INTERNATIONAL HYDROLOGICAL PROGRAMME

Urban water cycle processes and interactions

By

J. Marsalek, B.E. Jiménez-Cisneros, P.-A. Malmquist,
M. Karamouz, J. Goldenfum and B. Chocat

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Table of Contents

FOREWORD

Continuing urbanisation leads to ever increasing concentrations of population in urban areas. General statistics indicate that of the current (2005) world population of about 6.5 billion people, more than 54% live in urban areas, and in some countries this proportion reaches 90% or more. The process of urbanisation is particularly fast in developing countries, which account for a disproportionately high number of megacities with many millions of inhabitants. Consequently, the issue of urban environmental sustainability is becoming critical, because urbanisation and its associated environmental impacts are occurring at an unprecedented rate and scope.

These concerns have long been recognised by UNESCO in their International Hydrological Program (IHP), which has addressed the role of water in urban areas, effects of urbanisation on the hydrological cycle and water quality, and many aspects of integrated water management in urban areas. The current phase of IHP (IHP 6) is seeking solutions to water resource problems in urban areas by examining the means of implementation of integrated water management in urban areas. Towards this end, UNESCO held in 2001 a Symposium on Frontiers in Urban Water Management and the resulting publication (Maksimovic and Tejada-Guibert, 2001) proposed the way forward in this challenging field. At a subsequent meeting at UNESCO Headquarters, a program comprising eight mutually related studies on urban water management was initiated by UNESCO.

This report presents results of one of those studies; its main focus is on the assessment of anthropogenic impacts on the urban hydrological cycle and the urban environment, including processes and interactions in the urban water cycle. The need for this study follows from the fact that effective management of urban waters should be based on a scientific understanding of anthropogenic impacts on the urban hydrological cycle and the environment. Such impacts vary broadly in time and space, and need to be quantified with respect to the local climate, urban development, cultural, environmental and religious practices, and other socio-economic factors. The final product of this activity should be a guidance manual on anthropogenic alterations of the urban water cycle and the environment, with reference to various climatic zones and potential climate changes.

To address the broad range of conditions in urban water management, UNESCO established a working group for this study with representatives of various professional backgrounds and experience from various climatic regions. The Working Group for the study of the urban water cycle processes and interactions comprised the following members:

Mr. Gamal Abdo, Department of Civil Engineering, University of Khartoum, Khartoum, Sudan
Mr. Bernard Chocat, INSA Lyon, Lyon, France
Mr. Joel Goldenfum, IPH/UFRGS, Porto Allegre, Brazil
Mr. K.V. Jayakumar, Water and Environment Division, Regional Engineering College, Warangal, India
Ms. Blanca Jiménez-Cisneros, Environmental Engineering Department, Institute of Engineering, Universidad Nacional Autónoma de Mexico, Mexico
Mr. Mohammad Karamouz, School of Civil Engineering, Amirkabir University (Tehran Polytechnic), Tehran, Iran
Mr. Per-Arne Malmquist, Chalmers University of Technology, Goteborg, Sweden
Mr. Jiri Marsalek, National Water Research Institute, Burlington, Ontario, Canada.

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UNESCO Secretariat: Mr. J.A. Tejada-Guibert, officer in charge of Urban Water activities of the International Hydrological Programme VI (IHP-VI) and Deputy Secretary of IHP, Mr. C. Maksimovic, adviser for the IHP Urban Water component, Ms. B. Radojevic, consultant, and Mr. W. H. Gilbrich, consultant.

Mr. W.E. Watt, Emeritus Professor, Queen's University, Kingston, Ontario, Canada, who served as an external editor of the final report.

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All the members of the Working Group for this project, and in particular, those who provided written materials:

Prof. B. Chocat – contributed to Chapter 4

Prof. J. Goldenfum – contributed to Chapters 2 and 3

Prof. B.E. Jiménez-Cisneros – contributed to Chapters 3 and 4

Prof. M. Karamouz– contributed to Chapters 2 and 3

Dr. P.-A. Malmquist – contributed to Chapter 3

Dr. J. Marsalek – contributed to Chapters 1-4 and provided report integration and editing.

Chapter 1

Urban Water Cycle

1.1 INTRODUCTION

An urban population demands high quantities of energy and raw materials, and removal of waste, some of which turns into environmental pollution. Indeed, all key activities of modern cities: transportation, electricity supply, water supply, waste disposal, heating, supply of services, manufacturing, etc., are characterised by the aforementioned problems. Thus, concentration of people in urban areas dramatically alters material and energy fluxes in the affected areas, with concomitant changes in landscape; altered fluxes of water, sediment, chemicals, and microorganisms; and, increased release of waste heat. These changes then impact on urban ecosystems, including urban waters and their aquatic ecosystems, and result in their degradation. Such circumstances make provision of water services to urban populations highly challenging, particularly in megacities, which are defined as the cities with 10 million or more inhabitants. Yet, the number of these megacities keeps growing, particularly in the developing countries, and this further exacerbates both human health and environmental problems. The growth of the number of megacities is illustrated in Table 1.1, listing megacities in 1975 and 2003, and predictions for 2015.

Table 1.1 Megacities with more than 10 million people (after Marshall, 2005)

Megacities with more than 10 million people		
1975	2003	2015
Tokyo, Japan (26.6)	Tokyo, Japan (35.0)	Tokyo, Japan (36.2)
New York, USA (15.9)	Mexico City, Mexico (18.7)	Mumbai, India (22.6)
Shanghai, China (11.4)	New York, USA (18.3)	Delhi, India (20.9)
Mexico City, Mexico (10.7)	Sao Paulo, Brazil (17.9)	Mexico City, Mexico (20.6)
	Mumbai, India (17.4)	Sao Paulo, Brazil (20.0)
	Delhi, India (14.1)	New York, USA (19.7)
	Calcutta, India (13.8)	Dhaka, Bangladesh (17.9)
	Buenos Aires, Argentina (13.0)	Jakarta, Indonesia (17.5)
	Shanghai, China (12.8)	Lagos, Nigeria (17.0)
	Jakarta, Indonesia (12.3)	Calcutta, India (16.8)
	Los Angeles, USA (12.0)	Karachi, Pakistan (16.2)
	Dhaka, Bangladesh (11.6)	Buenos Aires, Argentina (14.6)
	Osaka-Kobe, Japan (11.2)	Cairo, Egypt (13.1)
	Rio de Janeiro, Brazil (11.2)	Los Angeles, USA (12.9)
	Karachi, Pakistan (11.1)	Shanghai, China (12.7)
	Beijing, China (10.8)	Metro Manila, Philippines (12.6)
	Cairo, Egypt (10.8)	Rio de Janeiro, Brazil (12.4)
	Moscow, Russian Federation (10.5)	Osaka-Kobe, Japan (11.4)
	Metro Manila, Philippines (10.5)	Istanbul, Turkey (11.3)
	Lagos, Nigeria (10.1)	Beijing, China (11.1)
		Moscow, Russian Federation (10.9)
		Paris, France (10.0)

Conflicting demands on resources necessitate integrated management of the urbanisation process, which is a most challenging task. Within this complex setting, this report focuses on the management urban waters, recognising that effective management of urban waters should be based on a scientific understanding of anthropogenic impacts on the urban hydrological cycle and the environment, and the means of mitigation of such impacts, and full recognition of the socio-economic system. Urbanisation impacts vary broadly in time and space, and need to be quantified with respect to the local climate, urban development, engineering and environmental practices, cultural religious practices, and other socio-economic factors.

Analysis of urban water management should be based on the urban water cycle, which provides a unifying concept for addressing climatic, hydrologic, land use, engineering, and ecological issues in urban areas. Furthermore, it was felt that the analysis of the urban water cycle would be conducive to a later examination of modern approaches to water management in urban areas, including total urban water cycle management. In this approach based on water conservation, integrated management measures are implemented, including integrated management and reuse of stormwater, groundwater, and wastewater.

The report that follows represents the first step of a comprehensive project and aims to develop a schematic representation of the urban water cycle (UWC), including the environmental components, and identify the major fluxes of water, sediment, chemicals, microorganisms, and heat, with reference to urban waters. Such a scheme may be presented in many variations reflecting various climatic conditions, both the current and the future ones (i.e., considering climate change). In the subsequent study phases, it is expected that these fluxes will be quantified and described by water balance/quality models approximating such processes. Connection between urban development and these fluxes will be established, and principles for low impact developments and restoration of the existing areas will be established. Some of the intermediate steps/results in the overall study include: (a) identification of the components of the urban water cycle and the effects of urbanisation on water resources, (b) quantification of the imprint of human activities on the urban hydrological cycle and its interaction with the environment under the present and future development scenarios, (c) understanding of the processes at the urban water and soil interface, including the water and soil interaction, with particular reference to soil erosion, soil pollution and land subsidence, (d) hydrological, ecological, biological and chemical processes in the urban water environment of sustainable cities of the future, (e) assessment of the impact of urban development, land use and socio-economic changes on the availability of water supplies, aquatic chemistry, (anthropogenic) pollution, soil erosion and sedimentation and natural habitat integrity and diversity, and, (f) assessment of the preventive and mitigation measures available for dealing with urban water problems.

