depending on the event frequency of occurrence (Marsalek et al., 1993). More frequent events should be fully contained and treated; less frequent events may be still fully or partly contained and treated to a lower degree, and finally, the infrequent events may have to be allowed to overflow, but with reduced volumes and some pre-treatment prior to their discharge into the receiving waters.

Methods of analysis

Modern design of urban drainage requires a thorough understanding of drainage processes with respect to drainage design and computational tools for determining state variables, such as runoff quantity and quality, at any point in the drainage system. The knowledge of drainage systems provides guidance in planning, analysis and design of drainage, and serves for the development of design guides and manuals. A large number of design manuals exist in the literature; practically all of them targeting specific national or municipal audiences. Typical comprehensive drainage manuals (Artina et al., 1997; WEF and ASCE, 1992) include chapters dealing with financial, legal and regulatory concerns; surveys and investigations; design rainfall; measurement instrumentation; design concepts and master planning; hydrology and water quality; sewer system hydraulics; computer modelling; design of drainage conveyances; special structures and appurtenances; combined sewer systems; design of BMPs; materials of construction and maintenance; structural requirements; construction contract documents; and, construction surveys.

Over the years, the degree of comprehensiveness of drainage design has increased from the sizing of drainage elements to environmental sustainability and the computational methods have evolved in a similar way from empirical formulas (e.g., the rational method) to comprehensive computer models. In fact, modern urban drainage systems are so complex that their design and operation can not be understood without the use of models. Other reasons for modelling include the need to choose the "best" from multiple possible solutions and the non-linearity of drainage system responses to hydraulic and pollution loading (McAlister et al., 2003).

The past 40 years of drainage modelling can be characterized by the following trends: (a) evolution of modelling and models to the point of maturity leading to broad acceptance of these tools and their results, (b) movement from independent system component modelling to integrated modelling encompassing the generation, collection and transport of runoff and municipal sewage; management and storage facilities; a sewage treatment plant; and the receiving waters, (c) parallel existence of large modelling packages (with a modular structure) capable of multiple-level analysis of large drainage systems and of smaller models serving a particular market niche, (d) acceptance of the need of large volumes of data serving as model inputs (e.g., rainfall/precipitation, physiographic data describing the drainage area and system, flow quality data, receiving water characteristics, and socio-economic data) or calibration/verification data, (e) the need for storage and management of digital data in spatially referenced databases (GIS systems), (f) automated collection of data by remote sensing and model setting (digital elevation models), and most recently, (g) the need to provide guidelines for a good modelling practice (a form of quality assurance/quality control).

A schematic presentation of major components of the urban drainage system with combined sewers is shown in Fig. 3.

