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Urban Water Quality

BY:

J. B. Ellis, J. Marsalek, B. Chocat

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NATIONAL WATER RESEARCH INSTITUTE
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Abstract

Steady growth of population, due to overall population increases and continuing migration from rural to urban areas, creates enormous demands and stresses on urban waters with respect to water supply, drainage, flood protection, wastewater management and beneficial uses of receiving waters and groundwater. Urban water issues are therefore in the forefront of water management priorities in practically all regions of the world, though often for broadly varying reasons. Key issues of urban water management are discussed in this article, which focuses on the evolution of urban drainage infrastructure, characterization of urban drainage, urban runoff impacts on receiving waters, urban drainage management, water and wastewater re-use and future perspectives and priorities. The discussion focuses on the collection and transport of urban effluents (sewer systems), characterization of urban drainage provided by combined or storm sewers (flows and their quality), impacts of urban drainage effluents on receiving waters and groundwater and impact mitigation by integrated urban drainage management with the emphasis placed on the management of surface runoff and water/wastewater re-use. While the progress in integrated engineering science, watershed-based management and new water technologies is impressive, the challenges of maintaining and improving urban water services, particularly in low-income countries, are formidable and may be further exacerbated by demographic, social and climate change.

NWRI RESEARCH SUMMARY

Plain language title

Urban Water Quality

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

Steady growth of urban population places enormous demands and stresses on urban waters with respect to water supply, drainage, flood protection, wastewater management, and beneficial uses of receiving waters and groundwater. The current state of knowledge in this field is summarized in this publication.

Why did NWRI do this study?

NWRI has been invited to contribute to this joint effort in collaboration with the Middlesex University (UK) and INSA (University) Lyon (France).

What were the results?

The study noted that urban water issues are in the forefront of water management priorities in practically all regions of the world. The key issues discussed included evolution of urban drainage infrastructure, characterization of urban drainage, urban runoff impacts on receiving waters, urban drainage management, water and wastewater reuse, and future perspectives and priorities.

How will these results be used?

These results will serve the users of the Encyclopedia of Hydrological Sciences, who wish to learn quickly about the existing knowledge of urban water quality and future challenges in this field.

Who were our main partners in the study?

Urban Pollution Research Centre, Middlesex University, UK and Institut National des Sciences Appliquees de Lyon, France.

Qualité de l'eau en région urbaine

J.B. Ellis, J. Marsalek et B. Chocat

Résumé

La croissance démographique soutenue, attribuable à un accroissement général de la population et à une migration des régions rurales vers les régions urbaines, impose une demande et un stress énormes aux services associés à la gestion de l'eau en région urbaine, entre autres en ce qui concerne l'approvisionnement en eau, le drainage et l'évacuation des eaux de ruissellement, la protection contre les inondations, la gestion des eaux usées et les utilisations bénéfiques des eaux réceptrices et des eaux souterraines. Les problèmes associés à l'eau en région urbaine viennent par conséquent au premier rang des priorités en ce qui concerne la gestion de l'eau, et ce, dans presque toutes les régions du globe, quoique souvent pour des raisons très variées. Les problèmes importants concernant la gestion de l'eau en région urbaine sont discutés dans cet article, qui met l'accent sur l'évolution de l'infrastructure de drainage urbain, la caractérisation et la gestion de ce dernier, la réutilisation de l'eau et des eaux usées, l'incidence du ruissellement urbain sur les eaux réceptrices, les perspectives d'avenir et les priorités. L'étude porte sur la collecte et l'acheminement des effluents urbains (réseaux d'égout), la caractérisation du drainage urbain assuré par des égouts unitaires ou des égouts pluviaux (débit et qualité), l'incidence des effluents de drainage sur les eaux réceptrices et les eaux souterraines, et l'atténuation des impacts par une gestion intégrée de drainage urbain, l'accent étant mis sur la gestion des eaux de ruissellement et la réutilisation de l'eau/des eaux usées. Bien que les progrès réalisés en ingénierie intégrée, en gestion des bassins hydrographiques et en technologie de l'eau soient impressionnants, les défis posés par l'entretien et l'amélioration des réseaux d'eau en région urbaine, plus particulièrement dans les pays à faibles revenus, sont gigantesques et peuvent être exacerbés par les changements démographiques, sociaux et climatiques.

Sommaire des recherches de l'INRE

Titre en langage clair

Qualité de l'eau en région urbaine

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

La croissance démographique soutenue impose une demande et un stress énormes sur les services associés à la gestion de l'eau en région urbaine, entre autres en ce qui concerne l'approvisionnement en eau, le drainage et l'évacuation des eaux de ruissellement, la protection contre les inondations, la gestion des eaux usées et les utilisations bénéfiques des eaux réceptrices et des eaux souterraines. L'état actuel des connaissances dans ce domaine est résumé dans la présente publication.

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

L'INRE a été invité à participer à cet effort commun, de concert avec la Middlesex University (GB) et l'INSA (Université) de Lyon, France.

Quels sont les résultats?

L'étude révèle que les problèmes associés à l'eau en région urbaine viennent au premier rang des priorités en ce qui concerne la gestion de l'eau, et ce, dans presque toutes les régions du globe. Les questions importantes qui sont abordées sont les suivantes : l'évolution de l'infrastructure de drainage urbain, la caractérisation et la gestion de ce dernier, l'incidence des eaux de ruissellement sur les eaux réceptrices, la réutilisation de l'eau et des eaux usées, les perspectives d'avenir et les priorités.

Comment ces résultats seront-ils utilisés?

Les résultats serviront aux utilisateurs de l'Encyclopedia of Hydrological Sciences, qui désirent connaître rapidement l'état actuel des connaissances sur la qualité de l'eau en région urbaine et les défis à relever dans ce domaine.

Quels étaient nos principaux partenaires dans cette étude?

Le Urban Pollution Research Centre, la Middlesex University, GB, et l'Institut national des sciences appliquées de Lyon, France.

97: Urban Water Quality

J BRYAN ELLIS,[1] JIRI MARSALEK[2] AND BERNARD CHOCAT[3]

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Steady growth of population, due to overall population increases and continuing migration from rural to urban areas, creates enormous demands and stresses on urban waters with respect to water supply, drainage, flood protection, wastewater management, and beneficial uses of receiving waters and groundwater. Urban water issues are therefore in the forefront of water management priorities in practically all regions of the world, though often for broadly varying reasons. Key issues of urban water management are discussed in this article, which focuses on the evolution of urban drainage infrastructure, characterization of urban drainage, urban runoff impacts on receiving waters, urban drainage management, water, and wastewater reuse and future perspectives and priorities. The discussion focuses on the collection and transport of urban effluents (sewer systems), characterization of urban drainage provided by combined or storm sewers (flows and their quality), impacts of urban drainage effluents on receiving waters, and groundwater and impact mitigation by integrated urban drainage management with the emphasis placed on the management of surface runoff and water/wastewater reuse. While the progress in integrated engineering science, watershed-based management and new water technologies is impressive, the challenges of maintaining and improving urban water services, particularly in low-income countries, are formidable and may be further exacerbated by demographic, social, and climate change.

