Integrated urban stormwater management: Evolution and multidisciplinary perspective

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INTEGRATED URBAN STORMWATER MANAGEMENT: EVOLUTION AND MULTIDISCIPLINARY PERSPECTIVE [1]

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Abstract

This paper proposes an introductory review of the historical evolution of urban stormwater management, as well as of current trends, challenges, and changes of paradigm. It reminds us first that most of the existing urban stormwater infrastructures in developed cities are based on the modern urban sewer systems developed in the second half of the 19th century in Europe. They have been built and for decades managed almost solely by urban sanitation and water specialists, relatively independently of other technical services and, more generally, of other stakeholders in cities. They contributed significantly to public health and fast conveyance of stormwater outside the cities. However, at the turn of the 1970s, it became evident with increasing urbanisation that they also had drawbacks: artificialisation of soils, reduction of aquifer recharge, pollution of surface water and ecological impacts, etc. The paper indicates how new concepts and paradigms thereafter emerged to manage stormwater by means of more sustainable and integrated approaches, aiming to solve the problems engendered by the previous approaches. This integration embraces more and more disciplines and issues, far beyond the traditional field of urban water engineers and specialists. The paper attempts to explain the need for this evolution, making urban stormwater management more much complex, dealing and interacting with ecology, biodiversity, bioinspiration, architecture, landscape and water values, citizens' well-being, history, culture, and socio-economic aspects.

Keywords: stormwater; sewer systems; history; blue green infrastructure; social sciences; urban planning.

1. INTRODUCTION

Most of the existing underground urban stormwater infrastructures in developed cities are to a very large extent based on the modern urban sewer systems created in the second half of the 19th century in Europe. They have been built and for decades managed almost solely by urban sanitation and water specialists, relatively independently of other technical services and, more generally, of other stakeholders in cities, in a centralised and technocratic way. These systems have significantly contributed to public health and to the comfort of inhabitants by quickly conveying stormwater outside cities. However, this progress has some drawbacks: discharges of contaminants into surface water bodies and associated ecological impacts, imperviousness of cities and significant modifications of the antecedent hydrological cycle and water balance, high costs of infrastructure (e.g. Dhakal and Chevalier, 2016). After more than one century, these drawbacks and their consequences became obvious, and the need for new, wider and more integrated approaches appeared (e.g. Niemczynowicz, 1999, Chocat *et al*., 2001; Dhakal and Chevalier, 2016), accounting not only for technical aspects but also for environmental, ecological, social and governance issues. This evolution was initiated in the 1970s, in different parts of the world, showing a clear change of paradigm compared to the 19th century, i.e. moving from "connect as much as possible, evacuate as fast as possible and don't treat stormwater" to "disconnect impervious areas, retain, detain and infiltrate where possible, treat stormwater if necessary, mimic pre-development water balance" (see e.g. Fletcher *et al*., 2015).

At the beginning of the 1990s, new issues emerged related to the presence of nature in cities, green and blue infrastructure (opposed to grey infrastructure designating the traditional underground pipe systems and their ancillaries), the (re)introduction of water in the urban environment, and the rehabilitation of urban rivers previously converted into underground sewers (e.g. Novotny and Brown, 2007). In this context, stormwater, previously considered mainly as a nuisance, began to be reconsidered with interest, and even as a resource for e.g. supplying aquifers highly affected by the imperviousness of urban soils, providing water resources that do not require drinking water quality, enhancing landscape and water visibility in the city, limiting urban heat islands, restoring biodiversity and ecology, improving public health and citizen well-being. Within a few decades, urban stormwater management has thus shifted from an exclusively quantitative approach to the consideration of pollutant discharges and the need for treatments to reduce impacts on aquatic environments, from an isolated technical vision to a multifunctional approach better integrated into broader urban projects.

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In the following sections, the paper presents a brief historical review of the emergence of modern sewer systems in the 19th century and its key design principles (Section 2), the first significant change of technical and engineering paradigm at the turn of the 1970s (Section 3), the growing number of disciplines and questions involved in achieving effective integrated urban stormwater management in the 1990s (Section 4), and the current emerging new questions and issues (Section 5), making urban stormwater management more much complex, sophisticated and holistic to answer continuously evolving environmental, ecological and social demands, dealing and interacting with ecology, biodiversity, bioinspiration, architecture, landscape and water values, citizens' well-being, history, culture, and socio-economic aspects.

For clarity, the following definitions apply in this paper: i) *wastewater* is water that has been used and polluted by domestic, commercial, and industrial activities in urban areas; ii) *stormwater* is water generated by rainfall in urban areas, resulting from runoff on impervious surfaces (roofs, streets, parking lots); iii) *rainwater* is water resulting from precipitation on roofs that can be harvested and stored for various uses. In *separate* sewer systems, wastewater and stormwater are conveyed in separate pipe networks. In *combined* sewer systems, wastewater and stormwater are mixed and transported together in the same pipe network. Their distinction is thus no longer possible, and the term *combined water* is used to avoid ambiguity if necessary.

2. THE AGE OF CONVENTIONAL URBAN SEWER NETWORKS

> " [Stormwater] in cities takes on so many impurities that it is soon deemed injurious; and wherever a water distribution point is to be found, one quickly stops using stormwater and only thinks about its fast and convenient removal." (Bechmann, 1888, p. 25, my translation).

Archaeological research has shown that sewer systems made of gullies, channels and surface or underground pipes intended for the evacuation of wastewater and stormwater, and arranged according to a coherent and coordinated overall plan, were built from the very beginning of the urbanisation process in Antiquity. The earliest found traces date back to 3500 BCE in the Indus valley, and 2500 BCE in the Mesopotamia valley and the Middle East (Ludwig, 1977; Viyogi, 1984; Vallet, 1997; Yon, 1997; Stordeur, 2000). The collection and disposal of urban water using novel and dedicated infrastructures can therefore be considered as a sign of the emergence and development of cities at the end of the Neolithic period. The quality of construction and the high degree of sophistication of the systems built e.g. in Mohenjo Daro, Pakistan around 3500-3000 BCE (Gray, 1940; Webster, 1962) imply that they resulted from at least decades, and probably centuries, of technical trials and improvements, in connection with centralized administration and government to ensure the necessary coordination and coherence in their development in space and time. In the following centuries and millennia of Antiquity, stormwater and wastewater systems were built by many civilizations around the world (Angelakis and Rose, 2014) with various degrees of sophistication, the most documented ones in Western countries being probably the Greek and Roman periods (Bechmann, 1888; Crouch, 1993; Malissard, 1994; Burian *et al*., 1999; Krejci, 2004).

