Urban drainage redefined: from stormwater removal to integrated management

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Abstract: Even though urban drainage has been practised for more than 5000 years, many challenges arising from growing demands on drainage still remain with respect to runoff quantity and quality; landscape aesthetics, ecology and beneficial uses; and operation of existing urban wastewater systems. Further advances can be achieved by adopting an integrated approach, optimal operation of the existing infrastructure, advanced pollution and runoff source controls, improved resilience of receiving waters, and adaptive water management. The specific research needs include new technologies and strategies for stormwater management, advanced treatment of urban wet-weather effluents, and tools for analysis and operation of drainage systems. High diversity of demands on, and region/site specific conditions of, urban drainage shapes the role of urban drainage experts - as mediators among the many stakeholders and fields involved.

Keywords: Combined sewer overflows (CSOs), drainage, stormwater, sustainable development, urbanization, wet-weather pollution

Early development of urban drainage

Provisions of safe drinking water, flood protection, drainage and sanitation rank highly among the needs of all societies. As such, these issues have been addressed since the times of early civilisations. Some of the early urban drainage structures were built around 5000 years ago in the Mesopotamian Empire (Wolfe, 2000). In the following centuries and millennia, most of these structures and systems were abandoned, but their remnants can still be found in some places.

After the decline of the Roman Empire, sanitation practices have generally deteriorated, and surface drains and streets were used indiscriminately as the only means of conveyance and disposal of all wastewaters. Notwithstanding this apparent lack of systematic approach, some interesting strategies for managing both wastewater and stormwater emerged. In fact, these effluents were not considered as “waste”, but rather as valuable resources (Maneglier, 1991). The harvesting of faeces for production of organic fertilisers (called “poudrette” in France) was in high demand in Paris until the end of the 18th century, and the “Grand voyer” in charge of these activities was very rich and powerful. Urine infiltrating into urban soils formed salpeter which was used for making gunpowder and for other purposes. Stormwater was collected and stored in cisterns, and constituted an important resource, especially in southern France. Some cities even developed integrated systems for managing stormwater. For example, in Venice, many well known city squares were used to collect stormwater, until the 17th century. Under each square, an underground water storage reservoir was dug, filled with sand, and made watertight with clay walls and bottom, to prevent saltwater intrusion. Fresh water filtered through, and stored in, the sand was collected in wells. During this era, neither horses nor pigeons were allowed on the
permeable pavement covering these squares! However, these methods of wastewater disposal were 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 (Wolfe, 2000).

Two arguments proved to be decisive in the choice of the “all to the sewer” solution:
• A “scientific” one, based on an analogy between the human body and the urban settlement; if the lack of blood circulation in a limb made it sick, the same would apply to preventing water circulation in a part of the city. So, the continuous motion of water appeared to be a necessity, and tanks and cisterns became two examples of pestilential stagnation.
• A political argument, particularly strong in France after the Revolution, which was based on the notion of equality: all citizens must be equal and treated equally by state and municipal administrators. A common network for collection of wastewaters constituted the best solution providing equal treatment.

During the same time period, progress was achieved in urban surface drainage, with the development of empirical design methods for sizing drainage pipes. Intuitive reasoning about conversion of rainfall into runoff led to the development of the rational method, which is generally credited to Mulvaney (Ireland, 1851), Kuichling (USA, 1889), and Lloyd-Davis (UK, 1906). In later years, many other variations of this formula have been developed and applied in other countries.

Thus, by the mid 19th century, engineers possessed a concept and a design method for wastewater disposal, and for the next 100 years or so, these were the only tools used in stormwater drainage and wastewater disposal throughout the world: stormwater and other wastewater should be collected in urban areas and disposed outside of the urban environment as quickly and as fully as possible.

The rational method dominated engineering drainage practice until the late 1960s, and it is still widely used in some parts of the world and certain applications (i.e., small drainage areas with simple tree-type sewer systems, no controls, no storage, no backwater, etc.). From the 1960s, rapid developments have occurred in urban drainage practice. First, a number of 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 hydraulic flow routing and computer modelling greatly advanced this field. At present, it is possible to calculate sewer network flows with the accuracy needed for people design, analysis and operation of sewer systems.