INTRODUCTION

Flood protection, drainage, and sanitation have always ranked highly in the needs of most societies, and, even in early civilizations, cities such as Ur and Babylon of the second century millennium B.C. Mesopotamian Empire possessed sophisticated wastewater collection and stormwater drainage systems, the remains of which can still be found. Significant advances in urban drainage technology were introduced during the period of the Roman Empire with roadway drainage, underground conduits, and sewer networks primarily intended for flood mitigation and the drainage of lowlands. The collection of rainwater for household and public use was also considered important especially given that domestic water consumption during the Roman period reached very high levels of 300 to 500 L per person per day.

Sanitation practices deteriorated after the decline of the Roman Empire with surface drains and streets being used in the Middle Ages as the only means of conveyance and disposal of all kinds of water-borne wastes. Water consumption declined to less than 15 L per head per day with already polluted urban waters being abstracted for further use in paper, fabric, and leather industries. Stormwater and foul sewage streams thus became indiscriminately mixed, becoming so noxious that they had to be covered and turned into sewers, giving rise to the birth of the "combined" sewer principle. The first beginnings of modern urban drainage practices were intended for stormwater control and were initiated in European cities during the nineteenth century, particularly following the numerous epidemics of typhoid and cholera in Europe and the United States in the 1830–1870 period. Inlets, gutters, and sewers replaced open street channels in Paris during 1810 to 1839 under the efforts of the engineers Bruneseau and Emmery, and, in 1843, the first comprehensively planned sewerage system for a major city was undertaken in Hamburg, Germany. The London sewer system designed by Bazalgette was introduced between 1859

Encyclopedia of Hydrological Sciences. Edited by M G Anderson.

and 1865, and, in the United States, main urban drainage systems were introduced in Chicago (1850s) and New York (1880). A good review of the history of urban drainage in the United States is given in Burian *et al.* (2000) with information on recent urban pollution control strategies provided in the chapter by Loagne and Lorin (*see* **Chapter 94, Point and NonPoint Source Pollution, Volume 3**).

The perspective of urban drainage also changed from a design standpoint during the late nineteenth century. Intuitive reasoning about conversion of rainfall into runoff led to the emergence of the Rational Method through the work of Mulvaney (1851), Kuichling (1889) and Lloyd–Davies (1906). By the end of the late nineteenth century, engineers possessed various design concepts and methods for wastewater disposal systems, and, for the next 100 years, these would become the standard tools used in urban drainage design throughout the world. Since the 1960s, rapid developments have occurred in urban drainage practice and this can be directly linked to the introduction of the computer and associated electronics such that it is now possible to calculate flows in sewer and drain networks with high precision and resolution to support cost-effective design, analysis, and operation.

Whilst these advances have helped in coping with urban flooding and have substantially improved the health of urban citizens, progress in water quality considerations and particularly those addressing the impact of increasing urban populations and their activities upon both surface and groundwaters have been much slower. Unfortunately, the processes that control water quality in drainage systems are much more complex and less deterministic than those which control flow rates (see McCutcheon, **Chapter 100, Water Quality Modeling, Volume 3**). More recently, major changes in drainage design and operation philosophy have been introduced as a result of

- the introduction and adoption of the concepts of ecological integrity and sustainable approaches to environmental and water resources management set within a watershed-wide framework;
- acceptance of the need to consider urban drainage, wastewater systems, and receiving waters in a holistic, integrated manner;
- the continuing development of computing power and an associated range of new analytical and real-time control techniques.

However, almost two-thirds of the world's population has no inherited sewered infrastructure, and many struggle with recurrent flooding and the daily need to find a place to carry out the most fundamental personal ablutions. Many would argue that the techniques and paradigms on which the wastewater disposal systems were developed in the developed nations are totally irrelevant to the needs and circumstances of developing urban populations and that new urban drainage paradigms are required. The major objectives for urban drainage remain public hygiene, flood protection, and environmental enhancement, although the emphasis in developed countries has been firmly placed to date on flood and pollution control. However, at the beginning of the twenty-first century, urban drainage has evolved to become much more than the simple transport and treatment of urban runoff and the time is ripe for the introduction of new paradigms based on more long-term sustainable strategies.

CHARACTERIZATION OF URBAN DRAINAGE

Introduction

Urban runoff includes dry weather sewage baseflow, stormwater, combined sewer overflows (CSO), as well as industrial effluent discharges and has been identified as a source of receiving water pollution for nearly 50 years. However, it is only in the last 20 years that national efforts within North America, Europe, Japan, and Australia have been made to identify and quantify the various pollutants and urban land uses responsible for such contamination. Surface Water Outfalls (SWOs) are essentially generated by storm rainfall conveying stormwater over impermeable urban surfaces to the separate surface water sewer system although non-wet weather flow can occur due to blockages, line breaks, vandalism, or misconnections. CSOs represent the combined volume of wastewater and stormwater runoff entering combined sewer systems, which exceeds the conveyance and treatment capacity of the drainage network, and is diverted to the receiving water by overflow regulators.

Urban Surface Water Pollutants

The range of pollutant concentrations and loadings associated with stormwater runoff from impermeable urban surfaces indicates that such surface water discharges can be highly variable in quality (Table 1), with standard deviations frequently being 75% (equivalent to a coefficient of variation, C_v, of 0.75) of the average event mean concentration (EMC) value. Table 1 would suggest that EMCs are frequently close to, if not exceeding the minimum NOEL (no observable effects limit) value and thus potentially present a problem to receiving water ecology. However, land use pollutant loading relationships do have a high degree of site specificity, and regional extrapolations on a continental scale cannot be readily applied. Further, the impact is varied with organism; some are victim to chronic low level exposure, others to acute higher concentration flushes. Nevertheless, the land use mean EMC value × Runoff Volume approach provides a convenient and appropriate screening-level methodology for estimation

Table 1 Pollutant concentrations and loadings for urban stormwater runoff

	Event mean concentration and range (mg L^{-1})		Load per unit area (kg imp.ha^{-1} $year^{-1}$)		
Pollutant parameter	Residential & commercial	Motorways & trunk roads	Residential/ commercial	Motorways & trunk roads	Minimum concentration causing observable biological effects
Total suspended solids	190	261	487		
	(1–4582)	(110–5700)	(347–2340)	(815–6289)	25 mg L^{-1}
BOD	11	24	59		N/A
	(0.7–220)	(12.2–32.0)	(35–172)	(90–172)	
COD	85		358		N/A
	(20–365)	(128–171	(22–703)	(181–3865)	
NH_4-N	1.45		1.76		1.7 μg L^{-1}
	(0.2–4.6)	(0.02–2.1)	(1.2–25.1)	(0.8–6.1)	
Total nitrogen	3.2		9.9		N/A
	(0.4–20.0)		(0.9–24.2)		
Total phosphorus	0.34		1.8		N/A
	(0.02–14.3)		(0.5–4.9)		
Total lead	0.21	0.96	0.83		12.26 μg L^{-1}
	(0.01–3.1)	(2.41–34.0)	(0.01–1.91)	(1.1–13.0)	
Total zinc	0.3	0.41	1.15		30 μg L^{-1}
	(0.01–3.68)	(0.17–3.55)	(0.21–2.67)		
Total hydrocarbons	1.9	28	1.8		
	(0.04–25.9)	(2.5–400)	(0.01–43.3)		
PAH	0.01	(0.03–6.0)	0.002	140	
Fecal coliforms	6430		2.1		
(*Escherichia Coli*)	(40–500 000)	10–10^3	(0.9–3.8)		N/A
	MPN per 100 m L^{-1}	MPN per 100 m L^{-1}	$\times 10^9$ counts ha^{-1}		