The final product of this activity should be a guidance manual on anthropogenic alterations of the UWC and the environment, with reference to various climatic zones and potential climate changes. This manual should advance (a) the understanding of processes that take place in the urban environment, and of the interactions of natural suburban, rural and urban environments for the successful analysis, planning, development and management of urban water systems, (b) development of innovative analytical tools for addressing the problems of spatial and temporal variability, and (c) assessment of the potential effects of climate variations and changes on urban water systems.

1.2 URBAN WATER CYCLE CONCEPT

One of the most fundamental concepts in hydrology and indeed in the water resource management is the hydrologic cycle (also referred to as the water cycle), which has been speculated on since ancient times (Maidment, 1993). There is some diversity of definitions of the hydrological cycle, but generally it is defined as a conceptual model describing the storage and circulation of water between the biosphere, atmosphere, lithosphere, and the hydrosphere. Water can be stored in the atmosphere, oceans, lakes, rivers, streams, soils, glaciers, snowfields, and groundwater aquifers. Circulation of water among these storage compartments is caused by such processes as evapotranspiration, condensation, precipitation, infiltration, percolation, snowmelt and runoff, which are also referred to as the water cycle components.

Combined effects of urbanisation, industrialisation, and population growth affect natural landscapes and hydrological response of watersheds. Although many elements of the natural environment are affected by anthropogenic factors with respect to pathways and hydrologic abstractions (or sources of water), the principal structure of the hydrological cycle remains intact in urban areas. However, the hydrologic cycle is greatly modified by urbanisation impacts on the environment and the need to provide water services to the urban population, including water supply, drainage, wastewater collection and management, and beneficial uses of receiving waters. Thus, it was noted that the hydrological cycle becomes more complex in urban areas, because of many anthropogenic influences and interventions (McPherson, 1973; McPherson and Schneider, 1974); the resulting "urban" hydrological cycle is then called urban water cycle (UWC). The urban water cycle is shown pictorially in some detail in Fig. 1.1 and schematically in Fig. 1.2, which displays just the major components and pathways.

The urban water cycle provides a good conceptual and unifying basis for studying the water balance (also called the water budget) and conducting water inventories of urban areas. In such studies, the above listed major components of the hydrological cycle are assessed for certain time periods, with durations exceeding the time constants of the system to filter out short-term variability. Water balances are generally conducted on seasonal, annual, or multi-year bases (van de Ven, 1988), and in planning studies, such balances are projected to future planning horizons. This approach is particularly important for urban planning (i.e., providing water services to growing populations) and for coping with extreme weather and climatic variations and potential climate change. In fact, an understanding of water balances is essential for integrated management of urban water, which strives to remediate anthropogenic pressures and impacts by intervention (management) measures, which are applied in the so-called total management of the urban water cycle (Lawrence et al., 1999).

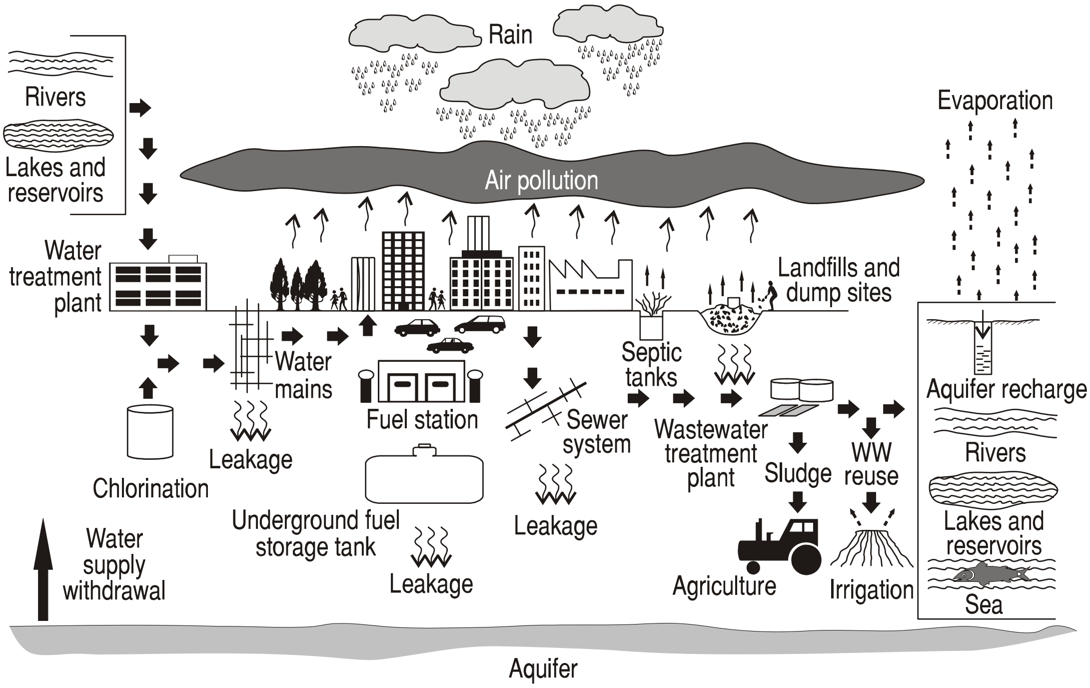


Fig. 1.1 Urban water cycle

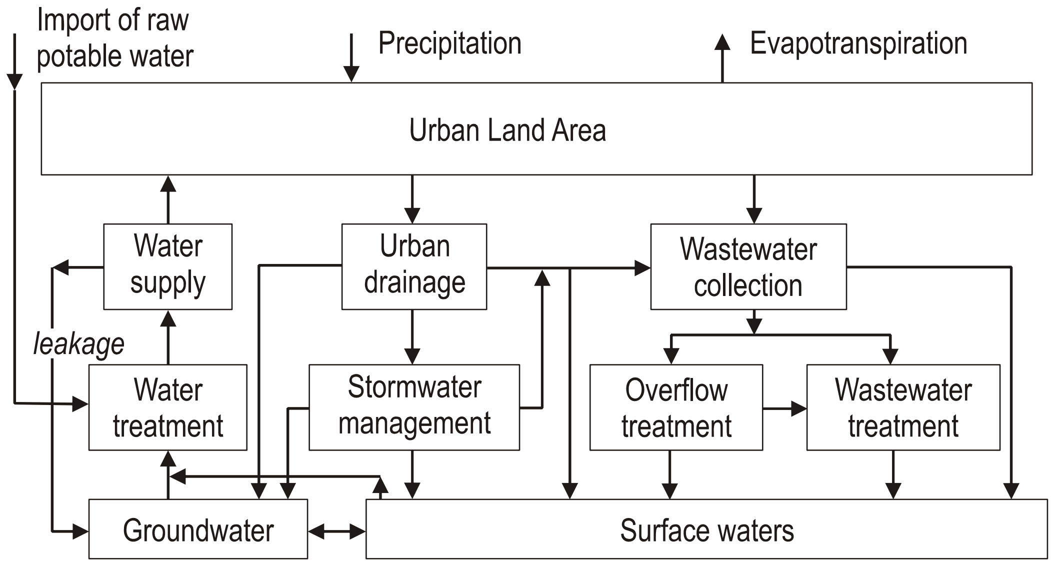


Fig. 1.2 Urban water cycle – main components and pathways

Thus, water, sediment and chemical balance studies help establish and quantify the urban water cycle, by addressing such issues as verification of pathways in the cycle; quantifying flows and fluxes of sediment and chemicals along the pathways; assessing component variations; and, assessing impacts of climatic, population and physiographic changes on the urban water cycle (UWC). Examples of urban water balances were offered by Hogland and Niemczynowicz (1980) and van de Ven (1988). A brief description of principal components of the urban water cycle follows.

Two main sources of water are recognised in the UWC, municipal water supply and precipitation. Municipal water is often imported from outside the urban area or even from another catchment in widely varying quantities reflecting local water demands and their management. Municipal water may bypass some pathways in the UWC; it is brought into the urban area, distributed within the area, some fraction is lost to urban groundwater, and the rest is used by the population, converted into municipal wastewater, and eventually returned to surface waters. The second source, precipitation, generally follows a longer route through the water cycle. It falls in various forms over urban areas, is subject to hydrologic abstractions (including interception, depression storage, and evapotranspiration), partly infiltrates into the ground (contributing to soil moisture and recharge of groundwater) and is partly converted into surface runoff, which may be conveyed to receiving waters by natural or constructed conveyance systems. With various success and accuracy, flow components were quantified for urban areas in studies of urban water balances (Hogland and Niemczynowicz, 1980).

Besides these clearly established (intentional) linkages among the various water conveyance and storage elements, others (unintentional) may also develop (e.g., water main leaks, sewer exfiltration) and have to be addressed in water management.

In addition to flow components of the urban water cycle, attention needs to be paid to the fluxes of materials and energy conveyed by air, water or anthropogenic activities. In general, these processes are less well known and quantified than those dealing with water only, and their description in urban areas is complicated by numerous remote and local sources and high variability in time and space. With respect to atmospheric pollutants conveyed in wet form with precipitation and dry form as gases and particulates, Novotny and Olem (1994) identified the major pollutants as acidity (originating from nitrogen and sulfur oxides emitted from fossil-fuel combustion), trace metals, mercury and agricultural chemicals (particularly pesticides and herbicides). These chemicals may fall directly into receiving waters, or be deposited on catchment surfaces and subject to scouring and transport into receiving waters during wet weather.