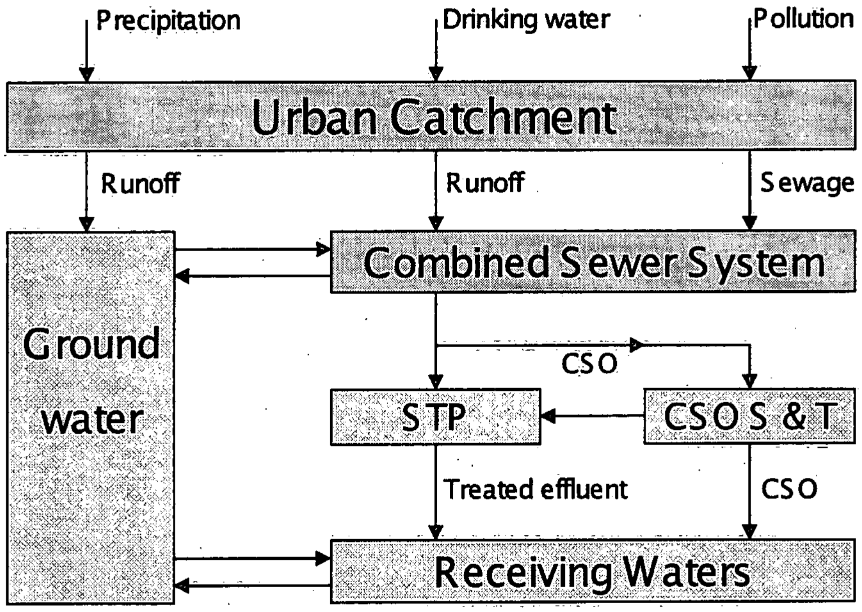

Fig. 3. Major components of the urban drainage system (STP = sewage treatment plant, CSO S&T = storage and treatment).

Development of drainage oriented models is continuing, with emphasis on further refinement of the leading existing packages (in an alphabetical order, DHI Mouse and Mike, Wallingford Infoworks CS, and U.S. EPA SWMM) and integration of models of system components. Several integrated urban catchment models have been developed (Rauch et al., 2002), but their practical applications are rather challenging. Further developments in this field include the development of simpler surrogate models allowing fast consideration of long-term effects and simulation of planning scenarios, greater use of stochastic modelling, and further expansion of the model scope to include all aspects of urban water management at a watershed scale

Environmental sustainability

Urban water researchers and managers have been searching for objective and meaningful ways of assessing the drainage system performance (Artina et al., 2004) and measuring the progress towards attaining the goals of sustainable development. In the context of urban drainage, sustainable development is usually reduced to 'environmental sustainability', and the ways of assessing such sustainability for environmental systems. Some guidance for measuring environmental sustainability can be obtained from the new 2005 Environmental Sustainability Index (ESI), which was proposed by the Yale and Columbia Universities (Esty et al., 2005). The ESI integrates many environmental data sets, by tracking natural endowments, past and present pollution levels, environmental management efforts, and the capacity of the society to improve its environmental performance, into 21 indicators of environmental sustainability. Such indicators facilitate comparison of environmental issues falling into five categories: integrity of environmental systems, mitigation of environmental stresses, mitigation of human vulnerability to environmental stresses, societal and institutional capacity to respond to environmental challenges, and global environmental stewardship. A similar approach was reported in an European Commission (EC) study which adopted five categories of urban drainage sustainability criteria: (a) Technical and scientific performance of best management practices, (b) Environmental impacts, (c) Social and urban community benefits, (d) Economic criteria, and (e) Feasibility criteria (Ellis et al., 2004).

The ESI and EC approaches can be combined, and with respect to sustainable urban drainage, described by the following six criteria:

(A) Integrity of environmental systems (water resources, aquatic ecosystems and terrestrial resources) and their beneficial uses – stormwater management should contribute to protection of these systems with respect to biodiversity, land resources (limiting the extent of lands with strong anthropogenic impacts), protection of water quality of the receiving surface waters or groundwater, and preserving water balances.

(B) Mitigation of environmental stresses – by stormwater best management practices, including a broad set of source controls and semi-structural or structural measures, recognizing that their applicability is subject to feasibility criteria.

(C) Mitigation of human vulnerability – by preventing flooding or runoff ponding in urban areas, and reducing flood damages and human exposure to chemicals, pathogens and disease vectors.

(D) Social, institutional and economic capacity, including environmental governance, science and technology, private sector responsiveness, and the society/community's ability and willingness to pay for sustainable drainage.

(E) Social and community benefits – stormwater drainage is a part of the urban environment and, therefore, the urban population is keenly interested in such systems and benefits, including educational opportunities, visual amenities, and recreational opportunities.

(F) Regional or global stewardship – includes participation in regional/national/international environmental agreements and programs, controlling export of pollutants and runoff from jurisdictions, and controlling greenhouse gas emissions.