However, the birth of modern sewer systems, which gave rise to contemporary systems, can be dated – symbolically at least – to 1842. Although the first concepts were thought as early as the 1820s-1840s by the pioneers of hygienism - in particular Edwin Chadwick in England (Chadwick, 1842) and Alexandre Parent-Duchâtelet in France (Parent-Duchâtelet, 1824) -, the first real large-scale sewer system was set up in Hamburg (Jung-Köhler, 1991; Eich and Wierecky, 2002). In May 1842, a huge fire destroyed more than a third of the city. The city of Hamburg called upon the English engineer William Lindley to plan its reconstruction. Following a first draft and a meeting with Chadwick in London in November 1842, Lindley drew up the master plan of the sewer and drinking water systems in April 1843. The sewer system was a combined system that collected wastewater from houses and stormwater from roadways in large pipes located under the roads (Lindley, 1845; Leo, 1969). In addition, the drinking water system was designed to maintain sufficient pressure all along the pipes for firefighting (Figure 1). Previously, sewer systems in European cities, partly inherited from the Middle Age period (e.g. Guillerme, 1983), were built in a much less coherent and sometimes erratic way, incorporating successive periods with different objectives, designs and styles of construction (Burian *et al*., 1999). One of the most epic descriptions of such pre-modern systems is given by Victor Hugo in his novel *Les Misérables* (Part 5, Book 2) (Hugo, 1862), especially chapters III and IV. The difference between previous and modern sewer systems is also described, in a completely different literary genre, in the sanitary fairy tale *The Water-Drops* written by Henry Morley (1850, pp. 487-488) in the *Household Words* magazine edited by Charles Dickens.

Following this first achievement in Hamburg and owing to pioneering hygienists and engineers travelling to major cities where they were called upon to draw up master plans, the development of modern sewer systems spread in just a few decades across Europe, North America, and beyond (Bertrand-Krajewski, 2005). The second half of the 19th century may be considered as a kind of "golden age" of urban sewer systems, with the rationalisation and the international dissemination of concepts, design rules and formulas, and construction techniques, presented in several grounding papers, textbooks, and manuals (e.g. Mulvany, 1851; Waring, 1876; Latham, 1878; Adams, 1880; Bürkli-Ziegler, 1880; Belgrand, 1887; Bechmann, 1888; Kuichling, 1889; Baumeister, 1890; Staley and Pierson, 1891; Wollheim, 1896; Hervieu, 1897; Wéry, 1898). Cities and countries were competing internationally to develop public health and reduce death rates thanks to urban water systems, statistics were published annually and compared with great attention. Sanitary engineering was a highly appreciated and recognised domain of expertise.

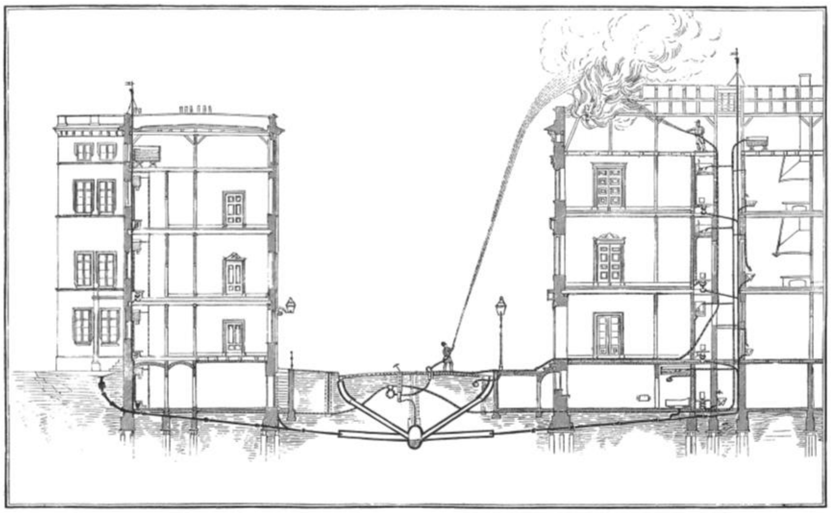

Figure 1: Cross-section of Hermann street in the newly built district of Hamburg, Germany (source: Architectonischen Vereine, 1868, p. 102). It illustrates the design proposed by William Lindley in 1842-1843 to rebuild the city of Hamburg after the great fire in May 1842, including a modern paved street with two lateral sidewalks, street inlets collecting stormwater, a combined sewer collecting both street runoff and wastewater from adjacent houses, a drinking water network with sufficient pressure for firefighting up to the 5th storey, and also gas lighting.

The general principles and rules for the conception of the systems were very similar, in spite of some minor technical variations and local adaptions, and irrespective of debates which were still taking place at the end of the 20th century on the respective advantages and disadvantages of combined and separate systems (e.g. Folwell, 1906; DeFilippi and Shih, 1971; Tarr, 1979; Burian *et al*., 1999), the former evacuating wastewater and stormwater in the same pipes, and the latter being made up of a separate network of pipes for each type of water.

> " […] such are the washing waters of streets, yards, houses, cars, etc., those for washing linen and clothes, toilet and bath water, household water, industrial water, urine and faeces, the latter diluting very easily, at least when fresh, in a sufficient amount of water. This set constitutes what is called *wastewater* and *sewage* (this is in short what water has become after it has been used for the various uses for which it is intended), and these liquids are so loaded with harmful principles that they shall be removed as fast as possible. But other waters are added to them, at least intermittently, which, if they are pure at the moment of their fall, do not take long to sweep roofs and especially the so dirty soil of cities, and to be loaded too with harmful substances; we are talking about *stormwater* which thus becomes similar to street washing water, and which, independently of the danger of flooding, should be drained in the same way very quickly." (Imbeaux, 1902, p. 346, my translation).