Other pollution sources include land use activities and poor housekeeping, including transportation, construction activities, use of building materials, road maintenance, attrition or elution or corrosion of hard surfaces, soil erosion, urban wildlife (particularly birds) and pets, deficient solid waste collection, and others. Besides direct deposition into urban waters (generally of secondary importance because of small water surface areas), these materials may be washed off and transported by urban runoff as dissolved or suspended pollutant loads, or as a bedload. During the transport, depending on hydraulic conditions, settling and re-suspension takes place on the catchment surface and in pipes, as well as biological and chemical reactions. These processes are often considered to be more intense in the initial phase of the storm (first flush effect); however, due to temporal and spatial variability of rainfall and runoff flow, first flush effects are more pronounced in conveyance systems with pipes rather than on overland flow surfaces.

While past studies of urbanisation and water management, particularly in developed countries, focused on science and engineering, there is growing recognition of the importance of the social conditions and links between the socio-economic system and the water and the environment (Lundqvist et al., 2001). Furthermore it is recognised that sustainable solutions to water related problems must reflect the cultural (emotional, intellectual, and moral) dimensions of people's interactions with water. Culture is a powerful aspect of water resources management. Water is known as a valuable blessing in most of the arid or semiarid countries and most religions. There are two cultural aspects that cause direct impacts on water resources management in urban areas: urban architecture and people's life style.

Traditional architecture in urban areas often reflects the climate characteristics of the area. However, the traditional architecture in many large cities is being replaced by modern "western" architecture because of population increase and globalisation, with concomitant changes in urban hydrology. The density of the population and buildings, rainwater collection systems, material used in construction, and wastewater collection systems are major factors among others that cause changes in the urban hydrologic cycle.

Life style in urban areas affects the hydrologic cycle through the changes in domestic water demands. Domestic water use per capita and water use in public areas such as parks and green areas are the main characteristics that define the lifestyle in large cities. Even though the economic factors are important for determining these characteristics, the pattern of water use, tradition and culture have more significant effects on the life style in urban areas.

1.3 TOTAL MANAGEMENT OF THE URBAN WATER CYCLE

The concept of the urban water cycle demonstrates the connectivity and inter-dependence of urban water resources and human activities, and the need for integrated management. Towards this end, the concept of total urban water cycle management was introduced in Australia and further elaborated on by Lawrence et al. (1999). The basic water management categories encompassed in this approach include:

- reuse of treated wastewater, as a basis for disposing potential pollutants, or a substitute for other sources of water supply for sub-potable uses;
- integrated stormwater, groundwater, water supply and wastewater based management, as the basis for: economic and reliable water supply; environmental flow management (deferment of infrastructure expansion, return of water to streams); urban water-scape/landscape provision; substitute sub-potable sources of water (wastewater and stormwater reuse); and, protection of downstream waters from pollution; and,
- water conservation (demand management) based approaches, including: more efficient use of water (water saving devices, irrigation practices); substitute landscape forms (reduced water demand); and, substitute industrial processes (reduced demand, water recycling).

While many of these measures have been practiced in the past, what has been missing was the understanding of the linkages among the various components, and the implication of the practices for long-term quality of groundwater, soils, and environmental flows.

Finally, it should be emphasised that the concept of the urban water cycle and of its total management applies to all climatic, physiographic, environmental, and socio-cultural conditions, and the levels of development, with appropriate modifications. Naturally, depending on local circumstances, different measures may attain different priorities, but the general principle of identifying the main sources of water, sediments, chemicals and biota, the applicable pathways or changes, and intervention measures, serving the integrated management of natural resources, remain the same and will be explored in the following chapters.

Referring to Fig. 1.2, the discussion of UWC is organized accordingly: after a general introduction of the UWC concept in Chapter 1, hydrological components of UWC are addressed in Chapter 2, urban infrastructure and water services in Chapter 3, and urbanisation effects on the environment in Chapter 4.

Chapter 2

Urban Water Cycle Hydrologic Components

Urbanisation contributes to changes in the radiation flux and the amount of precipitation, evaporation and evapotranspiration, infiltration into soils, and consequently causes changes in the hydrological cycle. The effects of large urban areas on local microclimate have long been recognised and occur as a result of changes in the energy regime, air pollution, and air circulation patterns caused by building and/or transformation of land cover. The changes in the rainfall-runoff components of the hydrologic cycle can be summarised as follows:

- transformation of undeveloped land into urban land (including transportation corridors),
- increased energy release (i.e., greenhouse gases, waste heat, heated surface runoff), and
- increased demand on water supply (municipal and industrial).

Fig. 2.1 shows rainfall-runoff components of the hydrologic cycle. Each of these components and the related processes are briefly explained in the following section; detailed descriptions can be found elsewhere (Viessman et al., 1989).

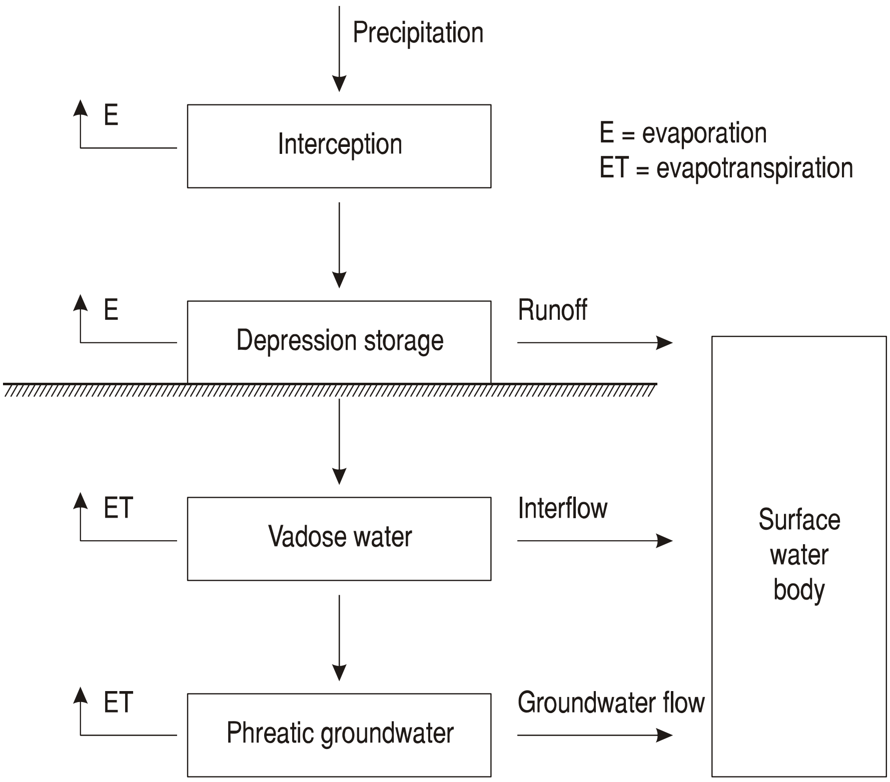


Fig.2.1 Rainfall–runoff components of hydrologic cycle

Further discussion of urbanisation impacts on water resources is presented in Chapters 3 and 4

2.1 WATER SOURCES

2.1.1 Municipal water supply

Two main sources of water in urban areas are recognised, municipal water supply and precipitation. Municipal water is often imported from outside of the urban area (or even outside the watershed in which the urban area is located), in quantities ranging from 50 to 700 L/capita/day, as demanded by municipal water users. Municipal water use is usually categorised as residential, commercial, industrial and "other" water demands, where "other" includes water lost through leakage, unaccounted for water uses (e.g., fire fighting and distribution system flushing), and water not assigned to the above three categories. Thus, the quantity of imported water depends largely on the population served by municipal water supply systems, and on institutional, commercial and industrial activities. Import of water supply (particularly from other catchments) represents a major influence on the urban water cycle; with typical urban water uses being non-consumptive, most of the imported water is discharged into groundwater (contributing to rising groundwater tables) or local receiving bodies as wastewater effluents with major impacts on such water resources. Under some circumstances, some of the sub-potable water demands can be supplied by reused or recycled water, thus conserving potable water sources (see Section 3.4.8). Furthermore, the water provided through municipal water supply systems may be locally consumed, or exported as virtual water in various products, or used in ground irrigation, or converted into wastewater, which may or may not be treated prior to discharge into receiving waters. A more detailed discussion of water supply is presented in Chapter 3.

2.1.2 Precipitation

The second important source of water is precipitation, which occurs in greatly varying quantities depending on local climate. The effects of large urban areas on local microclimate have long been recognised (Geiger et al., 1987); these occur as a result of changes in the energy regime, air pollution, and air circulation patterns, which are caused by buildings, land transformations, and by release of greenhouse gases. These factors contribute to changes in the radiation balance and the amounts of precipitation and evaporation, and consequently to changes in the hydrologic cycle. Such effects, with respect to changes in annual precipitation, air temperatures, and evaporation rates are also described in Section 4.3.

2.1.2.1 Climatic aspects

Climate is defined as the long-term behaviour of the weather in a region. The hydrologic processes in different climates are affected by the hydrometeorological variables, which attain different ranges of magnitude in different climates. There are four world climate categories corresponding to subtropical, continental, rain-shadow, and cool coastal arid lands.