Sustainable approaches to urban development have been promoted during the past 30 years, but only recently they gained broader acceptance as low impact development (LID, in the USA), sustainable urban drainage systems (SUDS, in the UK), and water sensitive urban design (WSUD, in Australia). In general, these approaches promote:

a. Total urban water cycle management, with reuse of stormwater and other effluents, integrated management of stormwater, groundwater, and wastewater; and water conservation, resulting in reduced water demand.
b. Minimizing development impacts by preserving natural resources/ecosystems and maintaining natural drainage, minimizing land clearing and grading, reducing imperviousness, and controlling urban sprawl.
c. Maintaining pre-development water balances on site by promoting rainwater/stormwater infiltration and evapotranspiration.
d. Maintaining, recreating or enhancing distributed detention and retention storage on sites, by using swales, flat slopes, rain gardens, bioretention areas and rain barrels/cisterns.

e. Maintaining predevelopment times of concentration and travel times by strategic routing of runoff flows.
f. Encouraging property owners and drainage system operators to use effective pollution prevention measures and to maintain all stormwater management measures.

Environmental sustainability rating can be assessed for individual stormwater management measures or treatment trains, using quantitative or comparative measures. Examples of quantitative indicators include limits on post-development runoff flows and volumes, and suspended solids and nutrient concentrations in urban stormwater. In a tentative rating of 11 common stormwater BMPs, Marsalek (2005) offered a relative rating of these BMPs by grouping them into three categories arranged in a descending order of sustainability: (A) green roofs, swales/vegetative strips, porous pavements, (B) infiltration facilities (trenches, basins), dry detention reservoirs, ponds and wetlands, and, (C) oil & grit separators, and high-rate treatment plants. In sustainability rating, the highest values are generally assigned to the measures, which address stormwater problems close to the source (e.g., managing rainwater before it is converted into runoff), provide the highest number of environmental benefits, require low capital and operation and maintenance costs, and contribute to lower greenhouse emissions. At present, the sustainability rating of stormwater management practices is still largely based on comparative rating of various schemes and options, but some quantitative (numerical) criteria or combinations of quantitative and qualitative criteria are starting to appear in the literature. Thus, the current approaches to environmental sustainability rating need to be refined to produce quantitative performance indicators for urban drainage systems.

Emerging challenges in urban drainage

A number of emerging challenges can be identified in the current urban drainage practice. Most of these have been recognized for some time, but not fully addressed or implemented by the urban drainage community of practice. Perhaps the most important challenge is the achievement of environmental sustainability of urban drainage, which was discussed in the preceding section. Another challenge is imposed by climate change, which has strong implications for traditional hydrological design (Benedini, 2004). The existing global circulation models provide data at large scales, but recent attempts to interpolate such data for small urban areas were not successful. Among the impacts of climate change on urban drainage systems one could name higher frequencies of extreme events, more rainfall of higher intensity (in some areas), and rising sea levels interfering with gravity outflow from sewers. Recognizing long service lives of drainage systems (100 years), the currently designed and built systems will have to cope with climate change. A precautionary approach is recommended, assessing the vulnerability of urban drainage infrastructure to these changes, risks, and developing risk mitigation measures based on adaptive controls (Waters et al., 2003).

Past design of urban drainage mostly relied on passive control of drainage systems by gravity flow (given by the system architecture and assets) and in water quality issues, on responding to environmental problems caused outside of the authority of drainage managers (e.g., inputs of various chemicals). Future improvements will arise from elevating control of inputs to drainage systems and drainage operation to a higher level. Concerning drainage flows, real time control holds promise for a greater operational effectiveness (Campisano et al., 2004; Colas et al., 2004; Schilling, 1989). Dynamic regulation and operation offers distinct advantages, particularly when centrally operated and designed for global optimization. However, the progress achieved so far in terms of actual installations has been rather slow. With respect to water quality, better control of chemical inputs into drainage systems is needed. A promising path is offered by controlling the use of chemicals in urban areas and banning non-essential use of dangerous chemicals. These source controls have a much better chance of success than attempts to deal with the removal of low concentration chemicals from drainage effluents, often at the end of the pipe. Further progress in urban drainage is impeded by increasing urban populations (at least in some parts of the world), aging assets, rising demands on and complexity of urban water management (need to adopt adaptive water management), and competition for investment resources with other sectors (Benedini et al., 1999). However, in spite of these concerns, the evidence from many locations around the world indicates a gradual improvement of the state of urban drainage.