(Table compiled from: USEPA (1983) *Final Report of the Nationwide Urban Runoff Program*, Vol. 1, US EPA: Washington; USEPA (2004) *Impacts and Control of CSOs and SSOs*, Report 833-R-04-001, US EPA, Washington; Deutsch J. C. and Hemain J. C. (1984) Main results of the French National Programme of urban runoff quality measurement. *Proceedings of the 3rd International Conference Urban Storm Drainage*, Chalmers University: Gothenburg, pp. 939–946; Marsalek J. (1991) Pollutant loads in urban stormwater. *Water Pollution Research Journal Canada*, **23**(3), 360–378; House M. A., Ellis J. B., Herricks E. E., Hvitved-Jacobsen T., Seager J., Lijklema L., Aalderink, H. and Clifforde, I. T. (1993) Urban drainage: impacts on receiving water quality. *Water Science Technology*, **27**(12), 117–158; D'Arcy J. B., Ellis J. B., Ferrier R. C., Jenkins A. and Dils R. (Eds.) (2000) *Diffuse Pollution Impacts: The Environmental and Economic Impacts of Diffuse Pollution in the UK*, Terence Dalton Publication (CIWEM), Lavenham.)

of annual loads and their confidence limits (Marsalek, 1991; Ellis and Mitchell, 2005). Mean EMCs can be calculated from observations or transported from existing databases such as the US NURP database (USEPA, 1983); runoff volume is produced by hydrological modeling. The volume is then multiplied by the mean EMC to obtain the loading, and estimate bounds derived from multiplication by the upper and lower confidence limits.

Properties of EMCs are of further interest in load and impact estimations. Firstly, the US NURP data indicate that geographic location and land use were of little utility in explaining site-to-site variability, or predicting data for unmonitored sites (US EPA, 1983). Under such circumstances, best EMCs are obtained by pooling data for all sites. Secondly, EMCs were found to be statistically independent of runoff event volumes, which implies that loads can be derived by multiplication of the mean EMC by runoff volume, and, furthermore, when sampling runoff events, randomly selected events of any magnitude are acceptable. Thirdly, analysis of EMC data in the NURP program (US EPA, 1983) and in other studies indicated that stormwater constituent concentrations as well as their EMCs are log-normally distributed. This fact can be used in estimating means of censored concentration data, and in estimates of loads and quantiles (Van Buren *et al.*, 1997). Many urban water quality planning and design tasks require spatially and temporally distributed data on stormwater, municipal sewage, and combined sewage flows in urban areas, for the analysis of existing sewerage systems or planning and design of new ones. Such tasks require the use of urban simulation models, which have greatly evolved during the past 30 years. There are many such models currently in use, but several broadly used software packages stand out in the modeling practice (listed alphabetically):

InfoWorks CS (collection system) of Wallingford Software (`http://www.wallingfordsoftware.com`), MOUSE of the Danish Hydraulic Institute (`http://www.dhi.com`), and the Storm Water Management Model of the US Environmental Protection Agency (`http://www.epa.gov/ceampubl/`). These models are modularly structured, and, in general, they calculate runoff and wastewater flows, their quality, route the flows and water quality constituents through transport, storage, management, and treatment facilities, and simulate the fate of effluents in receiving waters. Modules for simulation of real-time control of sewer systems are also available. In general, the available modeling tools serve well the needs of urban modelers and facilitate easy input data import from GIS or other databases (Zoppou, 2001).

Combined Sewer Overflow (CSO) Pollutants

Table 2 shows the range of pollutant concentrations associated with global CSO discharges, which are not that dissimilar between the various countries quoted, given the variation in geographic and climatic situation for the differing data locations. The pollutants in CSOs come from domestic sources (especially BOD_5, TSS and nutrients), trade effluents (especially fats, grease, metals, and synthetic organic compounds), as well as from atmospheric washout and impermeable surface water runoff during wet weather events. Concentrations can vary substantially on a diurnal basis, both within and between stormflow events, as well as from community to community. These pollutants impact the aquatic environment in various ways, as indicated later in the article, with solids, for example, aggravating fish gill tissue, increasing turbidity, and entombing embryos in the bed gravel. Oil can severely affect wildlife through ingestion following preening as well as from loss of external waterproofing, whilst both organics and metals can induce toxic effects upon the biota.

Aesthetic pollutants such as sanitary products, toilet tissue, and faeces also characterize CSO discharges with loads, depending on the magnitude and frequency of overflow events, watershed characteristics, as well as population size and character. Floatables, including sanitary products, litter, and detritus are also characteristic of CSOs and can have an adverse impact on wildlife, primarily through entanglement or ingestion as well as having adverse aesthetic impacts. A recent concern has arisen over the incidence of sewage contaminants associated with pharmaceuticals and personal care products (PPCPs) such as chelating agents (e.g EDTA), antibiotics, antiinflammatories, steroids, and endocrine disrupters that are being found at levels well above the widely accepted $1\,\mu g\,L^{-1}$ limit (Marsalek *et al.*, 2002).

Combined sewer networks should not be regarded simply as conveyance systems as they also serve as physical and chemical reactors having the potential to alter and modify the quality of received urban runoff. The sudden flow influx into a CSO brought on by a rainfall (or snowmelt) event can create a first-flush effect, which occurs when pollutants washed from impermeable urban surfaces combine with pollutants resuspended from in-pipe sediment. Studies of sewer entry–exit mass loads have shown that exchanges with in-pipe pollutant stocks make up a principal source of wet weather flow pollutants for solids, BOD/COD, hydrocarbons, and soluble metals such that they present a prime source of acute oxygen depletion in the receiving water (Ashley *et al.*, 2004).

Construction and Urban Runoff

The increases in sediment load associated with urbanization have been well documented, and it has been suggested that construction causes 50% of the urban sediment yield with as much as 10 tonnes per capita per annum (and averaging between 116 to 157 tonnes $ha^{-1}\,year^{-1}$) being transported in receiving waters during the initial construction phases (D'Arcy *et al.*, 2000). This sediment yield declines substantially as the urban area matures such that TSS concentrations can decline (especially for small urban watersheds) below levels observed in rural catchments.