The development of water quality aspects occurred somewhat later and focused on quality of stormwater, wet-weather flows in (or 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 the following: (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.

Contemporary urban drainage
In retrospect, urban drainage could be seen as a great success story with respect to the most pressing problems of urban dwellers, public hygiene and flood protection. “Sewers for everybody” was supposed to be the means for meeting this fundamental challenge.
However, in reality, the success is not so obvious, because the old concept is unable to provide all the needs of cities (Chocat et al., 1999). Many problems remain, others arise, depending on the local urban geography and population expectations:

- **Problems associated with runoff quantity.** Typical examples include increased runoff volumes and peak flows, causing environmental and property damages, and in extreme cases even the loss of life; decreased low flows in rivers, depressed groundwater tables, leading to subsidence of urban land and structural damages; and channel and erosion damaging habitat in urban streams. Some of these problems may be further exacerbated by climate change (Marsalek, 2000).

- **Problems associated with urban runoff quality.** Urban stormwater appears to be one of the most important diffuse sources of numerous pollutants, including trace organics, heavy metals, nutrients (particularly phosphorus), contaminated sediments, and pathogens. This pollution is difficult to control and contributes to the degradation of receiving water quality.

- **Problems associated with landscape aesthetics, ecology and beneficial uses.** Effluents from conventional drainage systems impact on the biological integrity of receiving water bodies, and particularly the abundance and diversity of flora and fauna. They also impair beneficial uses of receiving waters, such as potable water supply, bathing, fishing, general amenity and aesthetic quality of receiving waters, as well as the quality of the urban landscape with respect to recreation.

- **Problems associated with the operation of existing urban wastewater systems.** Examples include impaired performance of wastewater treatment plants resulting from the influx of stormwater; constraints on urban growth caused by an inadequate infrastructure, and ageing sewer systems requiring costly rehabilitation.

These challenges motivated the development of sustainable strategies for urban stormwater management and new alternatives to the traditional centralised sewer systems. It is also hoped that adoption of these strategies by developing countries would give them an opportunity to develop effective drainage systems more quickly and at lower costs. The objectives of such strategies are “not only to achieve safe and effective conveyance of floodwater and pollution control but also to provide aesthetic, recreational, ecological and economic benefits, including land enhancement” (Ellis, 1995). At the beginning of the 21st century, urban drainage becomes much more than simple conveyance of stormwater out of the city. This new strategy can be characterised by five goals, which are unified by the so-called total urban water cycle management (Lawrence et al., 1999):

- flood reduction to minimise peak discharge rates from urban catchments,
- pollution minimisation by collecting and managing pollution loads generated in urban catchments,
- stormwater retention (harvesting) and beneficial use of as much storm runoff as possible, within or near the contributing catchment,
- urban landscape improvement, by not hiding but rather showing water and incorporating it into functional green belts; and,
- reducing drainage investments, for example, through integration of stormwater into green areas and thereby reducing the cost of infrastructure.

Research on these new concepts is conducted in many parts of the world, with local emphasis on different priorities. In Australia, it focuses on three main objectives: improving urban flood control, minimising pollution, and harvesting stormwater in arid/semi-arid regions (Argue, 1995). In Japan, researchers are promoting the concept of “zero emission” in the design of urban drainage (Fujita, 1998). In the USA and Canada, the sustainability of new urban developments and reduction of the sanitary and combined sewer overflow (SSO and CSO) pollution are considered as necessities for the improvement of water quality (EPA,
Finally in Europe, the existing combined sewer systems are improved to cope better with the conflicting objectives of flood protection and pollution control.