Subtropical areas (e.g., Sahara, Arabia, Australia, and Kalahari) are characterised by clear skies with high temperatures. The summers are hot and the winters are mild, so the seasonal contrasts are evident with low winter temperatures due to freezing. Convective rainfalls develop only when moist air invades the region.

Continental interior areas (e.g., arid areas of Asia and western USA) have seasonal temperatures ranging from very cold winters to very hot summers. Snow can occur. Rainfall in the summer is unreliable in this climate.

Rain-shadow areas (mountain ranges such as the Sierra Nevada, the Great Dividing Range in Australia and the Andes in South America) are characterised by conditions similar to those in continental areas with diverse behaviour, but their climatic conditions are not as extreme as in the continental interior areas.

Cool coastal areas (e.g., the Namib Desert on the south-western coast of Africa and the Pacific coast of Mexico) have reasonably constant climatic conditions with a cool humid environment. When temperate inversions are weakened by upward moving moist air, thunderstorms can develop.

Arid climate is one of the more important climate types of the world. Rozanov (1994) suggested that the major cause of aridity was explained through the global atmospheric circulation patterns, with certain local effects imposed by topography; Thompson (1975) listed four main processes explaining aridity: (a) high pressure, (b) wind direction, (c) topography, and (d) cold ocean currents.

The majority of semi-arid and arid regions are located between latitudes 25 and 35 degrees, where high pressure causes warm air to descend, resulting in dry stable air masses. Aridity caused by orographic causes is common in North and South America, where high mountain ranges are perpendicular to the prevailing air mass movements. These air masses are cooled as they are forced up the mountains, reducing their water holding capacity. Most of the moisture is precipitated at high elevations of the windward slopes. The relatively dry air masses warm up as they descend on the leeward side of the mountain ranges, increasing their water-holding capacity and reducing the chance of any precipitation. This orographic aridity is referred to as the rain shadow effect (Dick-Peddie, 1991). The positioning over a continent where distance from oceans lessens the chance of encountering moisture-laden air masses is the cause of the semiarid and arid conditions in central Asia. Cold ocean currents cause the coastal arid regions of Chile and Peru and the interior part of northern Argentina, where cold ocean currents in close proximity to the coast supply dry air that comes on shore, but as the mass is forced up the mountain sides there is no moisture to be lost as the air mass cools. The desert climate is another important arid climate of the world.

2.1.2.2 Urban precipitation

Precipitation represents one of two primary water inputs to the urban water cycle and is derived from atmospheric water. Recognising that large amounts of water may accumulate in clouds without precipitation, the processes of condensation and precipitation are sometimes considered individually. Among the various causes of condensation, dynamic or adiabatic cooling is the most important cause, which produces nearly all precipitation. The condensation of water vapour into droplets occurs on condensation nuclei, whose occurrence is related to air pollution. Large urban areas affect the local microclimate as a result of changes in the energy regime, air pollution (providing condensation nuclei), air circulation patterns, and releases of greenhouse gases (Marsalek et al., 2001). Earlier studies have shown that total annual precipitation in, or downwind of, large industrialised cities is generally 5-10% higher than in the surrounding areas, and for individual storms, this increase in precipitation can be as high as 30%, particularly on the downwind side of large metropolitan areas (Geiger et al., 1987). Further changes are expected as a result of climate change, with global circulation models predicting either increasing or decreasing precipitation, depending on the specific location, and greater climatic variability with more pronounced extremes (Van Blarcum et al., 1995).

Among the various forms of precipitation, convective storms with high rainfall intensities are particularly important in the design of urban minor drainage elements or infrastructure (the sizing of conveyance elements), cyclonic precipitation may be more important in design of major drainage and storage facilities.

While climates were traditionally considered as either non-varying or changing very slowly, recent research on greenhouse effects indicates some imminent climate changes. Solar radiation reaching the earth is partly absorbed by the earth, but a substantial part is reflected back into space. The heat absorbed is radiated by the earth as infrared radiation. The greenhouse gases such as water vapour, carbon dioxide, methane, nitrous oxides, etc. absorb the infrared radiation and in turn re-radiate it in the form of heat. The amount of greenhouse gases in the atmosphere is increasing due to anthropogenic activities (Houghton et al., 1996). Thus, the emission of greenhouse gases contributes to climate change. It is forecasted that increased greenhouse gas concentration will lead to increasing average temperature, by 3-5°C in some regions by the year 2050. As concentrations of greenhouse gases increase even more, further climate changes can be expected. In urban areas, which are affected by global climate changes, some researchers suggest that the magnitude of the effects of changing climate on water supplies may be much less important than changes in population, technologies, economics or environmental regulations (Lins and Stakhiv, 1998).

Air temperature is also of interest in studies of precipitation, because it determines the form of precipitation (e.g., rain or snow). The urban heat island effect increases air temperatures over urban areas by as much as 4-6°C, compared to surrounding localities (see Section 4.3.1). These thermal phenomena then explain higher evaporation rates (by 5-20%) in urban areas (Geiger et al., 1987) and other related effects.

2.2 HYDROLOGIC ABSTRACTIONS

The most important component of the UWC with respect to drainage and flood protection is stormwater runoff. To determine runoff, one needs to consider water input (i.e. rainfall or snowmelt), hydrologic abstractions (sometimes called losses), and the routing of net water input in the catchment. Such routing is strongly affected by storage, which modifies the inflow hydrograph. A brief overview of such processes follows.

A significant fraction of precipitation is returned to the atmosphere by evaporation or evapotranspiration, depending on local landscape and water resources. The remaining water may infiltrate into the ground (recharging groundwater), or be converted into runoff and streamflow. Generally, rainwater infiltration in urban areas is reduced by high imperviousness of urban areas and this contributes to increased runoff and higher risk of flooding and erosion in receiving streams (Marsalek, 2003a). Reduced hydrologic abstractions and increased surface runoff are recognised as typical impacts of urbanisation on the hydrologic cycle (Leopold, 1968). Furthermore, urban runoff becomes polluted during overland flow and transport in storm or combined sewers, and consequently exerts water quality impacts on the receiving waters (Marsalek, 2003a). Therefore, during the last 30 years, stormwater management has been introduced, with the main goal of reducing anthropogenic impacts on the hydrologic cycle and mobilisation and transport of sediments and pollutants. Typical stormwater management measures are discussed later in Chapter 3.

2.2.1 Interception

Interception is defined as that part of water input that wets and adheres to above ground objects until it evaporates and returns to the atmosphere (Viessman et al., 1989). Water abstractions by interception are particularly important in vegetated (forested) catchments, where the amount intercepted depends on species, age and density of the vegetation, storm event characteristics, and the season of the year (Geiger et al., 1987). Interception abstractions occur early during rain storms and quickly diminish. In urban areas with low tree cover, interception is insignificant and often neglected. Although there are formulae for calculating interception as a function of rainfall and vegetation characteristics (Chow, 1964), the estimated interception if often included in the initial abstraction and deducted from the storm rainfall (Geiger et al., 1987). Traditional urban development with high imperviousness and low vegetation or tree cover reduces interception and its importance in urban runoff analysis.

2.2.2 Depression storage

Depression storage (also called surface storage) accounts for water that is trapped in small depressions on the catchment surface and retained until it infiltrates or evaporates. In some hydrology handbooks, wetting abstractions (i.e., water used for the initial wetting of catchment surface) are combined with depression storage and called the initial abstraction (Geiger et al., 1987). Depression storage depends on catchment surface characteristics, including the type of surface and its slope. On impervious urban surfaces, depression storage ranges from 0.2 mm (smooth asphalt pavement) to 2.8 mm (an average value for small urban areas); on pervious surfaces, depression storage ranges from 0.5 mm (bare clay) to 15 mm (wooded areas and open fields). The relative significance of depression storage depends on the storm rainfall (or snowmelt); the larger the rainfall, the less significant is depression storage in stormwater runoff calculations. A detailed listing of depression storage values for more than 25 types of surfaces can be found in Geiger et al. (1987).

2.2.3 Evaporation and evapotranspiration

Evaporation is the process occurring along the water-air or soil-air interface by which water in liquid or solid state transforms into water vapour escaping into the atmosphere. Higher rates of energy consumption and higher air temperatures in cities contribute to higher rates of evaporation in urban areas (by 5-20%) (Geiger et al., 1987). Transpiration is the process of vaporisation of water at the surface of plant leaves after the soil water has been transported through the plant (Overton and Meadows, 1976). For simplification, the process of transpiration is sometimes combined with evaporation from water and soil surfaces into evapotranspiration, which can be estimated by the Penman equation (Viessman et al., 1989). Furthermore, it is commonly assumed that water supply to these processes is not limited which permits the treatment of evapotranspiration at its potential rate (Geiger at el., 1987). Land use changes in urban areas lead to a reduced extent of green areas in cities and thereby contribute to reduced total transpiration from trees and vegetation. While evaporation and evapotranspiration are important in water budget calculations (note that in the Sahelian zone, the daily evaporation can be as high as 15 mm/day), during urban stormwater runoff, both abstractions are rather small and justifiably neglected.