The paradigm of modern systems stemmed from hygienist thinking, based on medical considerations relating to the health of urban populations, especially workers, in connection with mephitic and miasmatic theories, but also on social, economic and political considerations linked to the prestige of states and cities, which were thus at the cutting edge of modernity and progress thanks to these new urban infrastructures regarded as decisive elements of urban renewal in the second half of the 19th century (Lewis, 1952; Hamlin, 1998; Chevallier, 2010; Jorland, 2010). The paradigm consisted in connecting buildings and impervious urban surfaces as much as possible, and in collecting and evacuating wastewater and stormwater as fast as possible. Stagnant water in urban areas was considered the source of all problems and had to be avoided at all costs (Ward, 1852; Imbeaux, 1902). For a long time, the collected water was discharged without any prior treatment into water bodies (rivers, lakes, estuaries, seas). It soon became evident, however, that aquatic environments, especially rivers, were significantly degraded by these pollutant flows. The first wastewater treatment plants started to be developed at the turn of the 20th century, to restore and protect the quality of aquatic environments (Imhoff, 1999). Such treatment, however, was applied only to wastewater or combined water, ignoring separate stormwater.

> “It has been found that running streams furnish the best available means of disposal of liquid filth and refuse by cities. Water carriage, when available, has been found to be the cheapest, as well as the least objectionable means of disposing of the large quantities of filth that would otherwise accumulate, to the detriment of public health.” (Wheeler, 1887, p. 18).

In combined sewer systems, the flows and volumes of combined water collected during wet weather could largely exceed the treatment capacities of wastewater treatment plants. Special devices, called overflow structures, make it possible to discharge directly and without any treatment the flows exceeding the capacity of downstream sewer systems and wastewater treatment plants (Metcalf and Eddy, 1930; Koch, 1935). One of the arguments used to justify this approach was that, under conditions of high flows, highly polluted wastewater was so diluted by stormwater – which was considered to be little or not at all polluted compared to wastewater – that its impact on the aquatic environment was insignificant. A theory was developed on the minimum acceptable dilution ratios for these direct discharges without treatment (Burian *et al*., 1999). In separate sewer systems, which were often faulty due to the poor connection of wastewater and stormwater to their respective collection networks, only the wastewater system was connected to a wastewater treatment plant, while the stormwater system ended up travelling along the shortest path and without treatment into the nearest water body.

The drainage of urban stormwater was thus long considered an essentially quantitative problem that came under the specialised fields of hydrology and hydraulics. The aim was to keep cities dry, clean, hygienic, and serviceable for traffic even during wet weather (Barles, 1999), so as to permanently avoid the muddy, pestilential and impassable streets excellently described by several authors such as Mercier (1781) and du Camp (1875).

The principles of stormwater drainage being unanimously accepted, the main technical issue was about sizing the pipes. Which size should they be to evacuate the flows generated by a given rainfall event on a given urban area without overflow or flooding? This article does not aim to describe the successive solutions developed over a century, starting from the 1850s (e.g. Mulvany, 1851; Rawlinson, 1853; Latham, 1878; Adams, 1880; Bürkli-Ziegler, 1880; McMath, 1887; Kuichling, 1889; Sherman, 1932). It should simply highlight the principle that the flows to be evacuated, and thus the size of the pipes, are directly linked to rainfall events, more precisely to their average intensity over a certain period of time, and to urban catchment characteristics (area, degree of imperviousness, slope, time of concentration, etc.). At the turn of the 20th century, a statistical approach became widespread, consisting in sizing pipes according to standardised rainfall events, called design storms, and characterised by their return period. For a given duration which increases along with the size of the urban area, a rainfall event with a 10-year return period can be described by the quantity of water reached or exceeded on average every 10 years according to rainfall events observed over a very long period (several decades or more). The simple and therefore approximate next step in the reasoning was that sizing the pipes according to a given return period rainfall event would lead to failures of the sewer system (overflows, floods) with the same return period. Choosing the return period of design storms should therefore fall under political decisions. How frequently do we accept a failure of the sewer system and the associated material, economic and human damages? In France, a 10-year return period was usually chosen as a standard value for a long time, although shorter return periods were recommended in residential areas (e.g. 2 to 5 years), and longer ones (e.g. 50 years) in sensitive areas such as dense urban centres. Such recommendations are still included in current standards (EN-752, 2017).

> “And even as the fit uncurled its full force, before the first hour was out, the drains overflowed, the roads flooded, and the traffic snarled at every intersection, every underpass, the mouth of every colony. Sara’s master class would suffer stalled cars; her low-castes would slip down uncovered manholes. […] The canker seemed to be concrete. In an excess of sprucing up, the city had been choked. Delhiites, seeking ever new ways of displaying their affluence, had bought up every kind of new tile and stone hitting the market and laid it out where they could. Marble - green, pink, Bhutanese, Nepalese. Stone - Jaisalmer gold, Kota grey, Agra red, Jaipur pink. Granite - black, brown, speckled. Tiles – Italian, Moroccan, Spanish. Sidewalks, backyards, gardens, driveways, open areas, walkways – everything was being paved and cemented. Every pore blocked, every breath stemmed: the earth was given a hard, impermeable gloss. The fat drops simply bounced off it.“ (Tejpal, 2009, p. 51).

Modern sewer systems expanded along with the growing urbanisation and urban sprawl. Extensions of sewer networks on the outskirts of cities were mostly connected to the older systems built previously in historic centres. The large size, or even oversizing, of the older sewer systems made it possible up to the 1960s-1970s to include peripheral extensions without drastically damaging their operation and performance. However, fast-growing urbanisation and soil sealing led to increasingly large, even gigantic sewer systems, with pipes sometimes built using tunnel-boring machines with diameters of several metres and at extremely high costs.