Everywhere in the world, the concept of sustainability is becoming the main driving force for protecting or improving the urban environment. Even though the concept of sustainable development has never been formulated very precisely, some workable definitions exist, including the one proposed by ASCE (1998): “Sustainable water systems are designed and managed to fully contribute to the objectives of the society, while maintaining their ecological, environmental and hydrological integrity, and meeting the demands to the system without its degradation, now and in the future.” Furthermore, it is recognised that implementation of sustainable development in urban drainage “will mean the collaboration of many disciplines, the integration of knowledge from many fields all-within the context of political, regulatory and economic realities, to meet short term requirements while safeguarding long term social and environmental resources” (Bacon, 1997).

The current interest of researchers and practitioners in these new approaches is demonstrated by numerous conferences that are held in different parts of the world (for example the NOVATECH conference series in Europe). In the USA, the EPA is developing the risk management research plan for wet-weather flows, with an annual funding of about ten million dollars (Field et al., 1998).

The future of urban drainage

The major objectives of urban drainage remain public hygiene, flood protection and pollution control. In developed countries, the first two objectives have been accomplished and emphasis is placed mainly on pollution control. However, in developing countries, hygiene and flood protection are still major issues. World-wide, only about 15% of the wastewater is treated. Therefore, the R&D needs of the industrialised countries are hardly appropriate for the developing world.

In the past, rigid urban drainage standards were set according to the state of the art, and systems were implemented to fulfil exactly these design guidelines. This approach resulted in standardised systems performing reasonably well with respect to public hygiene and flood protection. However, regarding the third major objective, the protection of receiving waters, there are some shortcomings, because receiving waters were hardly considered in the design and optimisation of sewerage systems.

To use the full potential of the existing wastewater systems in pollution control, an integrated approach must be followed. Thus, the receiving water must be considered as a subsystem that fully interacts with the other subsystems, i.e. the catchment, the sewer system and the wastewater treatment plant (WWTP). Starting with the specific conditions in the receiving waters, an optimisation strategy for the infrastructure system should be derived (Rauch et al., 1998). With adequate operation strategies, the performance of the existing infrastructure can be improved without expanding its physical capacity. Operational solutions (largely based on “software”), e.g. flow-based on-line control, pollution-base on-line control (Schütze, 1998), increasing the WWTP loading during wet-weather (Bruns, 1998) according to a detailed analysis of the peak loads originating in sewers (Krebs et al., 1999a and b), and the treatment potential of the activated-sludge and the secondary-settling tank, are preferred in comparison to expanding physical facilities by providing additional storage, transport or treatment capacities. Furthermore, the benefits of improved operation should be combined with improved source controls designed to minimise the loading in the wastewater system. The third component of this approach is the improvement of the resilience of receiving waters (Larsen and Gujer, 1997; Krebs and Larsen, 1997).

If the existing system cannot be operationally improved but has to be changed, or if a new system is planned for a new urban area, the range of possible solutions becomes

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broader. Given the level of services that must be respected (hygiene, flood and water protection), the criteria for system development may include a condition that the nutrients in wastewater should be understood as resources rather than waste. Both, centralised (Larsen and Gujer, 1996) and decentralised systems (Otterpohl et al., 1997) are promising in this respect. Separation of different types of wastewater, e.g., black water (urine and faeces), brown water (faeces), yellow water (urine), grey water (washing water) and white water (runoff), at the source, provides more freedom and flexibility in choosing among the available options. Such options include avoidance, reduction, reuse and retention of certain wastewaters, which will be possible in sewerage systems of the future. Since none of these alternative systems has been as yet tested during its entire service life-cycle to show its long-term sustainability, the system development should be step-wise, in “the right direction”, increasing the degrees of freedom in anticipation of unknown future requirements. This approach is also referred to as an adaptive water management (Marsalek, 2000) and offers numerous advantages compared to the existing systems, which are difficult to change, because of inherent rigidity, high resource intensity, enormously high investment costs and long service life.