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Evolution of Urban Drainage: from Cloaca Maxima to Environmental Sustainability

Jiri Marsalek

Extended Abstract

Drainage of urban settlements has been practiced for thousands of years, but the recognition of drainage impacts on the environment and the interest in impact mitigation is relatively recent. It was only during the past 40-50 years that the understanding of drainage impacts has started to evolve for both stormwater discharges from separate sewer systems and combined sewer overflows (CSOs) from combined sewer systems. Traditionally, and for convenience, drainage impacts have been addressed under various categories, such as physical, chemical, biological, ecological and combined impacts, however, with a tacit understanding that the actual impacts are integrated and, as such, best measured by integrated indicators, including biological community performance (encompassing biodiversity) and the impairment of beneficial uses of receiving waters.

Concerning the individual impact categories, physical impacts of stormwater discharges and CSOs include increased runoff volumes and peak flows, sediment erosion and deposition, geomorphologic changes, habitat degradation, warming of receiving waters, densimetric stratification, and reduced groundwater recharge. Among these phenomena, the least understood are geomorphologic changes, which occur relatively slowly and manifest themselves fully only after long periods of time. Chemical impacts are generally associated with oxygen demanding substances, nutrients, and toxic substances. The resulting water quality changes may include depletion of dissolved oxygen, eutrophication, and toxic conditions in receiving waters. There is an extensive literature on stormwater quality, but the interpretation of these data on up to 600 chemicals is obscured by the lack of information on their chemical speciation, bioavailability and effects. Toxicity testing is helpful in this regard, but challenging for in-situ applications. Microbiological impacts on public health are connected with discharge of indicator bacteria and pathogens impacting on water supplies and recreational uses of receiving waters. Recently, another public health concern related to stormwater was noted, the creation of breeding grounds for disease vectors (e.g., spreading of West Nile virus by mosquitoes). Finally, combined effects of the impact categories are measured by assessing biological community structures (e.g., benthic communities) and sometimes also described by ecological effects and the impairment of beneficial uses of receiving waters.

Concerns about urban drainage impacts led to the development of CSO control programs applied in combined sewer systems and stormwater management in both combined and separate sewer systems. CSO controls include: (a) control of rainwater/stormwater inflow into combined sewers by stormwater management, including sewer separation, (b) CSO storage with online treatment at satellite facilities, or the stored flow return to, and treatment at, the central wastewater treatment plant when its capacity allows, and (c) real-time control of the whole system, including sewage collection, transport, storage and treatment.

In separate sewer systems, urban runoff impacts are mitigated by the so-called best management practices (BMPs) serving to control both runoff quantity and quality. Typical BMPs include policies and source controls, grass filters and swales, infiltration facilities, oil and grit separators, multimedia filters, stormwater management ponds, and constructed

wetlands, often arranged in a series as treatment trains. A great deal of experience has been gained concerning the performance of individual types of BMPs.

Requirements on both CSO control and stormwater management have increased by introduction of the concept of sustainable development in 1987. In spite of a broad support for this concept, the evolution of its practical applications has been relatively slow, with outstanding needs for objective and practical ways of measuring progress towards attaining the goals of environmental sustainability. Progress in sustainability of urban drainage can be assessed by the Environmental Sustainability Index (ESI) and a multi-criteria approach proposed in the European Commission's DayWater project. The ESI and EC approaches can be combined, and with respect to sustainable urban drainage, described by the following six criteria:

(a) Integrity of environmental systems (water resources, aquatic ecosystems and terrestrial resources) and their beneficial uses – CSO control and stormwater management should contribute to protection of these systems with respect to biodiversity, land resources (limiting the extent of lands with strong anthropogenic impacts), protection of water quality of the receiving surface waters or groundwater, and preserving water balances;

(b) Mitigation of environmental stresses – by CSO controls and stormwater best management practices, including a broad set of source controls and semi-structural or structural measures, recognizing that their applicability is subject to feasibility criteria;

(c) Mitigation of human vulnerability – by preventing flooding or runoff ponding in urban areas, and reducing flood damages and human exposure to chemicals, pathogens and disease vectors;

(d) Social, institutional and economic capacity, including environmental governance, science and technology, private sector responsiveness, and the society/community's ability and willingness to pay for sustainable drainage;

(e) Social and community benefits – urban drainage is a part of the urban environment and, therefore, the urban population is keenly interested in such systems and benefits, including educational opportunities, visual amenities, and recreational opportunities, and

(f) Regional or global stewardship – includes participation in regional/national/international environmental agreements and programs, controlling export of pollutants and runoff from jurisdictions, and controlling greenhouse gas emissions.

The current approaches to environmental sustainability rating need to be further refined to produce quantitative performance indicators for urban drainage systems.

Future challenges in urban drainage include coping with climate change, total (and adaptive) management of the urban water cycle, improved source controls particularly for new chemicals of concern, dynamic control of urban water systems, management of aging infrastructures, refined computer modeling, and better communications and addressing of social issues.

NWRI RESEARCH SUMMARY

Plain language title

Evolution of urban drainage

What is the problem and what do scientists already know about it?

The practice of urban drainage has been evolving for millennia to meet the society's needs. The speed of this evolution has particularly increased during the last 50 years and culminated in the application of sustainability criteria to urban drainage projects.

Why did NWRI do this study?

NWRI is currently addressing the issues of sustainability of urban drainage, and this study served to provide a historical perspective on the evolution of urban drainage practice.

What were the results?

The concept of environmental sustainability imposes the highest level of requirements on urban drainage. The progress towards achieving this goal can be assessed by such criteria as (i) integrity of environmental systems, (ii) mitigation of environmental stresses, (iii) mitigation of human vulnerability, (iv) social, institutional and economic capacity, (v) social and community benefits, and (vi) regional and global stewardship. Such criteria require further development and refinement.

How will these results be used?

These results will be used in future studies of urban drainage sustainability.

L'évolution du drainage urbain : du *Cloaca Maxima* à la durabilité de l'environnement

Jiri Marsalek

Résumé détaillé

Le drainage urbain est une pratique vieille de milliers d'années, mais ce n'est que tout récemment que l'on a commencé à s'intéresser à ses impacts sur l'environnement et à la façon de les atténuer. En fait, ce n'est que depuis 40 à 50 ans que notre compréhension des impacts du drainage a commencé à évoluer pour ce qui est des débordements d'eau de ruissellement provenant des réseaux séparatifs et du trop-plein d'égout unitaire (tpeu) des réseaux d'égout unitaire. Traditionnellement, et pour des raisons pratiques, les impacts du drainage ont été regroupés selon diverses catégories : impacts physiques, chimiques, biologiques, écologiques et combinés, avec une entente tacite sur le fait que les impacts réels sont intégrés et doivent donc être mesurés par des indicateurs intégrés, comme la performance de la communauté biologique (englobant la biodiversité) et la dégradation des utilisations positives des eaux réceptrices.