The engineering response to increasing failures and deficiencies of the sewer systems was relatively simple: building similar but larger centralised systems to cope with the urbanisation and reduce probabilities of failure. This reasoning was thwarted by several factors. A financial factor: the very significant increase in the construction and operation costs of larger systems. A technical factor: considering the necessary slope of the pipes, sewer systems had to be built at ever-increasing depths. An environmental factor: the increasing volumes of stormwater being collected and discharged without treatment in the aquatic environment contributed to its degradation.

3. THE DEVELOPMENT OF NEW TECHNICAL SOLUTIONS

These difficulties led to rethinking urban stormwater management. New approaches were developed from the 1960s to the 1990s in particular in Europe, North America, Australia and Japan, with various concepts and terminologies: BMP (Best Management Practices) and LID (Low Impact Development) in the USA and New-Zealand, source control in Europe, alternative techniques in France, WSUD (Water Sensitive Urban Design) in Australia, SUDS (Sustainable Urban Drainage Systems) in the UK, etc. (Fletcher *et al.*, 2015). More recently, the Sponge City approach was developed in China from 2014 onwards, combining LID and green infrastructure with traditional grey infrastructures (Tu and Tian, 2015; Jia *et al*., 2017; Jiang *et al*., 2018; Leng *et al*., 2020). What they had in common was a break with the previous paradigm which consisted in collecting and disposing of stormwater as quickly as possible. The new approach consisted rather in detaining and then discharging stormwater at a lower rate, so as not to overload the downstream sewer systems, or in locally infiltrating the least polluted runoff water. A large range of techniques was developed, such as detention basins, infiltration basins, swales, trenches, permeable pavements, detention roofs, etc. (Azzout *et al.*, 1994; Grotehusmann *et al*., 1994; Geiger and Dreiseitl, 1995; CIRIA, 2001). The initial design and sizing criteria were essentially based only on hydraulics (flows and volumes).

After approximately one century of negligence, and despite evidence reported early in the 19th century (e.g. Parent-Duchâtelet, 1824), but with completely different urban conditions in terms of buildings, roads materials, and traffic conditions, pollutants in stormwater were investigated in a scientific way, in connection with the contamination of rivers. Monitoring programmes started around the 1970s-1980s in the USA, in Europe and in Japan. Stormwater was revealed to be significantly polluted, by a very large range of pollutants, leading to negative impacts on aquatic environments and requiring specific treatments (Field and Lager, 1975; US EPA, 1983). For example, DeFilippi and Shih (1971) concluded from monitoring campaigns that "the approach of total separation of existing combined sewer systems should be reconsidered because significant pollution loads were found in separated storm sewers." Techniques were also developed to ensure a certain level of treatment using natural settling, chemically boosted settling, mechanical and biological filtration, etc.

These novel stormwater management facilities were implemented rapidly in new cities and urban suburbs, and then more slowly in dense urban centres, as part of urban renewal projects. Many of them require dedicated areas. Due to the high costs of land in cities, the multifunctionality of the facilities became standard. Water engineers and technicians thus had to work together with experts in roads, green spaces, cleanliness, as well as with urban planners and architects for projects such as combining a detention basin with an urban park or a sports field, combining infiltration areas with pavements, car parks, etc. These new interactions between formerly independent various specialists are not obvious and require special attention and efforts to be successful and to break the long-lasting independent silos of technical departments in cities, including new forms of education and training skills (Howe, 2012). The technical, social, organisational, and psychological aspects of the transition are intricate and must be adequately and specifically addressed (e.g. Brown *et al*., 2013; Dhakal and Chevalier, 2016, 2017; Cossais *et al*., 2019; Ibrahim *et al*., 2020). From being specific and separate technical objects, which were only included in urban projects late on and which were long the sole responsibility of water specialists, stormwater management facilities became multifunctional devices to be designed as part of an interdisciplinary approach and integrated early on into urban projects.

At the beginning of the 1990s, new reflections appeared about the importance of nature in cities, the enhancement of water in urban areas, and the rehabilitation of former water courses which had been buried and used as urban sewers. The concept of green infrastructure coupled with stormwater management emerged (Walmsley, 1995; Dover, 2015; Schröpfer, 2020), frequently named blue-green infrastructure to emphasize the relationship between water related aspects and vegetation in built areas. In this context, stormwater started to be reconsidered with interest and valued for refilling urban aquifers highly impacted by the imperviousness of soils, for uses that do not require drinking water quality (reserves for firefighting, toilet flushing, watering, outdoor washing, etc.), for landscape enhancement and visibility of water in cities. Figure 2 shows the example of Potsdamer Platz in Berlin, Germany. In this case, the project aimed to articulate several objectives: i) controlling stormwater locally by collecting rainwater from roofs in underground tanks (5 tanks with a total capacity of 2600 m^3, of which 900 m^3 are left empty in case of heavy precipitation), creating above-ground ponds with a 15 cm depth buffer capacity corresponding to an additional storage capacity of 1300 m^3, and controlling the excess of collected rainwater by discharging it into the nearby Landwehr open channel (up to 3 times in 10 years according to detailed hydrological modelling); ii) using the collected rainwater as a valued part of the prestigious architectural design located in a small, dense, constrained and expensive location; iii) providing an original and attractive urban landscape with ponds for both work and leisure activities, with living water thanks to rhythmic waves created by the movement of water over small cascades; iv) providing high quality water by means of settling particles in underground tanks, purification by vegetation, and the filtering of algae growing in warm summer months; v) using the rainwater also for toilet flushing and watering the vegetated roofs during dry periods (Dreiseitl and Grau, 2009, pp. 16-21).

Figure 2: Potsdamer Platz in Berlin, Germany. Architects: Renzo Piano and Christoph Kohlbecker, stormwater management: Atelier Dreiseitl (photo Jean-Luc Bertrand-Krajewski).

Figure 3: Stormwater ponds in the Porte des Alpes business district in Lyon, France (photo Greater Lyon).