2.2.4 Infiltration

Infiltration is the process of water movement into the soil under gravity and capillary forces. Through this process, shallow aquifers are recharged and, by discharging to surface waters, contribute to streamflow during dry periods. Two basic approaches to describing infiltration include a soil physics approach relating infiltration rates to detailed soil properties (e.g., hydraulic conductivity, capillary tension and moisture content) and a hydrological approach, which is parametric and utilises lumped soil characteristics to estimate infiltration rates. The latter approach is commonly used in urban runoff calculations. For more information on infiltration calculations methods used commonly in urban runoff modelling (Horton, Green-Ampt, Philip, and Holtan approaches) see Viessman et al. (1989).

Compared to natural areas, infiltration rates decrease in urban areas because of the following factors:

- increased imperviousness of urban catchments (pavements, rooftops, parking lots, etc.),
- compaction of soils in urban areas, and
- presence of a man-made drainage system providing for quick removal of ponded water, without allowing water enough time to infiltrate into the ground.

In the first in-depth analysis of the urban hydrological cycle provided by Leopold (1968), it was noted that increased imperviousness of urban catchments contributed to lower infiltration and thereby to reduced groundwater recharge, reduced interflow/baseflow, and higher rates of surface runoff. Higher rates of runoff then contribute to higher incidence of flooding. However, recent studies indicate that urbanisation may result in a net gain in overall groundwater recharge, mostly because of losses from water supply mains, leaking sewer systems, and stormwater infiltration (Lerner, 2004).

2.2.5 Lumped hydrologic abstractions

In some empirical procedures for runoff calculation, hydrological abstractions are lumped into empirical coefficients. Examples of such approaches include the runoff coefficient, which applies to the runoff peak flow, the Φ-index applied to pervious areas and accounting for interception, evaporation, wetting, depression and infiltration abstractions (Chow, 1964), and the runoff curve number method of the Soil Conservation Service (SCS) (U.S. Department of Agriculture, SCS, 1975).

2.3 WATER STORAGE

Water infiltrating into the ground contributes to soil moisture and to groundwater recharge.

2.3.1 Soil moisture

Large parts of urban areas are covered by impervious surfaces, reaching the imperviousness of 100% in downtown areas, and resulting in reduced infiltration and evapotranspiration, because of reduced vegetated areas. Consequently, the vadose zone in urban areas differs significantly from that in natural areas. Another factor contributing to changes in soil moisture in urban areas is a partial removal of topsoil during the urban development and construction, and changes in soil structure resulting from the use of heavy machinery. After development, less topsoil may be returned and lower soil layers may have been compacted, with reduced soil moisture storage and greater need for irrigation.

2.3.2 Urban groundwater

Urbanisation affects not only surface waters, but also groundwater, with respect to both its quantity and quality. The state of groundwater then impacts on the water balance of an urban area and on the operation of the urban infrastructure, including storm, sanitary and combined sewers, stormwater management facilities, and sewage treatment plants. A detailed analysis of urban groundwater and its pollution can be found in Lerner (2004); a brief introduction of the groundwater issues is included here for the sake of completeness.

Groundwater can be characterised according to its vertical distribution into two zones, the zone of aeration and the zone of saturation (below the water table). The zone of aeration is divided, from top to bottom, into the soil-water, vadose and capillary zones (Todd, 1980). In urban areas, groundwater interacts with surface waters and urban infrastructure, and is further affected by land use activities. An Internet-based Urban Groundwater Database (www.utsc.utoronto.ca/~gwater/IAHCGUA/UGD/) indicates that urban groundwater issues and problems vary depending on the climate, urban area, land use activities, environmental practices, and other local conditions. In drier climates and developing countries, the typical trend is toward overexploitation of groundwater for municipal and industrial water supply, with the resulting lowering of groundwater table, land subsidence, salt water intrusion in coastal areas, and groundwater pollution. In developed countries, urban aquifers are generally not used for water supply; the water tables may still decline due to insufficient recharge caused by high imperviousness of urban areas. Less commonly, urban water tables may be rising due to low withdrawal of groundwater and leakage from water mains (e.g., Nottingham, UK). In all urban areas, the occurrence of pollution from various sources has been reported (Lerner, 2004).

2.4 STORMWATER RUNOFF

Changes of runoff regime represent one of the most significant impacts of urbanisation. Urbanisation affects surface runoff in three ways: (a) by increasing runoff volumes due to reduced rainwater infiltration and evapotranspiration, (b) by increasing the speed of runoff, due to hydraulic improvements of conveyance channels, and (c) by reducing the catchment response time and thereby increasing the maximum rainfall intensity causing the peak discharge. Thus urbanisation changes the catchment hydrologic regimen. These changes were quantified in the literature, with the mean annual flood increasing from 1.8 to 8 times, and the 100-year flood increasing from 1.8 to 3.8 times, due to urbanisation (Riordan et al., 1978). Stormwater direct runoff volume increased for various return periods up to 6 times. In general, the magnitude of such increases depends on the frequency of storms, local climate and catchment physiographic conditions (soils, degree of imperviousness, etc.), as partly illustrated in Fig. 2.2. Fig. 2.3 then shows two runoff hydrographs from the same catchment – before and after urban development. The figure demonstrates changes in the runoff hydrograph caused by urbanisation. As discussed later in Section 3.3.2.2, the post-development runoff peak can be controlled by storage. Note that storage reduces the peak, but not the volume of runoff, which contributes to increased runoff flows over extended time periods, with concomitant effects on channel erosion in downstream areas (see Section 4.4.1.2).

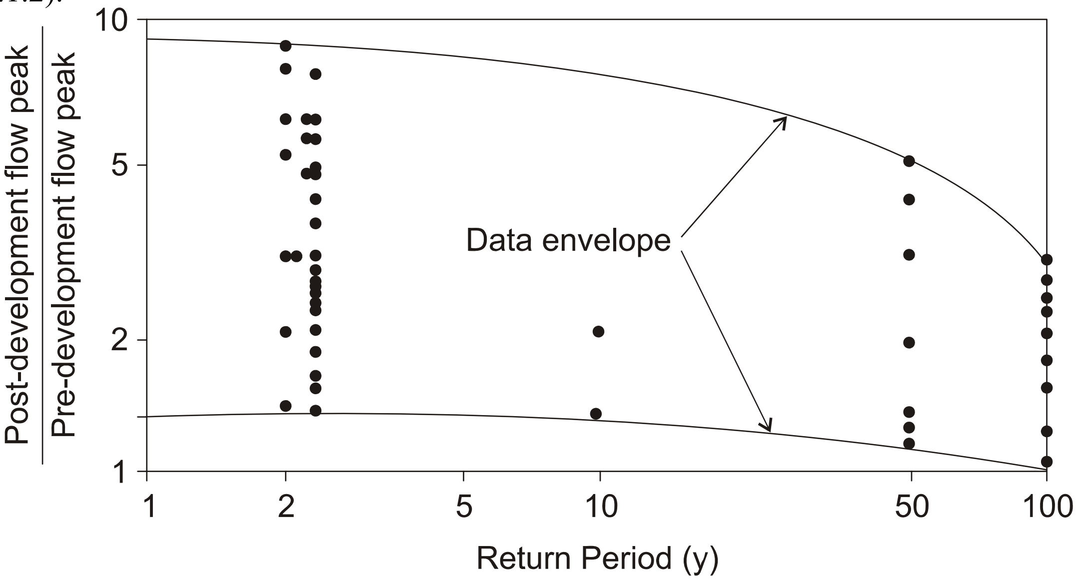


Fig. 2.2 Effects of watershed development on flood peaks (Marsalek, 1980)