En termes de catégories individuelles d'impacts, les impacts physiques des débordements d'eau de ruissellement et du trop-plein d'égout unitaire sont entre autres l'accroissement des volumes d'écoulement et des débits de pointe, l'érosion et le dépôt des sédiments, les changements géomorphologiques, la dégradation de l'habitat, le réchauffement des eaux réceptrices, la stratification densimétrique et la réduction de la recharge des eaux souterraines. Parmi ces phénomènes, les moins bien compris sont les changements géomorphologiques, des processus relativement lents qui ne se manifestent pleinement qu'après de longues périodes. Les impacts chimiques sont généralement associés aux substances à demande élevée en oxygène, aux nutriments et aux substances toxiques. Tous ces impacts modifient la qualité des eaux réceptrices en y induisant des changements, dont l'épuisement de l'oxygène dissous, l'eutrophisation et des conditions toxiques. Il existe une abondante littérature sur la qualité des eaux de ruissellement, mais l'interprétation de ces données relatives à 600 substances chimiques est compliquée par le manque d'informations sur leur spéciation chimique, leur biodisponibilité et leurs effets. Des essais de toxicité pourraient résoudre ces problèmes, mais leur mise en œuvre est relativement complexe pour les applications *in situ*. Les impacts microbiologiques sur la santé publique sont liés aux rejets de bactéries et d'agents pathogènes indicateurs qui peuvent contaminer les réserves d'eau et nuire aux activités récréatives pratiquées dans les eaux réceptrices. Dernièrement, on a observé un autre impact sur la santé publique associé aux eaux de ruissellement, qui constituent un bon milieu de reproduction pour des vecteurs de maladies (p. ex. le virus du Nil occidental propagé par les moustiques). Enfin, les effets combinés de ces divers facteurs ont été mesurés en évaluant les structures des communautés biologiques (p. ex. les communautés benthiques) et parfois aussi décrits en termes d'impacts écologiques et de pertes d'utilisations valorisées des eaux réceptrices.

Les préoccupations concernant les impacts du drainage urbain ont conduit à élaborer des programmes de limitation du trop-plein d'égout unitaire et à les appliquer à la gestion des réseaux d'égout unitaire et des eaux de ruissellement dans les réseaux unitaires et séparatifs. Les mesures de contrôle du trop-plein d'égout unitaire sont : a) la limitation de l'écoulement des eaux pluviales et de ruissellement dans les réseaux d'égout unitaire par la gestion des eaux de ruissellement, y compris la séparation des égouts, b) le stockage du trop-plein d'un égout unitaire avec traitement en direct à des installations satellites, ou le retour de

l'écoulement emmagasiné et son traitement à une usine d'épuration centrale quand sa capacité le permet, et c) le contrôle en temps réel du système en entier, dont la collecte, le transport, le stockage et le traitement des eaux usées.

Dans les réseaux d'égout séparatifs, les impacts des eaux de ruissellement urbaines sont atténués par ce qu'il est convenu d'appeler les pratiques de gestion exemplaires (PGE), qui servent à contrôler à la fois la quantité et la qualité des eaux de ruissellement. Parmi les PGE types figurent les politiques et les contrôles à la source, les bandes filtrantes et les rigoles de drainage gazonnées, les bassins d'infiltration, les dessableurs-déshuileurs, les filtres polyvalents, les bassins de gestion des eaux pluviales, et les milieux humides artificiels, qui sont souvent appliquées successivement en séquences de traitement. On connaît maintenant mieux la performance de chaque type de PGE.