In a few decades, the perception of urban stormwater changed: from a nuisance to a resource, from an exclusively quantitative management to an approach accounting for pollutant loads and the need for some treatment to reduce impacts on aquatic ecosystems, from an isolated technical domain to a multifunctional perspective more integrated in urban projects (Geldof, 1995; Chocat *et al*., 2001; Wong, 2007; Mitchell, 2006; Ashley *et al*., 2013; Schröpfer, 2020). The most advanced approaches have resulted in true aquatic ecosystems by integrating stormwater management, parks, and urban landscapes as places for urban well-being, recreational and social activities, protection and enhancement of biodiversity, and reduction of urban heat islands. Figure 3 shows the example of the Porte des Alpes area in Lyon, France. The objective in 1997 was to replace a pre-existing grey infrastructure built in 1977 for the stormwater management in a commercial area (detention pond and separate stormwater sewers) by a piece of blue-green infrastructure infiltrating stormwater from both the existing commercial area and the new tertiary activities area built upstream (Graie, 2020, pp. 25-32). The new infrastructure had the following main objectives: i) local stormwater control including settling and infiltration treatments; ii) reduction of flood risk in the downstream existing commercial area; iii) fraction devoted to nature and green spaces of 50 % of the 90 ha area with blue and green corridors; iv) safe public access promoted to high-value landscape, visible water, diversity of vegetation, ecological value, and information / education panels; v) creation of new blue-green ecosystems with water quality control and inventories of flora and fauna every 5 years; vi) multi-purpose infrastructure (one of the downstream tanks is a football playground, and there is an annual canoeing competition on the pond); and vii) unified technical organisation to operate the infrastructure bringing together staff from various previously separate departments (water, parks and gardens, roads and traffic, cleanliness) from the early design of the project onwards. The infrastructure includes a network of vegetated swales and trenches leading stormwater to constructed ponds (shown in Figure 3). At the outlet of the ponds, the stormwater is conveyed to detention and infiltration tanks and trenches, where it is infiltrated into the underlying aquifer. After 10 years, an evaluation review was made and reported that the infrastructure was technically efficient, attractive to the public, and that the constructed ponds had become rich and complex ecosystems with a high biodiversity similar to natural lakes (Sibeud and Mazereel, 2007).

4. TOWARD AN INTEGRATED URBAN APPROACH

> "Water is a physical element that could be used as a basis for redefining the urban environment." (AS Architecture Studio, 2009, p. 166).

Over the last 20 years, trends for continuing the evolution of urban stormwater management can be perceived, especially where critical stakes exist (severe drought, high seasonal variation of rainfall) or in relation to the issues of sustainability, climate change, population growth, governance and citizen participation, amenities and liveability in growing cities worldwide, the reinforcement of environmental decision criteria, and the need for nature in cities. "The model of the sustainable city challenges the hygienic principles of urban development: wetness finds its place in the city (permeabilization of soils and porosity of materials, visible above-ground stormwater management, re-organization of green spaces along aquatic corridors" (Cavin and Bourg, 2010, p. 129, my translation).

The management of urban stormwater is more and more decentralised and integrated into urban design, architecture, and buildings, with a fast expansion of the concepts of blue-green infrastructures, blue-green cities (Novotny and Brown, 2007; Keeley *et al*., 2013; Dover, 2015; PUB, 2018; Jiang *et al*., 2018) and water-wise cities (Bertrand-Krajewski *et al*., 2016). Based on numerous examples and various experiences all around the world, Schröpfer indicates that global and integrated thinking is essential: "The first [point] is understanding architecture as an urban ecosystem, following a kind of systems thinking that embeds the quality of urban and architectural design in the scientific and analytical thinking that informs best practices in infrastructure, sustainability, and urban planning. The second is the recognition of the role of comprehensive green and blue urban networks, systems of water and greenery that seamlessly transition our natural environment into our built one." (Schröpfer, 2020, p. 284).

Initially a landscape technique, green roofs are now considered as true facilities for stormwater management, with retention and evapotranspiration optimised to reach the "zero-discharge" objective for all non-exceptional storm events (e.g. Bertrand-Krajewski and Herrero, 2017; Shafique *et al*., 2018). Rainwater harvesting (Han and Mun, 2011) and storage allows watering raingardens, urban gardens, and farms (permaculture). Architecture becomes green (Figure 4) and explicitly accounts for stormwater in the design of roofs, façades, water resources and energy savings. Green roofs and green walls also contribute to enhance biodiversity in cities (Madre *et al*., 2014; Mayrand and Clergeau, 2018).

Figure 4: Vegetated roof and walls of the Flon metro station in Lausanne, Switzerland. Architects: Bernard Tschumi Architects and Merlini & Ventura, vegetation: Canevaflor (photo Jean-Luc Bertrand-Krajewski).

The new paradigm consists in no longer connecting buildings to collection networks for fast drainage, but on the contrary in disconnecting impervious surfaces from networks, in reducing the need for centralised collection networks in favour of local stormwater management at the scale of the building, the plot or the district (Nelson, 2012). For example, in France, the Greater Lyon regulation has required since 1995 that stormwater from private properties be either entirely infiltrated on each parcel, or discharged with a controlled outflow into the nearest surface water course with a certain fraction of stormwater being mandatorily infiltrated locally (Grand Lyon, 2019, article 12). There are only exceptional derogations. Direct connexion of stormwater overflows to public sewer systems is forbidden. It is also suggested that stormwater can be used for watering gardens, ground washing in buildings, toilet flushing, reserve for firefighting, and so on. Making surfaces pervious again (Vigano, 2006; Secchi and Vigano, 2011), disconnecting, retaining, detaining, (re) using, infiltrating, evapo(transpi)rating, valuing harvested rainwater, adapting treatment levels to uses (fit for purpose) have become key words.

Modifying urban designs and practices to reduce runoff and associated pollutant loads is also an important aspect of the new paradigm, for example by replacing chemical weeding by non-polluting thermal or mechanical weeding, or even by renouncing systematic weeding. Changing urban materials and practices to release fewer contaminants into stormwater is necessary for future cities. Rainwater is henceforth harvested, used, recycled, valued, and even saved because the envisaged uses may sometimes exceed the available rainfall resources. It is no longer a matter of systematically extending the large, centralized sewer systems inherited from the 19th century but of adapting, modifying, retrofitting, or even preferably abandoning them.