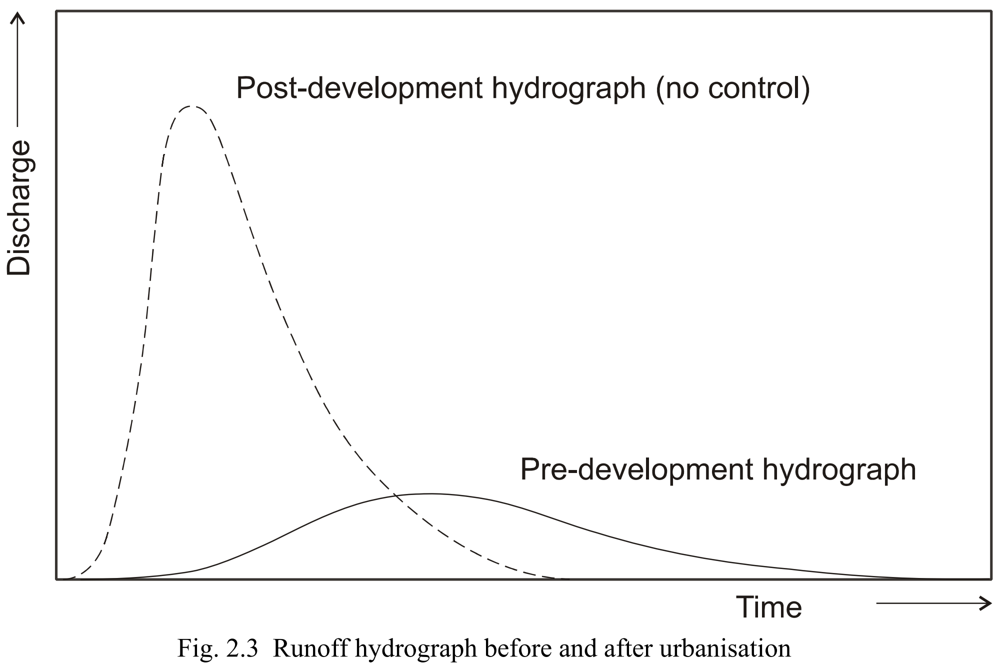


Fig. 2.3 Runoff hydrograph before and after urbanisation

2.5 INTERFLOW AND GROUNDWATER FLOW

Reduced infiltration due to high imperviousness of urban catchments should contribute to smaller interflows. However, the situation is more complicated in urban areas because of another source of water to shallow aquifers - leakage from water distribution and wastewater collection networks. Leakage from water mains is particularly important, because such pipes are pressurised. Even low water losses, expressed as 15% of volume input, provide water volumes equivalent to groundwater recharge by several hundred millimetres of rainfall (Lerner, 2004). Exfiltration from leaky sewer pipes depends on the relative positions of sewers and the groundwater table, which determines the direction of water transport and may vary in time. Leaky sewers in dry soils will function as a source of groundwater, but leaky sewers below the groundwater table will drain aquifers and convey this flow to sewage treatment plants. Finally, other sources of inputs to groundwater are stormwater infiltration facilities, which are applied in modern stormwater management. Such facilities include porous or permeable pavements, permeable manholes, drainage swales, and infiltration wells, trenches and basins.

There may be also an influx of groundwater into the urban area, or into municipal sewers (Hogland and Niemczynowicz, 1980), and such waters may contribute to increased volumes of municipal sewage treated at the local plant and the effluent discharged into receiving waters.

2.6 NATURAL DRAINAGE: URBAN STREAMS, RIVERS AND LAKES

The final components of the urban water cycle are sinks, in the form of receiving waters representing elements of the natural drainage system. Two types of receiving waters are commonly recognised, receiving surface waters and groundwater. In both cases, there are conflicts arising from multiple water uses. Receiving waters generally provide beneficial water uses, including source water for water supply, fishing, recreation and ecological functions (e.g., aquatic habitat), but they also serve to transport/store/purify urban effluents conveying pollution. Similar conflicts were reported for groundwater, which may serve for water supply as well as (often unintentionally) for disposal of some pollutants. Thus, to protect downstream water uses, it is necessary to manage urban effluents with respect to their quantity and quality, in order to lessen their impact on water resources.

Wastewater from various municipal sources, including residential, commercial, industrial and institutional areas is collected by sewers or open drains and conveyed to treatment facilities, or discharged directly into receiving waters. Depending on local climate and population density, on an annual basis, the municipal effluent volume may exceed the volume of stormwater runoff from the urban area.

In urban drainage design, urban streams are considered as elements of the major drainage system, and are often modified to accommodate increased flows resulting from urbanisation. The situation concerning urban lakes is similar, with urbanisation changing their hydrological regime. In most cases, however, the main water management challenge is dealing with the water quality impairment (particularly siltation of streams and eutrophication of lakes), as discussed further in Chapter 4.

2.7 NEEDS FOR URBAN WATER INFRASTRUCTURE

Extensive changes of the hydrological regime in urban areas have been historically managed by building an urban infrastructure, starting with water supply aqueducts, followed by stormwater and sewage collection, and eventually sewage treatment plants. Such systems providing water services, including water supply, drainage and sewage management, then in turn interactively affect the hydrological cycle in urban areas. For example, import of drinking water into urban areas changes the urban water budget, particularly through leakage from water mains into urban aquifers. Increased stormwater runoff has to be managed in urban areas, sometimes by source controls, but more often by enhancing the conveyance capacity of natural channels and by building new ones and underground sewers. These measures were implemented to manage local flooding in urban areas, but they also contributed to faster hydrological response of urban catchments and further increases in peak stormwater flows. Finally, most of water imported into and used in urban areas is transformed into wastewater, which is discharged into receiving waters and further increases demands on their capacity, with respect to conveyance, storage, and self-purification. In developed countries with long tradition in providing urban water services, infrastructure systems have been built over centuries and do provide good services to urban dwellers, as long as their operation and maintenance is adequately funded. As an alternative to these "central" systems, new distributed systems are currently promoted and may represent an attractive alternative in developing countries without the central systems, or funds to build and maintain them. The issues of urban infrastructure and provision of water services are addressed in Chapter 3.

Chapter 3

Urban Water Infrastructure

3.1 DEMANDS ON WATER SERVICES IN URBAN AREAS

Urban areas are highly dynamic and complex entities. They require various resources including water, food, energy and raw materials, and produce wastes, which need to be safely disposed of. With respect to urban water management, such a continuous movement, use, and disposal of energy and materials can be visualized schematically as flows of water, food and wastes into and out of urban areas, or as ecocycles of water and nutrients supporting urban areas (Fig. 3.1).

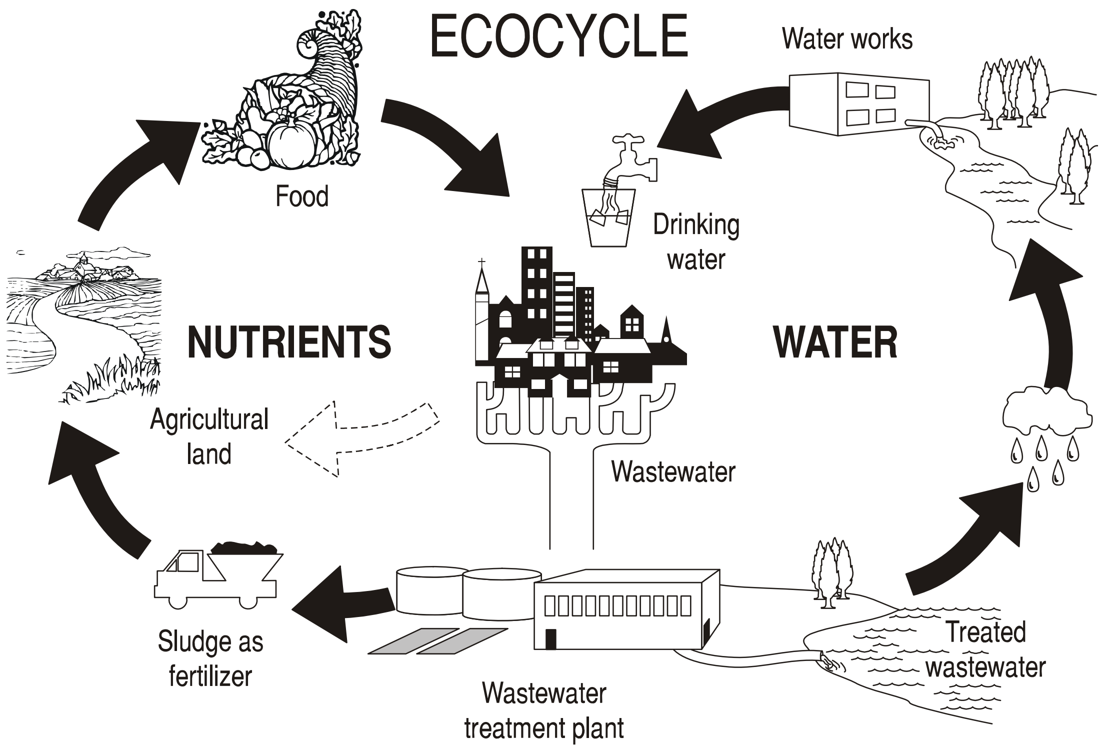


Fig. 3.1 Ecocycles of water and nutrients supporting urban areas

Sustainable operation of urban areas includes the provision of sustainable water services. Historically, the main components of urban water systems and the provision of related water services, including water supply, drainage, sewage collection and treatment, and receiving water uses, were addressed separately. Their interactions were often disregarded or underestimated; such an approach is obviously untenable. Consequently, an integrated approach to water management, sometimes referred to as an ecosystem approach, has evolved. The interdependency and interactions among the principal system components are fully recognised and used in the development of solutions to water problems. The uses of the receiving waters, including natural functions, in-stream uses and withdrawals (e.g., for water supply) are often the driving force dictating the level of control of urban drainage and wastewater effluents.

Recently, the depletion and degradation of urban water resources has led to the advocacy of a sustainable urban water system, characterised by lower water consumption, preservation of natural drainage, reduced generation of wastewater through water reuse and recycling, advanced water pollution control, and preservation and/or enhancement of the receiving water ecosystem. Specifically, sustainable urban water systems should fulfil the following basic goals:

- supply of safe and good-tasting drinking water to the inhabitants at all times,
- collection and treatment of wastewater in order to protect the inhabitants from diseases and the environment from harmful impacts,
- control, collection, transport and quality enhancement of stormwater in order to protect the environment and urban areas from flooding and pollution, and
- reclamation, reuse and recycling of water and nutrients for use in agriculture or households in case of water scarcity.

Most of the goals of sustainability have been reached or are within reach in North America and Europe, but are far from being achieved in developing parts of the world.