Table 2 CSO pollutant concentrations

	TSS ($mg\,L^{-1}$)	BOD ($mg\,L^{-1}$)	COD ($mg\,L^{-1}$)	Cd ($\mu g\,L^{-1}$)	Cu ($\mu g\,L^{-1}$)	Pb ($\mu g\,L^{-1}$)	Zn ($\mu g\,L^{-1}$)	P_{total} ($mg\,L^{-1}$)	N_{total} ($mg\,L^{-1}$)	*E. Coli* (100 mL)
US	237–635	43 – 95	120–560			150–290			2.9–4.8	
Canada	190							1.4	8.3	
UK	***425***	***90***				***250***	***870***	***10***	***8.3***	
	176–647	43–225	260–507			80–450	100–1070	6.5–14.0	2.1–28.5	$10^6 - 10^8$
Europe	105–721	39.9 – 200	148–530	1.1–9.6	37–170	42–450	357–1070	2.4–4.0	2.1–14.4	$10^7 - 10^8$

(Table compiled from: Ellis J. B. (1986) Pollutional aspects of urban runoff. *Urban Runoff Pollution, NATO Technical Series,* Torno H. Marsalek J. and Desbordes M. (Eds.), Springer–Verlag: Berlin, pp. 1–34; WRC (1991) *Sewer Quality Archive Data,* Report FR0203, Foundation for Water Research, Medmenham; Arnberg–Neilsen K., Hvitved–Jacobsen T., Johansen B. N., Mikkelsen P. S., Poulsen B. K., Rauch W. and Schlutter F. (2000) *Stormwater Concentrations in Foul Sewers,* Milloproject 532, Danish EPA; EPA (2004) *Impacts and Control of CSOs and SSOs,* Report to Congress, EPA 833-R-04-001, Office of Water, Washington.)

Highway construction can result in equally large increases in sediment yield. For example, in addition to recorded illegal off-site discharges, TSS concentrations of between 3235 and 20 340 mg L^{-1} and 8635 and 46 800 mg L^{-1} have been recorded respectively for the Annan and Kirtle Water over the period April 1993 to May 1995 during the construction of the M74 motorway in Scotland, UK (D'Arcy *et al.*, 2000). The cumulative effect of these nonpoint sediment discharges resulted in 3.9 km of the River Annan and 16.2 km of the Kirtle Water being downgraded from the highest water quality classification standard.

Urbanization and Surface Runoff Flows

The transformation of a watershed from a rural to an urban condition produces three major changes in the hydrological characteristics of receiving streams:

- An increase in flow volume primarily due to the reduction in infiltration following increases in impermeable surfacing with increases in runoff volume being greatest for frequently occurring small, intense storms.
- A decrease in lag time due to a combination of impervious surface runoff and the expansion of the urban drainage net, which reduces hydraulic roughness and increases the velocity of overland flow.
- An increase in peak discharge; this is the combined result of increases in runoff volume and decreases in lag time. A full urbanized watershed with some 50% impervious cover will increase the peak discharge of a 2-year storm by approximately four times.

The relative increase in 0.01 through 0.2 probability storms for runoff peaks and volumes, that is, 100 through 5-year return period storms are 1.8 to 3.0 times the runoff from undeveloped land (for example, see **http://udfcd.org/techpapers.htm**). As the recurrence probability increases to 0.5, that is, a 2-year storm, the runoff after urbanization is about 40 to 60 times or more the undeveloped rate. However, it is the annual (or 1.5-year recurrence interval flow) and more frequently occurring smaller storms that are the dominant channel forming events and which generally shape the watercourse along with being responsible for delivering the majority pollutant load to the receiving water. Further detail on flow effects and related urban drainage design arising from urbanization is also provided by Endreny in **Chapter 117, Land Use and Land Cover Effects on Runoff Processes: Urban and Suburban Development, Volume 3.**

Given the need to capture and convey large floods up to the 100 RI storm event that result from increased surface runoff, traditional engineering of urban waterways has been to employ straightened concrete-lined channels with safety walls or gabion buttresses. Flows along these watercourses are flashy and potentially hazardous to local residents, thus longitudinal slopes need to be reduced using grade control drop structures, low/trickle flow channels, on-line riffle/pool sequences, sinuous low-flow paths, and so on.

Flow and Quality Pathways

Figure 1 illustrates the various source inputs (heavy-bordered boxes), outputs (or sinks shown by dashed boxes) and pathways of water and pollutants for both natural and anthropogenic sources that are encountered within an urban catchment. There may be unintentional pathways whereby flows leave the sewer pipes via exfiltration or where elevated groundwater levels act as a source and add water into the sewer system via pipe infiltration. The former loss is generally of a small scale and less than 2 to 3% of total flow volume due to joint sealing by sediment and biofilm growth in the sewer pipe (Ellis *et al.*, 2004). The latter gains by infiltration can be much more substantial, particularly following prolonged rainfall periods that elevate the catchment water table above the level of the sewer pipe invert.

URBAN RUNOFF IMPACTS ON RECEIVING WATERS

Introduction

The various impacts of urbanization on the water cycle are independent, and they have a synergy that reinforce each other and lead to a general deterioration and loss in water use. This yields the paradox that it is urban areas, which have the greatest requirements in terms of water and aquatic amenity use, water quality, and flood protection, but are characterized by the highest flood and pollution risks and have the most highly degraded aquatic environments. Some detail on the relationship between infrastructure and resulting water quality is also given by Baker in **Chapter 188, Land Use and Water Quality, Volume 5.**

The most significant urban receiving water impacts are caused by discharges from both separately sewered SWOs and CSOs with the nature and magnitude of the impact being dependent on the characteristics of the generating watershed and the interactions with the receiving waterbody. Such impacts need to be evaluated in terms of specific characteristics at each site, including physical habitat changes, water quality changes, sediment and toxic pollutant impacts, impacts on biological communities, and groundwater impacts. Discharges of fecal bacteria also pose health risks, particularly during and immediately after wet weather events. Such physical, chemical, and biological effects will operate at varying temporal and spatial scales. Temporal scales correspond to the nature of acute (short-term) and chronic (long-term accumulative) impacts with intermittent water quality criteria normally related to exposure duration and return period of the impact-causing event