At the same time it must be recognised that the fundamental needs of urban water management are not met in large parts of the world, where the most urgent problems are the following:

- an effective separation of water supply and wastewater disposal, in order to guarantee hygienic conditions and safe supply of drinking water,
- the reduction of losses from water-supply pipes and of uncontrolled spills of wastewater,
- the development of long-term strategies for the rehabilitation of water supply and drainage systems (Herz, 1998), and,
- the education of people with respect to the responsibilities, benefits and hazards associated with urban waste management.

Urban drainage as a research field

The development of the urban drainage system outlined above requires know-how, strategies and information that must be provided by the research, in order to avoid expensive mistakes caused by trial-and-error approaches. First, it should be noted that the focus of the field has changed dramatically with the current main emphasis on sustainable approaches and pollution prevention.

Twenty-five years of research on wet-weather flow pollution has resulted in some major indisputable achievements. Using the knowledge of natural sciences, it is possible to begin to understand some fundamental mechanisms of drainage impacts on the environment. At the same time, the current knowledge and predictive capability of un-calibrated models, with respect to such critical issues as urban runoff pollution, its transport, and impacts of intermittent discharges on the aquatic ecosystem remain mediocre. Even worse, there is a lack of evidence that the current efforts to protect the environment against intermittent discharges have been successful. The main reasons being that the design, monitoring and assessment studies are equally based on simplified performance criteria (e.g., the number of overflows per year) and water quality parameters. But recent experience indicates that those substitute variables do not provide a full picture of the state of the aquatic environment. Consequently, stakeholders increasingly doubt the value of control measures with respect to intermittent pollution. It is difficult to justify spending huge sums of money on such facilities as detention basins, if the receiving waters are not endangered, or if experience suggests that those measures will be ineffective. In fact a question arises, whether the prevention of intermittent pollution will remain as a key issue of urban drainage in the future.
This leads to another observation with respect to the urban drainage researchers and practitioners community, a progressing diversity of the field. Some 25 years ago, the research and practice centred on collecting and transporting wastewaters from urban areas and minimising export of pollutants. Consequently, hydrology, hydraulics and transport of wastewater with dissolved and suspended matter were the main issues of interest. At that time, urban drainage was truly a discipline on its own. Since then, the field expanded by adopting many different options for discharge, transport and treatment of wastewater, and it no longer possesses a clear, common goal. Both the physical diversity of, and the complexity of processes in, the drainage system require consideration of many phenomena, processes and problem solutions. It is no longer possible to cover all these aspects in depth. Hence, contemporary urban drainage, as a field, is diversified with respect to its objectives and participation of various disciplines. A fundamental question arises, is it a separate field or just a conglomerate of different disciplines dealing with the urban water cycle? Symptoms seem to indicate that the latter is true; most importantly, until recently, there has not been a dedicated authoritative journal for publishing groundbreaking research on this issue. Instead, important findings are scattered in journals covering either the pollution (e.g. Water Research) or hydrological processes (e.g. The Journal of Hydrology). Only recently a new journal appeared (Urban Water), and in due time it could become a common platform for publishing world-class papers on urban drainage. When examining the program of the Paris 2000 IWA congress, it is clear that many papers addressing urban drainage have been placed outside of the urban drainage sessions.

This diversity of the field can be noticed not only in terms of science, but also in terms of geographical influences. The main reason for this diversity is the complexity of the system, which needs to be described for specific problems. For example, environmental problems caused by intermittent discharges vary depending whether the receiving water is a fast flowing alpine creek, a sluggish brook in northern Europe or a large Scandinavian fjord. National regulations have been developed to meet exactly these problems. The result is that the "national urban drainage schools of thought" are quite different, especially in Australia, Germany, France, Japan, the United Kingdom, Denmark and the USA. As the problems encountered are different, the international exchange of ideas is less influential than in other fields.