Numerous projects dealing with stormwater management, and more generally with all urban waters, aim to integrate landscape, environmental, architectural, local cultural and historical values: “1. Consider all parts of the water cycle, natural and constructed, surface and subsurface, recognising them as an integrated system; 2. Consider all requirements for water, both anthropogenic and ecological; 3. Consider the local context, accounting for environmental, social, cultural and economic perspectives, and 4. Strive for sustainability, aiming to balance environmental, social and economic needs in the short, medium and long term”. (Mitchell, 2006).

The universal approach of sewer networks inherited from the 19th century dedicated almost exclusively to hydraulic control (fast stormwater conveyance) has tended, over the last fifty years, to be progressively replaced by, or at least completed and/or associated with, diversified and increasingly complex approaches adapted to various local contexts and including an increasing number of objectives, functionalities, and issues. This evolution is graphically summarised in Figure 5, the first version of which was elaborated in 2009 and shared some points with the “Urban water management transitions framework” figure published in the same year by Brown *et al*. (2009) in their paper on the transition toward water sensitive cities.

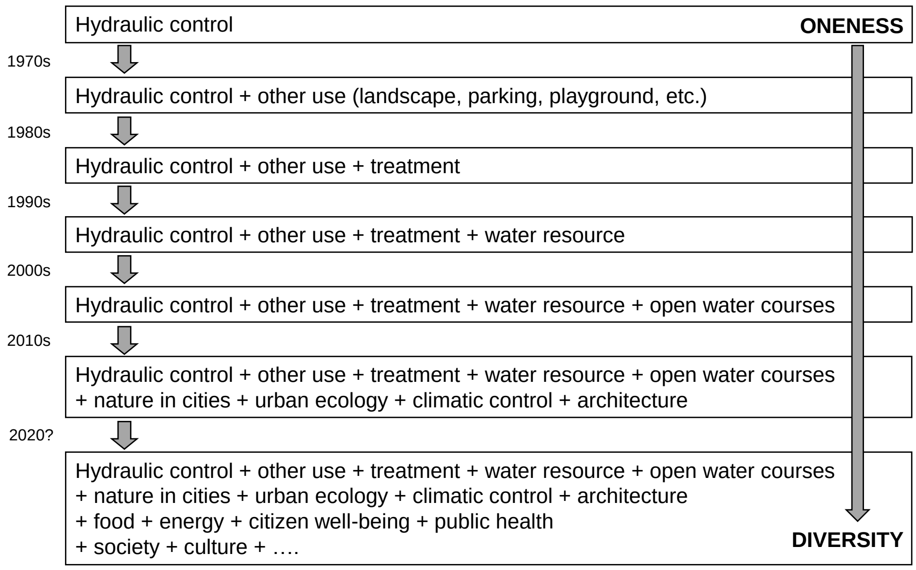

Figure 5: Evolution of urban stormwater management over the last fifty years - From the universal approach of sewer networks dealing almost exclusively with hydraulic control (oneness of the engineering solution) to an increasing integration of objectives, disciplines, functionalities, social and cultural demands (diversity of integrated approaches) (adapted from Bertrand-Krajewski, 2009).

5. THE EMERGENCE OF NEW QUESTIONS…

> "However, environmental engineering alone is not enough, and actually often fails, when it is not applied in accordance with the socio-cultural needs and customs of the people involved." (Dreiseitl and Grau, 2009, p. 12).

> "T. Paquot: […] Many people who study the natural sciences are not necessarily open to human and social sciences.
> S. Latouche: Many people who study human sciences are also not open at all to the natural sciences.
> P. Jouventin: In my opinion, the future lies in their convergence." (Jouventin *et al*., 2019, p. 37, my translation).

Integrated urban stormwater management generates urban landscapes, places and spaces that are bluer and greener, less dense, more gratifying, and enjoyable to live, enhancing gender balance and social diversity in public space, with added value compared to the traditional mineral urban environment (Dreiseitl and Grau, 2009; Chien, 2015; Suppakittpaisarn *et al*., 2019; Schröpfer, 2020), including new stakes related to public health (Egorov *et al*., 2016; Suppakittpaisarn *et al*., 2017; WHO, 2017) and safety (Kondo *et al*., 2015). These added values may contribute to a significant increase of rents and prices of flats or houses in the concerned areas (Nelson, 2012). In such conditions, can "blue and green" urban districts remain affordable for their inhabitants? Is the urban ecological retrofitting accessible to all? There is indeed a risk of (ecological or environmental) gentrification, with social consequences (segregation and exclusion) which should be accounted for in projects dealing with blue and green infrastructures and/or nature based solutions (e.g. Dooling, 2009; Haase *et al*., 2017; Bockarjova *et al*., 2020, Taguchi *et al*., 2020).

The Habitations Jeanne-Mance project in the centre of Montreal, Canada (McMeekin and Juteau, 2013) is an interesting example. This project was part of the Action Plan on Climate Change of the Quebec government, aiming to reduce urban heat island effects and to improve stormwater management. A large parking lot in the middle of a social housing district was reconstructed to create raingardens and a bioretention tank, and to use rainwater for watering, greening and landscape renovation, and increasing biodiversity (Lavallée *et al*., 2012). At the beginning, the inhabitants were not enthusiastic about the project. Indeed, in a local context where stormwater management was only one of the matters of concern, they feared they would have to move because the houses would be sold or because their rents would increase after the renovation of the district, following the increase of its market value. The guarantee they obtained that the houses would not be sold and the fact that, according to the local law on social housing, their rent could not be higher than 25 % of their incomes, independently of the market value of the apartments, modified their perception of the project (Tarditi and Laliberté, 2020). They were then closely associated with the project: involvement in the choices of renovation, in their realisation and maintenance, training in horticulture, environmental education, etc. The former impervious parking lot became not only a place for ecological management of stormwater, but also a truly living and friendly place for the inhabitants. This social aspect of the project was the reason why it obtained the "special award" of the jury of the Novatech Awards 2013 (Graie, 2013).