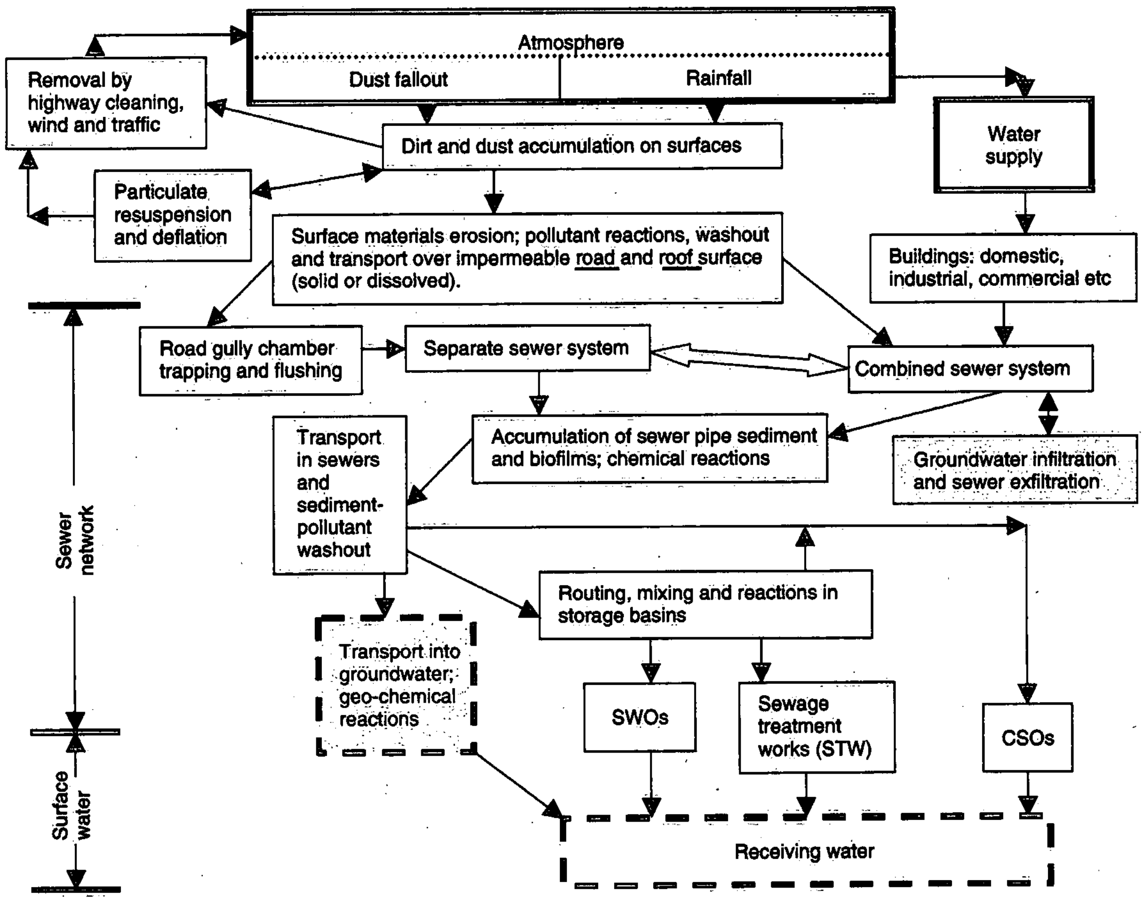

Figure 1 Urban runoff pathways

as well as the pollutant concentration. The typical recovery time after a CSO event is on the order of 5 to 7 days. However, it cannot be concluded that compliance with such criteria will provide guaranteed long-term protection as continued episodic exposure and perturbation can lead to a permanent weakening of the aquatic ecosystem and prevent ultimate recovery.

Receiving Water Impacts

Physical habitat changes Urbanization can permanently modify the nature, form, habitats, and behavior of receiving water bodies that are frequently "canalized" or heavily modified to contain the flood channel and improve storm flow conveyance. Such regulated channels will have altered fluvial dynamics typified by increased sedimentation and high erosion potential, which, in turn, influences stream morphology and channel characteristics as well as in-stream habitat and substrate conditions. Bed sedimentation also limits exchange between surface and underground waters across the hyporheic zone.

Water quality changes Dissolved oxygen (DO) depletion from intermittent urban discharges is a well recognized phenomenon with the soluble organics transported in the water phase exerting an immediate DO depletion with the scouring effect of increased flow on basal sediments adding to this effect, which can be further exacerbated by the presence of ammonia. Settleable solids accumulate on the bed and can result in delayed DO depletion due to an increase in the sediment oxygen demand (SOD) as well as facilitating anoxic conditions under ice cover during winter months. Pollutants discharged from both CSOs and SWOs contribute a range of adsorbable and settleable pollutants derived from sewer deposits, wastewater effluents, and urban surfaces. Owing to the nature and amount of biodegradable organics, anaerobic conditions may prevail in receiving water sediments and accumulated metals, hydrocarbons, and bacteria can then impose long-term, chronic impacts on the sediment community. Approaches to multidimensional water quality modeling of waterbodies receiving polluting discharges are outlined by Lin and Falconer in **Chapter 17, Hydrological and Environmental Modeling of Transport Processes in Rivers and Estuaries, Volume 1.**

Ecological changes The generic characteristics of urban receiving water ecology are habitat instability and ecotoxicity. The urban stream is dominated by taxa, which can tolerate successive erosional–depositional sequences and transient, low-quality food sources with limited leaf decomposition and short retention times for organic matter. Numerous studies have demonstrated the adverse biotic effects resulting from episodic urban discharges with suppression of ecological diversity occurring downstream of outfalls. The analysis of ecological diversity and associated community structures, together with benthic toxicity testing, provide powerful tools for assessing urban runoff impacts (Rochfort *et al.*, 2000; Ellis, 2000). However, many urban drainage studies have failed to demonstrate with any statistical certainty that water concentrations downstream of SWOs are any more toxic than upstream of the discharge. Acute toxicity tests undertaken by the Canadian National Water Research Institute (Marsalek *et al.*, 1999) on 58 stormwater and 65 CSO samples showed the majority to be nontoxic or only potentially toxic at 67% and 93% for stormwater and CSOs respectively. Similar results have been obtained in studies of highway runoff in the United Kingdom (Moy *et al.*, 2003).

The inhibition of acute toxicity observed by many stormwater studies may simply reflect the pollutant-complexing and binding effects, which occur in the presence of organic rich effluent. Genotoxicity and longer-term chronic toxicity may present more severe problems for urban waterbodies receiving stormwater runoff and CSO discharges. Bioavailability can be locally enhanced by sediment organic carbon content and pH as well as particle size, with interstitial waters being the principal route of uptake for sediment-associated contaminants. It may be the cumulative and interactive effects of water and toxic sediment quality as well as fluctuating flow and physical habitat constraints, which collectively lead to patterns of reduced biotic community status and diversity in urban receiving waters.

Public health risks The design of CSOs and SWOs means that untreated sanitary waste and contaminated effluents discharge to urban receiving waters, and it is widely recognized that urban runoff contains a wide variety and frequently high numbers of pathogenic bacteria and viruses which raise potential public health risks. During 2002, 21% of US beach closures were due to bacterial discharges associated with stormwater runoff in comparison to CSOs, which were responsible for only 1% of closures (US EPA, 2004).

Groundwater impacts There is little clear evidence of any substantial or widespread impact of urban runoff or sewer exfiltration on groundwaters (Ellis *et al.*, 2004), although both winter salting and herbicide applications in urban areas can generate levels above the drinking water standard in adjacent groundwaters.

Aesthetic deterioration Research into the public's perception of urban receiving water quality and the potential for the sustainable management of water uses for amenity, recreation, and nature conservation has shown that they generally perceive most urban rivers as being polluted, even when the chemical and ecological quality may be acceptable (House, 1996).