The Millennium Development goals put strong emphasis on poverty reduction and reduced child mortality. The two specific goals related to water are:

- to halve, by the year 2015, the proportion of people who are unable to access or afford safe drinking water, and
- to stop the unsustainable exploitation of water resources by developing water management strategies at local, regional, and national levels, which promote both equitable access and adequate supplies.

In addition to these goals, the proportion of people lacking access to adequate sanitation should be halved by 2015. Sanitation systems must be designed to safeguard human health as well as the health of the environment.

The urban populations of the world, especially in Africa, Asia, and Latin America, are expected to increase dramatically. The African urban population is expected to more than double over the next 25 years, while that of Asia will almost double. The urban population of Latin America and the Caribbean is expected to increase by almost 50% over the same period (WHO & UNICEF, 2000). Consequently, urban services will face great challenges over the coming decades to meet the fast-growing needs. Water management considerations in provision of urban water services, including the basic requirements on urban water infrastructure, are presented in this chapter. Three urban infrastructure sub-systems are considered in this discussion: water supply, drainage, and wastewater management and sanitation.

Finally, it is the provision of urban water services and construction of related infrastructure which changes components of the hydrological cycle in urban areas and leads to its replacement by the urban water cycle. Specifically, water supply generally involves import of large quantities of water into urban areas, sometimes from remote catchments. Some of this water finds its way into urban aquifers, via losses from the water distribution networks. Most of the remaining imported water is used within the urban area and turned into wastewater. Increased catchment imperviousness and hydraulically efficient urban drainage contribute to higher volumes and flow rates of runoff, and reduced recharge of groundwater. The collection of sewage also captures some groundwater through sewer infiltration and thereby reduces groundwater tables in urban areas. For most cities in developed countries, collected wastewater is treated at sewage treatment plants, which discharge their effluents into receiving waters, thus contributing to higher export of water from the urban area and potentially causing pollution of receiving waters. Thus, elements of the urban water infrastructure and their interactions with the hydrological cycle are of particular interest when dealing with urban water cycle.

3.2 WATER SUPPLY

In the “Global Water Supply and Sanitation Assessment 2000 Report” (WHO and UNICEF, 2000), the state of urban water services worldwide has been assessed. A main finding was that the percentage of people served with some form of improved water supply rose from 79% in 1990 to 82% in 2000. At the beginning of 2000, about one-sixth of the world’s population (1.1 billion people) was without access to improved water supply services. The majority of these people lived in Asia and Africa. Even if the situation in rural areas is generally worse than in urban areas, the fast-growing cities of the world create special challenges for improving the urban water services. The urban drinking water supply coverage ranges from 85% in Africa to 100% in Europe and North America. These numbers should not be regarded as reliable since the definition of urban areas with their large fringe areas is imprecise. The term “improved water supply” is also fairly generous, comprising not only household connections but also public standpipes, boreholes, protected dug wells, and protected springs and rainwater collection.

In most cities in North America and Europe and in a large number of cities in other parts of the world, however, the citizens benefit from a water supply service that fulfils the major requirements on water quantity and quality. In these cities, water is normally treated in a water treatment plant and distributed by a pipe system to households. The challenge is to provide similar services to all urban inhabitants in the world, using similar technologies or appropriate alternatives.

The report “Water and sanitation in the world’s cities – local action for global goals” (UN-HABITAT, 2003) describes the situation worldwide and gives many illustrative examples from the cities in different parts of the world. A sample of water supply data for the 10 most populous cities in the world (in 2000) is presented in Table 3.1. Points of interest include (a) a large variation in water use per capita (130-570 L/capita/day), (b) large withdrawal rates (25-88 m^3/s), (c) significant losses (15-56%), and (d) seven out of the 10 cities listed were in developing countries.

Table 3.1 Water supply in the world’s 10 most populous cities (2000 data) (UN-HABITAT, 2003)

City and Country	Inhabitants in 2000 (million)	Water supply (m^3/s)	Water supply (L/captia/day)
Tokyo, Japan	27.9	81	250
Mexico City, Mexico	19.7	69	331
Sao Paulo, Brazil	17.8	63	306
Shanghai, China	17.2	81	407
New York, USA	16.4	57	300
Mumbai, India	16.4	25	130
Beijing, China	14.2	39	239
Lagos, Nigeria	13.4	(missing data)	(missing data)
Los Angeles, USA	13.1	88	570
Calcutta, India	12.7	25	171

Water losses were reported just for 5 cities, ranging from 15 to 56%.

Explanations of basic terminology used in water supply, provided by the U.S. Geological Survey, can be found in Table 3.2 (Mays, 1996).

Table 3.2 Definitions of water use terms (Mays, 1996)

Term	Definition
Consumptive use	The part of withdrawn water that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment.
Conveyance loss	The quantity of water that is lost in transit from a pipe, canal, conduit, or ditch by leakage or evaporation.
In-stream use	Water that is used, but not withdrawn from a ground or surface-water source for such purposes as hydroelectric-power generation, navigation, water quality improvement, fish propagation, and recreation.
Off-stream use	Water withdrawn or derived from a ground or surface-water source for public water supply, industry, irrigation, livestock, thermoelectric-power generation, and other uses.
Return flow	The water that reaches a ground or surface water source, after release from the point of use, and thus becomes available for further use.
Withdrawal	Water removed from the ground or delivered from a surface–water source for off-stream use.

3.2.1 Historical development

Some milestones in the development of modern, centralised drinking water systems are worthwhile to review (WaterWorld and Water & Wastewater International, 2000). Already some 3000 years BC the drinking water was distributed in lead and bronze pipes in Greece. In 800 BC the Romans built aqueduct systems that provided water for drinking, street washing and public baths and latrines. In the beginning of the 19th century, the first public water supply systems were constructed in North America and in Europe. The early cities were Philadelphia, USA, and Paisley, Scotland. In the middle of the 19th century, filter systems were introduced in some cities where the water quality started to be a problem. The spread of cholera necessitated the use of disinfection; and the first chlorination plants were installed around 1900 in Belgium and New Jersey, USA. During the 20th century, all large cities in North America and Europe introduced successively more and more advanced treatment of centrally supplied drinking water, including physical, biological and chemical treatment. This was primarily done for surface waters; groundwater supplies in many countries even at present either require minimal treatment, or no treatment at all (e.g., in Slovenia and Denmark). Towards the end of the 20th century, microfiltration of raw drinking water was introduced. It is an innovative treatment process being employed on an increasing scale. Water treatment and distribution is effectively governed by various laws and regulations, such as the U.S. Safe Drinking Water Act in USA (introduced in 1974, amended in 1986 and 1996) and the 1998 European Union Drinking Water Directive 98/83/EC (CEC, 1998). A broader, internationally developed guidance on drinking water quality can be obtained from the World Health Organization (WHO, 2004).

3.2.2 Water demand

The provision of adequate water supply and sanitation to the rapidly growing urban population is a problem for government authorities throughout the world. In many developed or developing parts of the world, locating new sources or expanding existing sources is becoming more difficult and costly, and is often physically and economically infeasible. The actual cost of water per cubic metre in second and third generation water supply projects in some cities has doubled, compared to the first and second generation projects (Bhatia and Falkenmark, 1993).

The ability to manage existing water resources and plan for developing new water resources is tied directly to the ability to assess both the current and future water use. The main objective of water demand management is to improve the efficiency and equity in water use and sanitation services. For this purpose, different instruments have been developed and these can be generally classified into the following categories:

- water conservation measures,
- economic measures,
- information and educational measures, and
- legal measures.

The efficiency of each of these instruments depends highly on local conditions. In different sections of this chapter, various aspects of managing water demands for domestic, industrial and agricultural purposes are discussed.

Water demand is the scheduling of quantities that consumers use per unit of time (for particular prices of water). Water use can be classified into two basic categories: consumptive and non-consumptive uses; the former remove water from the immediate water source, in the latter, water is either not diverted from the water sources, or it is diverted and returned immediately to the source at the point of diversion in the same quantity as diverted and meets water quality standards for the source.

Municipal water uses include residential/domestic use (apartments and houses), commercial (stores and small businesses), institutional (hospitals and schools), industrial, and other water uses (fire-fighting, swimming pools, park watering). These uses require withdrawal of water from surface or groundwater sources, and some parts of the withdrawn water quantity may be returned to the source, often in a different location and time, and with different quality. Further explanation of individual water uses follow.

Domestic water use includes water used for washing and cooking, toilet flushing, bath and shower, laundry, house cleaning, yard irrigation, private swimming pools, car washing and other personal uses (e.g., hobbies). Public services water use includes water used in public swimming pools, institutional uses by government agencies and private firm offices, educational institutions (such as schools, universities and their dormitories), fire fighting, irrigation of parks and golf courses, health services (hospitals), public hygienic facilities (public baths and toilets), cultural establishments (e.g., libraries and museums), street cleaning and sewer flushing, entertainment and sport complexes, food and beverage services (restaurants), accommodation services (hotels), and barber shops and beauty parlours. Small industries include laundries, workshops, and similar establishments. Transportation water use includes water used for operation of taxis, buses, and other transportation means (stations and garages), ports and airports, and railways (stations and workshops).