Integrating the social dimension in the conception and realisation of stormwater management projects is nowadays an essential aim (Dreiseitl and Grau, 2009). Really involving inhabitants, inviting them to participate in the projects and to initiate new ones is a key factor for establishing new relations between humans, water, and nature (Green *et al*., 2012; Dicks, 2014; Rivière-Honneger *et al*., 2014). New projects dealing with urban water and green infrastructure should not only lay claim to social objectives which usually remain vague and consensual, but should really take them explicitly into account and propose ways and methods to evaluate their realisation and their effectiveness. Some approaches are emerging, aiming to identify possible conflicts between stakeholders, conciliate engineering and social stakes, and open a new field of research and action and stimulate discussion (Vierikko and Niemelä, 2016; Ward *et al*., 2019; Meerow, 2020).

The re-introduction of water, nature and green landscapes in cities opens new questions in terms of design, perception, interpretation, signification, and value (Nassauer, 1995; Suppakittpaisarn *et al*., 2019), especially with urban generations who have less contact with nature (Saunders *et al*., 2006). The cultural, social, historical, symbolic, and imaginary dimensions are decisive (Strang, 2004) and cannot be addressed only by water technicians. Indeed, Illich (1985) argued that water had become a scientific, technical, and industrial matter to the detriment of its poetic and imaginary power, which are essential for human beings. From a complementary point of view, and in a very stimulating manner, Linton (2010) suggests that many our contemporary water problems are due to the fact that water became a scientific abstraction after Lavoisier demonstrated from 1783 to 1785 that it was nothing but the chemical compound, H_2O. From that moment, water lost its environmental, cultural, social, and symbolic meanings. It thus becomes essential to reconsider water in a more holistic, social, cultural, and philosophical way, and not only as a physical fluid and chemical compound in the hands of water specialists, managers, and decision makers. In a similar vein, Dicks (2014) proposes a phenomenological approach for "letting water appear", which requires a "radical deconstruction of several millennia of technological accretions" (Dicks, 2014, p. 430). This is an opportunity to contribute to restore the fundamental and deep meaning of the landscape for human beings: "In all human societies before something happened which is modernity, ordinary practice engenders beautiful landscapes. The concerned people feel or felt comfortable there, and us, visitors, we find it is beautiful. In modern societies, on the contrary, it is exactly the opposite: the ordinary practice engenders unsightliness, and thus one gets worried about *preserving the landscape* by means of special measures." (Berque, 2008, pp. 71-72, my translation).

> "Urban planners of the future will not be distinguishable from gardeners." (Henning, 2010, p. 66).

The example of the Cheong Gye Cheon River in Seoul, South Korea (Lee, 2006) is interesting in several ways. This river had been gradually transformed into an open sewer, then covered with a wide automobile boulevard in the 1960s-1970s and finally topped by a motorway viaduct in the 1990s. In 2005, the viaduct was demolished, the boulevard removed, and the former river re-created and re-developed over a length of almost six kilometres. Designed by urban planners, this re-creation, which is not a renaturation (the aim was not to restore the state of the river before urbanization or to create a real river in the sense of a true ecosystem) and clearly remains artificial (the inflow comes from both the Han River and subway dewatering), has three sections that, from upstream to downstream, are respectively dedicated to history, culture and urban, and nature. Restoration has produced an extremely busy, attractive and lively urban environment (Lévy, 2015), with historical elements (some remains of the viaduct piles have been preserved in the riverbed), aquatic ecosystem elements, a significant cooling effect of temperatures along the river and in adjacent streets, guaranteed water quality and significant biodiversity, improved traffic management and public transport system, reduced noise pollution and improved air quality (Lee, 2006; Maughan, 2014). It is now a symbol of Seoul and the place for the annual Seoul Lantern Festival.

The trend toward diversity illustrated in Figure 5 and in the above paragraphs cannot be taken for granted. There is indeed a significant risk that inter- and trans-disciplinarity will not be achieved (Howe, 2012), that the inertia and resistance of traditional silo-thinking remains strong, that the on-going evolutions in stormwater management are seen only as a new set of technical solutions (e.g. Dhakal and Chevalier, 2016; Jiang *et al*., 2018) applicable anywhere in the world without its necessary adaptation to and rooting in local environment, culture, history, geography and society, and that urban green and water landscapes would become similar everywhere.

For a long time, urban stormwater management led us to build cities against nature, following the paradigm of impervious surfaces, drying, and fast drainage, completely breaking the natural hydrography of the place and the cycle of water prior to urbanization. The literature published by scholars from various disciplines over the past few decades on urban stormwater management issues and the evolution of technical guidelines, regulations and practice observed in various cities and countries around the world incite us to build "water sensitive cities" (Brown *et al*., 2009) or "water wise cities" (Bertrand-Krajewski *et al*., 2016) instead of considering stormwater only as a nuisance to get rid of. At the beginning of the 20th century, the Brazilian engineer Saturnino de Brito achieved the status of a pioneer among his contemporaries by proposing to replace the usual exclusively functional routes of the sewer systems, completely decoupled from their local and natural context, with a "sanitary design of cities", aimed at combining the usefulness of the sewer networks considered as the decisive criterion, the consideration and respect of topography, wooded areas, natural water systems and pre-existing old urban centres, green spaces, and aesthetics by inviting artists to contribute to the urban design (de Brito, 1916; Nascimento *et al*., 2013). De Brito, however, remained a sanitary engineer rooted in his time, adept at positivist and progressive conceptions of his epoch, and at the hygienic model of fast wastewater and stormwater disposal. A few decades later, Ian McHarg, in his book *Design with Nature*, proposed a multi-criterion analysis of urban development projects, linking landscape value, environmental, ecological, and social criteria to the hydrological component (McHarg, 1967). The very title of the book clearly indicated the ambition to build and develop with nature, adopting a long-term perspective. This approach has gradually made its way into the mainstream and continues to inspire the most advanced projects combining several dimensions and disciplines. For example, Herbert Dreiseitl, a sculptor, artist, and landscape architect, has carried out numerous integrated urban stormwater management projects. His book *Recent waterscapes* is subtitled "Planning, building and designing with water" (Dreiseitl and Grau, 2009).