INTEGRATED URBAN DRAINAGE MANAGEMENT

Concepts and Main Issues

Urban discharges may cause numerous adverse effects on receiving waters with the impacts being exacerbated by traditional drainage systems and end-of-pipe solutions, which often appear to be expensive and inefficient. Increased concerns about such impacts have led to the development of new solutions based on the general concept of integrated urban water management (Figure 2), which provides a holistic integration of flood protection, water supply management and protection, groundwater quality, wastewater management, and receiving water quality. Such total urban water cycle management must be firmly linked to the question of urban sustainability (Lawrence *et al.*, 1999; Marsalek and Chocat, 2002). The emerging issue is probably to minimize the impacts of construction through better planning and design of the urban development itself. This idea is central in the concepts of low impact development (LID), sustainable development design (SDD), and "smart growth" planning (SGP). A characteristic of SDD/SGP smart growth development is a reduced footprint, leaving intervening and adjoining land available for open space, habitat development, and off-site drainage controls such as wetlands or detention basins.

Different Kinds of Actions

Sustainability implies an equilibrium among the three sets of demands; the needs of environmental protection, economic needs, and the needs of the society. So far, most attention has focused on environmental needs (e.g. attenuation of increased flows, sediment exports, chemical and bacteria fluxes). Relatively little is known about the economic and social aspects of new water and wastewater management systems needed to facilitate a full development of urban water resources to meet the needs of society. However, the introduction of sustainable principles for future urban developments being required by many regional and national planning administrations is driving new agendas and approaches for strategic urban infrastructure including the implementation of alternative drainage designs and integrated water resource management approaches, as indicated in Figure 2.

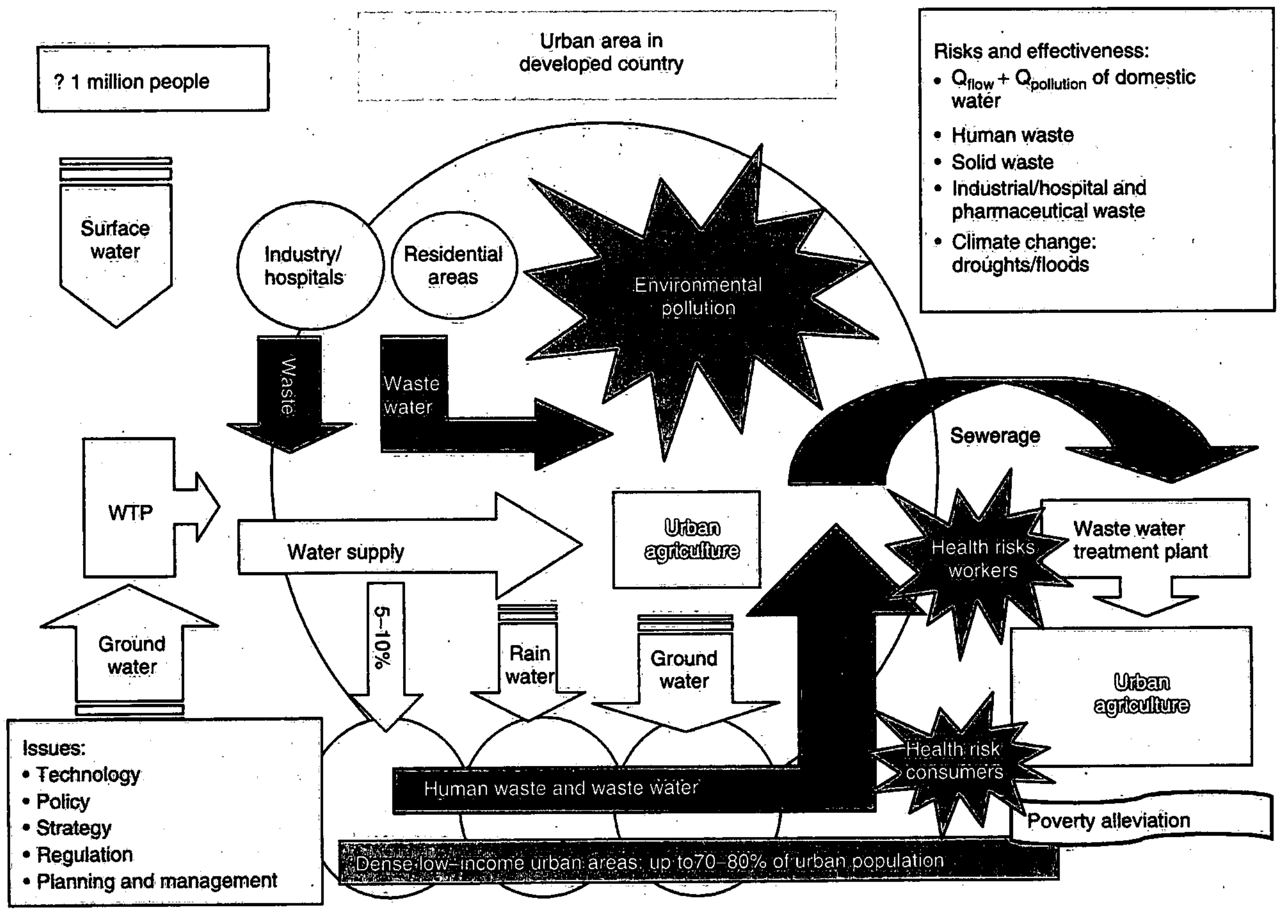

Figure 2 Sustainable urban drainage management. A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

Integrated Urban Water management implies actions at four levels, which can be referred to as follows:

1. *Policies and nonstructural controls*: These proactive measures are generally highly cost-effective, and for that reason are considered in all stormwater management plans and include public awareness/education/participation; urban development planning; management of material use, exposure, and disposal controls; spill prevention and cleanup; prevention/elimination of illegal dumping and illicit connections; and street and stormwater facilities maintenance (ASCE, 1998). These approaches require a close cooperation between planners, drainage designers, and community stakeholders from the early stages of land development.
2. *Best Management Practices* (BMPs) *for stormwater control and treatment*: These include a variety of reactive structural source and site controls offering cost-effective flow and quality control performance (**www.bmpdatabase.org**; **www.wsud.org.au**) as well as potential ecological and amenity benefits (**www.ciria.org.uk/suds**):

- Lot-level source controls; such measures include enhanced rooftop detention, flow restrictions at catchbasins to enhance local storage/detention, measures to slowdown runoff flow and enhance infiltration along with implementing stormwater harvesting and reuse.
- Local stormwater storage either on roofs or in small cisterns or reservoirs.
- Biofiltration by grass filters, swales, and pocket wetlands; these measures reduce runoff volume by infiltration and enhance runoff quality by such processes as settling, filtration, adsorption, and biouptake resulting in TSS reductions of at least 50%.
- Infiltration facilities; these BMPs serve to reduce the volume and rate of runoff, reduce pollutant transport and recharge groundwater.
- Permeable and porous pavements; introduced within urban areas in order to reduce runoff from impermeable surfaces. Total outflow TSS

concentrations for such structures are typically 10 to 20 mg L^{-1} with both solid metals and organics being reduced by 60 to 80%.