Thus, urban drainage covers a multitude of different problem areas, processes and methods. The complexity of the field and the large number of specific problems lead to great diversity with respect to both the science and procedures employed. Hence, the main characteristic of an urban drainage expert is not a deep understanding of all the processes relevant to urban drainage, but the capability to mediate among the experts from all the fields affecting urban drainage. There are indications that this mediation is succeeding, as documented e.g. by the French encyclopaedia of urban drainage and sewerage (Chocat, 1997) and an international urban drainage glossary (Ellis et al., in press). Other documents of interest include position papers (Ellis and Marsalek, 1996; Field et al., 1998; Niemczynowicz, 1999; Marsalek, 2000) and launching the journal Urban Water. Furthermore, many researchers consider themselves belonging to a common scientific community and participate regularly in urban drainage conferences, as shown, e.g. by the successful triennial International Conferences on Urban Drainage and the NOVATECH conference series.

Research needs

A pragmatic way to define research needs is to ask what are the prerequisites for successful research. Is one common approach, based on engineering tasks for improving urban drainage systems needed, or are several separate approaches needed, each based on specific scientific disciplines?
Four key areas in which advances are needed can be identified:

- alternative technologies for stormwater management (structural best management practices),
- innovative strategies for stormwater management,
- treatment of urban wet-weather discharges, and
- tools for the analysis of drainage system operation.

First, it should be observed that the development of new strategies for technologies is strongly impeded by economic problems (costs, financing), sociological problems (acceptance by the public, changes in duties and responsibilities), urban planning challenges (integration into the landscape, cooperation between the wastewater department staff and others involved), problems with policies and regulations, etc. From a technical point of view, three levels of problems must be overcome.

• **First level problems** concern the lack of knowledge of the impacts associated with different contaminants in urban runoff (nutrients, heavy metals, trace organic oxidants, pathogens, etc.) and of their interference with the receiving environment and its beneficial uses.

• **Second level problems** concern the uncertainty of impact assessment (in terms of modelling and measurement), particularly with respect to long-term impact.

• **Third level problems** concern the use of improved information for decision making; e.g., what is the best way of considering the environmental/ecological impacts in the planning, design and implementation of works for controlling stormwater discharges.

Research needs can be divided into five groups:

• **Characterisation and modelling of stormwater discharges**: sources of pollutants, the magnitude of pollution loads, fate of pollutants in different environmental compartments (on the surface, in vegetation, soils and water, etc.), effects of pollution on biota and beneficial uses, etc.

• **Effects of stormwater discharges on the quality of receiving waters**: including the identification of places where pollutants become immobilised and the risks of excessive accumulation or leaching; long-term effects of pollutants on different types of receiving waters, methods of pollutant control without knowing exact pollutant locations, nutrient processes, and analysis and numerical modelling of the integrated system.

• **Efficiency of stormwater control measures**: insufficient data are available on the performance of control measures for stormwater pollution. This problem is particularly important when the performance efficiency must be measured over a long period of time (several decades is a minimum for many structures). The development and sharing of long-term databases with common protocols on drainage effluents and the receiving waters is a vital necessity.

• **Defining meaningful criteria for the receiving waters quality**: it is easy to produce subjective criteria, e.g., the quantity of fish residing in a given part of the river. However, it is much more difficult to establish relationships between these subjective criteria and the traditional “scientific” indicators, such as concentrations of toxicants, dissolved oxygen, nutrients, etc.

• **Collecting and organising data for life-cycle analysis of stormwater management measures**: this includes research on strategies for life-cycle assessment (LCA) and environmental-impact assessment (EIA) in order to benchmark the drainage system.

The identification of research needs underlines the fact that a particular challenge in the urban drainage research is the system complexity, both in physical and institutional terms. Measurements and experiments should aim to clearly separate between the descriptions of the basic phenomena and locally specific boundary conditions. Identification of generally valid “urban drainage unit processes” would allow to transfer the knowledge between
catchments, and thereby reduce the need for case studies that only result in very costly site-specific conclusions (Vanrolleghem et al., 1999).

Thus, even if the complexity is not sufficient on its own to declare urban drainage as a specific scientific field, it seems to lead to the necessity to maintain specific links between the actors of this engineering field. The IAHR/IWA Joint Committee on Urban Drainage has played a major role in building these links in the past, retains the responsibility to maintain them, and will further reinforce them in the future.

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