> "Nature herself has met many of the problems that now beset us, and she has usually solved them in her own successful way. Where man has been intelligent enough to observe and to emulate Nature, he, too, is often rewarded with success." (Carson, 1962, Ch. 6).

In the 19th century, sewer systems were frequently described as mimicking the human metabolism. Morley (1850, p. 488) compared the flow in modern drainage pipes with "the circulation of the blood". The osteologist Frederick Oldfield Ward further developed the analogy, in his address *Circulation or stagnation* to the General Congress of Hygiene at Brussels in September 1852: "Furthermore, this system, which has for its object not only the carrying away of the fertilising matter which hitherto has been allowed to remain for a longer or shorter period in the midst of human habitations, but also the application of this matter to the use of agriculture, and its transformation from a source of disease and expense into one of riches and nourishment. This system, I say, does not allow (unless provisionally) the discharge of excrement into rivers - a process which we regard as deplorable waste. To prevent this waste, and to replace it by fruitful circulation, we connect towns and country by means of an immense tubular organisation consisting of two divisions, the one the urban drainage, the other the rural distribution, and these two divisions are again subdivided into two distinct parts, the one arterial, the other venous." (Ward, 1852, pp. 267-268). He further developed and disseminated this idea four years later in another congress in Brussels (Ward, 1856). This analogy between water circulation in cities and blood circulation in human or animal bodies became a standard (e.g. Latham, 1876) and was still flourishing decades later (e.g. Bechmann, 1888, pp. 19-20; de Brito, 1901, p. 13) and even further extended to respiratory and digestive systems to include wastewater treatment and purification in addition to wastewater and stormwater collection by water engineers (e.g. Imbeaux, 1902, p. 346) or by Elisée Reclus, a French geographer of the 19th century and a precursor of ecology in his amazing description of a watercourse from its source to the sea (Reclus, 1869, pp. 200-202).

The notion of urban metabolism was initially introduced by Wolman (1965) as an analogy or an inspiring metaphor mainly based on substance flow analysis, aiming to describe urban processes with an ecological approach and perpetuating the analogy with the organismal metabolism. However, the urban metabolism approach was not convincing and even led to confusion with a truly urban ecology approach, as discussed by Golubiewski (2012) who qualifies urban metabolism as "an antiquated analogy". Concepts of ecosystems, and more recently biomimicry and bio-inspiration, may likely lead to new developments in urban stormwater management (Nelson, 2012). It does not appear that biomimicry is frequently mentioned by water specialists for neighbourhood or city-wide approaches, although concepts such as Low Impact Development (Dietz, 2007), Water Sensitive Urban Design (Lloyd *et al*., 2002) or Sponge City in China (Tu and Tian, 2015) borrow some aspects by proposing to rediscover or reproduce the natural water cycle as it existed before urbanization, including restoring the natural proportions between runoff, infiltration, evaporation and evapotranspiration, coupled with irrigation and agriculture (e.g. Van Rooijen *et al*., 2005; Perdersen Zari, 2015). The concept of Nature Based Solutions (NBS), initially proposed by the International Union for Conservation of Nature (IUCN) and the World Bank, appeared around 2002 (Cohen-Shacham *et al.*, 2016) and quickly became very popular in the field of urban water management. However, the IUCN definition does not explicitly refer to bio-inspiration. This reference is more explicit in the definition adopted by the European Union (EU) in 2015: "Living solutions *inspired by*, *continuously supported by and using Nature* designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social and environmental benefits." (Maes and Jacobs, 2015).

An analysis of urban stormwater management through the nine principles of biomimicry established by Benyus (1997) could lead to a completely renewed and amplified approach. Explicitly adopting bio-inspiration as a means of rethinking urban water management based on mature natural ecosystems is essentially emerging among architects and urban planners (Schuiten *et al*., 2010a, 2010b; Callebaut, 2015) and its seems that, unfortunately, water specialists have only contributed moderately to the debate (Nelson, 2012). Indeed, NBS is frequently used simply as a new fashion acronym replacing LIDs, WSUD, etc. without necessarily considering the more fundamental aspects which would deserve attention to deeply rethink urban water management. To move beyond these limitations, Dicks *et al*. (2020) propose a theoretical and conceptual framework, and explore the applicability of biomimicry at the city scale, associating philosophical and engineering considerations and tentatively using the model of the forest for planning, water, energy, transport and food in cities.

6. CONCLUSION

This paper proposed a brief overview of the evolution of the urban stormwater management since modern sewer systems were developed in the middle of the 19th century. For approximately a century, stormwater was considered mainly as a nuisance for the city and was conveyed as fast as possible in receiving water bodies by sewer networks designed according to hydrological and hydraulic quantitative criteria, in order to make cities comfortable and healthy for their inhabitants and to reduce flooding frequency. Stormwater was managed by water specialists used to working within their own independent engineering domain driven by technical performance and efficiency, with limited interactions with other stakeholders of the city. During the last 50 years, significant changes and trends appeared, in various parts of the world under different contexts. These progressive and still, at various degrees, on-going transformations resulted from a number of reasons that emerged at different times, in particular but no only: i) the evidence that stormwater was polluted, leading to detrimental impacts on receiving aquatic ecosystems; ii) the increasing size and cost of traditional sewer systems and the need to explore new cheaper solutions allowing the urbanisation of new areas; iii) the need to reduce the artificialisation of the urban hydrological cycle, to decrease runoff and to increase infiltration; iv) the increasing concern and social demand about preservation and restoration of the environment; v) the wishes of city planners and inhabitants to benefit from bluer and greener environments, landscapes and ecosystems in cities; vi) the trend toward more inclusive and participatory processes for governance and decision making in cities. As a result, the observed trend in stormwater management is an evolution from a separate engineering field providing a clearly delimited technical service to cities to an increasingly sophisticated and complex domain, attempting to integrate numerous objectives, functions and issues, requiring combined and interacting contributions of multiples disciplines and stakeholders (engineering sciences, environmental sciences, architecture, urban planning and design, landscape, social sciences, etc.) with the ambition to provide more sustainable and liveable cities.

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