- Water quality inlets, which provide some stormwater treatment by sedimentation and skimming of floatables and oil. French and UK experience with these systems indicates very low effectiveness, except for interception of accidental oil spills with low pollutant removal rates and release of captured pollutants being reported (Bardin *et al.*, 2001).
- Filters; stormwater sand filters have been introduced in the United States with considerable success, although reports from Australia and New Zealand have been less encouraging. They are effective in removing pollutants (Urbonas, 1994), but, to maintain their effectiveness, they may have to be back-washed regularly and the risk of clogging should be reduced by stormwater pretreatment.

3. *Community-level BMPs:*

- Community infiltration facilities; these facilities comprise infiltration trenches and basins of somewhat larger scales than those provided at the site level.
- Stormwater management ponds; stormwater ponds (or wet retention basins) are used widely in Australia, Canada, Western Europe, and the United States to provide various types of controls, including flow control (reduction of flow peaks), sedimentation, and removal of dissolved pollutants by marginal aquatic plants. Outflow pollutant concentrations from these facilities are normally a function of the influent concentrations, but reductions of an order of magnitude are feasible for solids and solid-associated pollutants. Ponds may accumulate large quantities of contaminated sediments, which may be polluted with heavy metals and persistent organic pollutants, including polycyclic aromatic hydrocarbons (PAHs). Both metals and PAHs in deposited sediments may be released into the water column in response to changes in the water quality and flow-through rates.
- Constructed wetlands; wetland BMPs provide stormwater detention and treatment by various processes, including filtration, infiltration, and biosorption, and serve as cost-effective treatment systems for both particulate and dissolved pollutants.
- Extended detention (dry) basins; such basins are widely applicable and can provide stormwater settling in those areas where it is difficult to maintain wet facilities.

These BMPs are often used within multiple (treatment-train) systems. In these hybrid systems, two or more BMPs may be stacked vertically or in a series, to increase the system performance or reliability, or to reduce the maintenance. Such multiple treatment train systems are rapidly becoming the norm in new greenfield and brownfield urban developments as they provide an effective approach to full effluent treatment.

4. *Watershed-level Measures*: The watershed or catchment is a logical unit for water and wastewater management planning and forms the basis, for example, for most European drainage regulation and management. Urban drainage and stormwater management strategy should be included in watershed plans, developed in a hierarchical manner, using an ecosystem approach and providing a basis for the development of more detailed drainage management plans. Yet, in many countries, such an approach is difficult to implement efficiently since organizations involved in urban management are frequently different from those involved in watershed management. The development of new strategies or technologies is strongly impeded by economic problems (costs, financing), sociological problems (acceptance by the public, fragmentation of duties and responsibilities), urban planning challenges (integration into the landscape), organizational cooperation, problems with policies and regulations, and so on. Nevertheless, such integrated, source-control strategies represent a sustainable approach for both developed and developing countries, enabling the adverse effects of urbanization to be addressed at an affordable cost.

WATER AND WASTEWATER REUSE

Background

The concept of total water cycle management in urban areas provides a logical context for water reuse and recycling (Lawrence *et al.*, 1999). The extent to which such measures are practiced depends on water availability, economic incentives, regulatory feasibility, and public acceptance. Reuse can be either direct (reclaimed water is transported to the points of reuse), or indirect, whereby reclaimed water is first discharged into receiving waters or aquifers and then reused (see Figure 2).

Wastewater Effluent Reuse

Stormwater Reuse: Rainwater/stormwater reuse is currently practiced in many countries as a result of the widespread use of stormwater management, which often involves various forms of rainwater/stormwater reuse and thus provides double benefits – mitigation of runoff and its pollution, and provision of subpotable water supply. Typical examples of stormwater reuse include collection and reuse of residential and commercial roof runoff for irrigation or toilet flushing, collection of roof water from dome stadiums for toilet flushing and landscape irrigation, and treated stormwater reuse for industrial processes, boiler feed, or cooling waters. In stormwater reuse, the most feasible source appears to be roof runoff, which represents the source with the best water quality; other sources of stormwater, particularly runoff from streets and highways, may be too polluted and expensive to treat for reuse. Even in the case of roof runoff, there are concerns (Eriksson *et al.*, 2002) about its quality, mostly due to heavy metals (from roofing materials, depending on the rainwater pH), chemicals in dry atmospheric deposition (depending on local or remote sources and air transport), and fecal bacteria (bird droppings). Collected roof water is usually treated, using such processes as filtration, screening, settling, and UV disinfection.

Greywater Reuse: In the management of domestic wastewater, one of the options receiving much attention in recent years is the at-the-source separation into two separate flows; blackwater, or toilet waste, and greywater representing all remaining household wastewater. Greywater has been studied as an alternative source of water for nonpotable applications, including irrigation, and toilet flushing. Examples of greywater reclamation and reuse include subsurface irrigation, greywater treatment, and disinfection for toilet flushing, greywater reuse in experimental housing, and a major in-building water recycling scheme at the Millennium Dome (UK), where the system provided 55% of the water demand at the site in the form of greywater from washroom sinks, rainwater from the Dome roof, and groundwater (Hills *et al.*, 2002).

Unseparated Wastewater Reuse: General wastewater reclamation and reuse has been called "the greatest challenge of the twenty-first century" (Asano, 2002). It has the potential to bring about two great benefits – (i) provide a reliable source of water and (ii) keep wastewater pollutants out of receiving waters. Basic principles of wastewater reuse include three underpinning principles (i) providing reliable treatment corresponding to the intended reuse, (ii) protecting public health, and (iii) winning public acceptance (Asano, 2002). The approach taken to wastewater reuse depends on the intended category of reuse, with seven types of reuse commonly practiced: (i) agricultural irrigation, (ii) landscape irrigation, (iii) groundwater recharge, (iv) industrial process water, (v) environmental and recreational uses, (vi) subpotable urban uses, and (vii) indirect or direct potable reuse.

Recharge and Direct Reuse

Groundwater recharge is another large-scale application practiced by spreading/infiltration basins or direct injection to groundwater aquifers. The ideal soils for soil-aquifer treatment (SAT) balance rapid recharge (i.e. a coarse-textured soil) with efficient contaminant adsorption and removal. Recreational and environmental (ecological) uses involve nonpotable uses related to land-based water features such as the development of recreational lakes, wetlands, and stream augmentation (Asano, 2002). Nonpotable urban uses include fire protection, air-conditioning, toilet flushing, construction water, flushing of sanitary sewers, heat source or sink (in heating, air-conditioning or snowmelting), snow making, and landscape irrigation.