Les exigences relatives à la limitation du trop-plein des égouts unitaires et de la gestion des eaux de ruissellement se sont accrues depuis l'avènement du concept de développement durable en 1987. Malgré l'appui généralisé à ce concept, son application pratique a été relativement lente, et il est devenu primordial de déterminer des moyens objectifs et pratiques pour mesurer les progrès réalisés vers l'atteinte des objectifs de durabilité de l'environnement. Sur le plan du drainage urbain, les progrès peuvent être évalués à l'aide de l'indice de durabilité environnementale (IDE) et d'une approche à critères multiples proposée par le projet DayWater de la Commission européenne. On peut combiner l'IDE et l'approche de la CE, et utiliser les six critères suivants pour définir la nature du drainage urbain durable :
a) intégrité des systèmes environnementaux (ressources en eau, écosystèmes aquatiques et ressources terrestres) et de leurs utilisations – la limitation du trop-plein des égouts unitaires et la gestion des eaux de ruissellement doivent contribuer à protéger ces systèmes en ce qui a trait à la biodiversité, aux ressources terrestres (en limitant l'étendue des terres où les impacts anthropiques sont significatifs), à protéger la qualité de l'eau des eaux de surface réceptrices ou des eaux souterraines et à maintenir le bilan hydrique;
b) atténuation des stress environnementaux – en limitant le trop-plein des égouts unitaires et grâce aux pratiques de gestion exemplaires des eaux de ruissellement, dont un vaste ensemble de contrôles à la source et de mesures semi-structurales et structurales, tout en gardant à l'esprit que leur application est assujettie à des critères de faisabilité;
c) atténuation de la vulnérabilité humaine – en prévenant les inondations et la formation de bassins d'eaux de ruissellement dans les régions urbaines, et en réduisant les dommages causés par les inondations et l'exposition humaine aux vecteurs d'éléments chimiques, de pathogènes et de maladies;
d) capacité sociale, institutionnelle et économique, y compris la gouvernance environnementale, la science et les technologies, la sensibilisation du secteur privé et la capacité et la volonté de la société/collectivité d'assumer les coûts d'un système de drainage durable;
e) avantages sociaux et communautaires – le drainage urbain faisant partie de l'environnement urbain, la population citadine est vivement intéressée par ces systèmes et leurs avantages, notamment les occasions éducatives, les attraits visuels et les activités récréatives,
f) la gérance régionale ou mondiale – dont la participation à des ententes et à des programmes régionaux, nationaux ou internationaux, la limitation des exportations de polluants et du ruissellement provenant d'autres provinces, territoires ou États et la réduction des émissions de gaz à effet de serre.

Les approches actuelles permettant de mesurer la durabilité environnementale devront être affinées davantage pour déboucher sur des indicateurs de performance quantitative pour les réseaux de drainage urbain.

Les défis que posera le drainage urbain dans l'avenir sont l'adaptation aux changements climatiques, la gestion totale (et adaptative) du cycle de l'eau en milieu urbain, l'amélioration des contrôles à la source, en particulier pour les nouvelles substances chimiques préoccupantes, la gestion dynamique des réseaux d'aqueducs urbains, la gestion des infrastructures vieillissantes, l'affinage des modèles informatiques et l'amélioration des communications et du traitement des questions sociales.

Sommaire des recherches de l'INRE

Titre en langage clair

L'évolution du drainage urbain.

Quel est le problème et que savent les chercheurs à ce sujet?

Le drainage urbain évolue depuis des millénaires afin de répondre aux besoins de la société. La vitesse de cette évolution s'est particulièrement accrue depuis 50 ans et a atteint des sommets avec l'application des critères de durabilité aux projets de drainage urbain.

Pourquoi l'INRE a-t-il effectué cette étude?

L'INRE examine actuellement les questions relatives au drainage urbain durable, et la présente étude fournit une perspective historique sur l'évolution des pratiques de drainage urbain.

Quels sont les résultats?

Le concept de durabilité environnementale impose un très haut niveau d'exigences en ce qui concerne le drainage urbain. Pour mesurer les progrès réalisés dans l'atteinte de cet objectif, on peut recourir à des critères tels que (i) l'intégrité des systèmes environnementaux, (ii) l'atténuation des stress environnementaux, (iii) l'atténuation de la vulnérabilité humaine, (iv) la capacité sociale, institutionnelle et économique, (v) les avantages sociaux et communautaires et (vi) la gérance régionale et mondiale. Il est nécessaire de préciser davantage ces critères et de les affiner.

Comment ces résultats seront-ils utilisés?

Les résultats serviront aux fins d'études ultérieures du drainage urbain durable.

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