The most challenging category of wastewater reuse is potable reuse, practiced either by replenishment of water supply storage, or by direct input of highly treated reclaimed water into the water distribution system. Although direct reuse has been demonstrated in the City of Windhoek, Namibia (Harhoff and van der Merwe, 1996), similar applications in industrial countries are highly unlikely, mostly because of the lack of public acceptance and concerns about a safe and complete removal of new chemicals of concern (e.g., endocrine disruptors, pharmaceuticals, personal care, and therapeutic products) and pathogens from the reclaimed water (Marsalek *et al.*, 2002).

FUTURE PERSPECTIVES

Today it is generally accepted that urban surface water, groundwater, and wastewater should be considered in relation to each other and to their interactive impacts on water flows, receiving water pollution and aquatic ecology. This is recognized in the very high investment effort being made in many countries to reduce urban flooding and pollution risks and to provide sustainable urban drainage systems. Since the passage of the US Clean Water Act in 1972, the EPA, states and local water pollution control agencies have undertaken numerous actions and initiatives to reduce both CSO and SWO impacts. Some $11 billion has been invested since 1998 on injunctive relief schemes and $75 million on urban drainage improvement schemes (US EPA, 2004). The Urban Wastewater Treatment Directive and forthcoming Water Framework Directive within Europe is likewise driving stepwise improvements for urban drainage infrastructure with capital investment within the United Kingdom alone reaching £2.8 billion over the 2000–2005 period.

However, in any analysis of future trends and drivers affecting urban water systems, sustainable development is only one, albeit important, influencing factor. Population and demographic trends are of equal significance. The number of megacities with greater than 10 million inhabitants is expected to increase to over 20 by 2050 (with 80% being located in developing countries), with some 70% of the world population living in urban areas. Inevitably such large-scale urbanization has severe implications for urban water conditions and requirements, particularly given that on a global scale, only about 15% of wastewater is treated (`www.thewaterpage.com`). In western cities, although major demographic shifts including ageing populations and falling average household occupancy are likely to keep population levels relatively stable, such trends are also likely to lead to higher per capita water and wastewater infrastructure demands. The rise of consumerism, individualism, and increased disposable incomes in western societies will also generate new drivers for future water and wastewater resource supply and management as exemplified by the substantial rise in bottled water supplies, water-using domestic appliances, separated waste streams and waste recycling schemes.

A major influencing factor on future urban water resource management will be climatic change. Such change will have major implications for water resources, urban flooding, and receiving water pollution as predicted in the recent UK government Foresight Future Flooding report (OST, 2004). This analysis of urban drainage risk was conducted within the context of scenarios of differing socioeconomic futures, as depicted in Figure 3. The vertical dimension shows the system of governance, ranging from autonomy where power remains at the regional/national level to globalization or interdependence where power increasingly moves to other institutions such as the European Union. The horizontal dimension in the figure shows social values, ranging from individualistic values to community-oriented values. Central to the scenario identification is the recognition that different mechanisms of state and market regulation will influence decision-making. The driver with the greatest influence on future urban drainage was precipitation and its spatial and temporal change. Other important physical drivers were identified as urban creep, increases in groundwater infiltration, and receiving water pollution in addition to regulation, public attitudes to flooding and the ability/willingness to pay for future infrastructure improvements.

Chocat *et al.* (2004) have proposed the evolution of four possible future scenarios for urban drainage. The "green" scenario, dominated by decentralized source-control approaches with minimum sewer connections and extensive wastewater recycling and water conservation, is equivalent to the community-based, local stewardship quadrant of Figure 3. The conservative "technocratic" scenario adopting centralized advanced technology, monopolistically retained, and managed within the public sector, reflects the regionalized, national enterprise socioeconomy of Figure 3. The "privatization" scenario is clearly consumer and world market oriented and represents the predominant strategy operating within many developing countries at present. The final scenario suggested by Chocat *et al.* (2004) is that of "business-as-usual" which stumbles between the technocratic tradition and green ideas as well as picking up varying degrees of privatization.

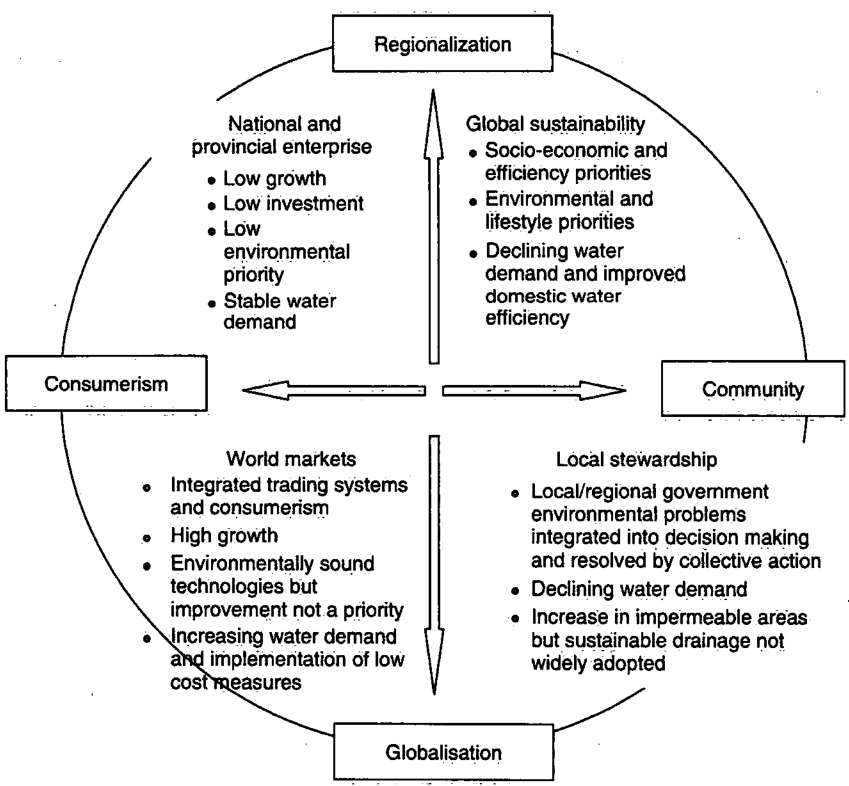

Figure 3 Socioeconomic futures

The scenario analysis approach provides no firm indication of which future might be more probable than another, although it is important to note that technical solutions do not map clearly to particular socioeconomic futures and that the high existing sunk asset value of urban drainage means that there is always likely to be considerable inertia and conservatism in the water industry. Thus, it is feasible to visualize a "no-change" (or little change) future scenario with urban water resource managers having a lack of control with respect to land use planning and chemical usage as well as being underfunded.

Alternative perspectives have been widely canvassed, with some indicating a complete revolution in future urban water systems in terms of new paradigms, new contexts, and new methodologies (Maksimovic and Tejada-Guibert, 2001). This thinking is based on the introduction of multidisciplinary, integrated approaches to urban drainage incorporating sustainable principles, the adoption of network, risk, and vulnerability analysis, complex modeling, incorporation of educational and social values as well as anticipatory and contingency scenarios for addressing new impacts such as climate change.

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