Good estimation of municipal water demands can be obtained by disaggregating the total delivery of water to urban areas into a number of classes of water use and determining separate average rates of water use for each class. This method is called disaggregate estimation of water use. The disaggregate water uses within some homogenous sectors are less variable than the aggregate water use. Therefore, a better accuracy of estimation of water use can be obtained.

In order to estimate the total municipal water use in a city, the study area should first be divided into homogenous sub-areas, on the basis of water pressure districts or land-use units, and then the water use rates can be assumed to be constant for different users within each sub-area. Temporal (annual, seasonal, monthly, etc.) variation should also be considered in disaggregating the water uses.

The most commonly used method for water use forecasting is regression analysis. The independent variables of the regression model should be selected on the basis of the available data for different factors affecting the water use and their relative importance in increasing or decreasing water uses. For example, the most important factor in estimating water use in an urban area is the population of each sub-area. A multiple regression method can also be used to incorporate more variables correlated with water use in municipal areas for estimating and forecasting the water demand in the future. Population, price, income, air temperatures, and precipitation are some of the variables that have been used by different investigators (Baumann et al., 1998).

Time series analysis has also been used to forecast future water demands. For this purpose, time series of municipal water use and related variables are used to model the historical pattern of variations in water demand. Long memory components, seasonal and non-seasonal variations, jumps, and outlier data should be carefully identified and used in modelling water demand time series.

In recent years, more attention has been given to conserving water rather than developing new water sources. In many countries, this has been accepted for both economic and environmental reasons as the best solution for meeting the future water demands. Therefore, water demand management is a proper strategy to improve efficiency and sustainable use of water resources taking into account economic, social, and environmental considerations (Wegelin-Schuringa, 1999; Butler and Memon, 2005). In water demand management, increasing attention is paid to water losses and unaccounted for water, which generally include: (i) leakage from pipes, valves, meters, etc.; (ii) leakage/losses from reservoirs (including evaporation and overflows); and, (iii) water used in the treatment process (back-wash, cooling, pumping, etc.) or for flushing pipes and reservoirs. Typically, the losses may vary from 10-60% (See Table 3.1), with the higher values reported for developing countries. Other measures focus on water saving technologies, such as dual-flush toilets, flow restrictors on showers and automatic flush controllers for public urinals, automatic timers on fixed garden sprinklers, moisture sensors in public gardens, and improved leakage control in domestic and municipal distribution systems. All these measures are practical, but regulations and incentives are needed for their implementation.

Costs of water supply services and technological developments designed to lower these costs have a major influence on the level of water demand in the developing countries. In rural areas, the distance from households to the standpipes, or the number of persons served by a single tap or well, are the major factors controlling the demand.

3.2.2.1 Water supply standards: quantity

Adequate quantities of water for meeting basic human needs are a prerequisite for human existence, health, and development. If development is to be sustained, an adequate quantity of water must be available. In fact, as development increases, in most instances, the demand for water on a per capita basis will also increase for personal, commercial, industrial and agricultural purposes.

Domestic consumption of water per capita is the amount of water consumed per person for the purposes of ingestion, hygiene, cooking, washing of utensils and other household purposes including garden uses. Per capita water consumption can be measured (or estimated) through metered supply, local surveys, sample surveys or total amount supplied to a community divided by the number of inhabitants. As sustained development can be achieved without or with a limited increase in per capita water consumption, the per capita water use is usually limited by locally specific regulations or standards. The actual domestic water use rates broadly vary, from a minimum of 50 L/capita/day (Gleick, 1998) to 500 L/capita/day (or more), depending on water availability, pricing, traditional water use and other factors. Urban areas with high water use can create large reserves by introducing and practicing demand side management (Baumann et al., 1998).

The supply source plus storage facilities in urban areas are planned to yield enough water to meet both the current daily demands and the forecasted consumptions in the near future. Water supply systems in urban areas should satisfy some quantitative guidelines and standards. As a general rule, when using surface supplies, the tributary watershed should yield the estimated maximum daily demand for ten years into the future, and the storage capacity of a supply reservoir should be equal to at least 30 days maximum daily demand five years into the future. Ideally, for well supplies there should be no mining of water; that is, neither the static groundwater level nor the specific capacity of the wells (litres per minute per metre of drawdown) should decrease appreciably as demand increases. These values should be constant over a period of five years except for minor variations that correct themselves within one week.

3.2.2.2 Water supply standards: quality

The quality of water is assessed in terms of its physical, chemical, and biological characteristics and its intended uses. Water to be used for public water supplies must be potable (drinkable), that is without polluting contaminants that would degrade the water quality and constitute a hazard or impair the usefulness of the water. To ensure drinking water safety, the so-called multiple barrier approach is advocated; it consists of an integrated system of measures that safeguard water quality from the source to the tap. For safety, a redundancy of protection measures is built into these systems. The quality of drinking water is prescribed by the appropriate standards. In this context, the term standard represents a definite rule, principle or measure established by an authority. Where health is of concern and scientific data are limited, precautionary standards may be justified.

Quality criteria for drinking water have been presented in many documents. Particularly well known are the regulations mandated by the U.S. Environmental Protection Agency, title 40, parts 141 and 143 and of the Safe Drinking Water Act (1974, amended in 1986 and 1996). These are the current regulations for evaluating the suitability of surface or groundwater resources for public water supply in the USA (for the latest version, visit www.epa.gov/safewater/mcl.html). These guidelines provide primary and secondary standards; the primary standard is for human health protection and the secondary standard implies a regulation that specifies the maximum contamination levels that are permissible in order to protect the public welfare, but may adversely affect appearance or odour of water.

On the international forum, the most authoritative document on drinking water quality is the World Health Organization (WHO) guidelines for drinking water quality (WHO, 2004). These guidelines address a framework for safe drinking-water, health-based targets, water safety plans, surveillance, applications of guidelines in specific circumstances, microbial aspects, chemical aspects, radiological aspects and acceptability aspects. Specific circumstances include emergencies and disasters, large buildings, packaged/bottled water, travellers, desalination systems, food production and processing, and water safety on ships and in aviation. The guidelines are suitable for use by both developed and developing countries. Most frequent concerns about the drinking water quality are those posed by pathogens and arsenic.

Requirements on industrial water supply quality depend on the type of industry, and may even differ in various segments of a particular industrial sector. For a detailed description of water quality requirements in various types of industries, the reader is referred to Corbitt (1990).

There are many water uses that can be met by sub-potable water. Typical examples are irrigation of urban landscape, agricultural irrigation, aquaculture, some domestic uses (e.g., toilet flushing), industrial reuse (e.g., cooling waters or process waters), recreational waters and groundwater recharge. Sub-potable water requirements can be met by reclaimed urban wastewater, with the main benefits consisting in saving potable water and reducing pollution discharges into receiving waters. In water reuse, the most important issue is to specify the quality of water to be reused for a particular purpose. Such specifications then determine the required level of treatment. Some guidance for water reuse can be obtained from WHO guidelines, which are under review (WHO, 1989). Further discussion of wastewater reclamation and reuse is presented in Section 3.4.8.

3.2.3 Water supply sources

The gap between society's needs for water and the capability to meet such needs is continually widening. Water supply, an important element of the overall urban water cycle, attempts to bridge this gap. Water needed in urban areas may come from groundwater or surface water sources such as lakes, reservoirs, and rivers. It is called untreated or raw water, which is usually transported to a water treatment plant. The degree of treatment depends on the raw water quality and the purpose that this water will be used for. Different water quality standards for municipal purposes have been developed and used during the past several decades. After treatment, the water is usually distributed via a water distribution network.

Four major characteristics of water supply are quantity, quality, time variation, and price. If the quantity and time distribution of raw water conformed to the water use patterns in an urban area, then there would be no need to store water or regulate its distribution by man-made structures or devices. But in almost all urban areas, the time variation of available water resources does not follow demand variations. Therefore, certain facilities should be implemented to store the excess water during wet (high flow) seasons to be consumed in low flow periods.

Costs of initial investment in, and operation and maintenance costs of, the water supply should be incorporated in the economic studies for development planning. In the same way, if water quality does not satisfy the standards for different water uses, treatment plants should be implemented and their costs should be incorporated in the urban water resources development studies. In general, water supply methods can be classified into the following categories:

- large-scale and conventional methods of surface and groundwater resources development,
- non-conventional methods.

Conventional methods of water supply include large-scale facilities such as dam reservoirs, water transfer structures, and well fields. Dam reservoirs are the most important source of water in many large cities around the world. Quite often the dam reservoirs serving for water supply of urban areas are located tens or hundreds of kilometres away from the areas served, sometimes in another river basin.

Water supply storage facilities range from large reservoirs created by building dams to small scale storage tanks. The term "reservoir" has a specific meaning with regard to water supply systems modelling and operation. It is an "infinite" source that can supply or accept water with such a large capacity that the hydraulic grade elevation of the reservoir is unaffected and remains constant.

In many large cities around the world, water demand has exceeded the total water resources in the basin in which the city is located. In such cases, one of the approaches to water supply management is to develop new inter-basin water transfer schemes in order to keep ahead of the ever-increasing requirements due to the growing population and improved standards of living. A different approach is referred to as demand side management, in which water conservation is practiced to the maximum practical extent to reduce demands on the water supply and manage the needs for infrastructure expansion (Butler and Memon, 2005).

3.2.3.1 Conjunctive use of sources and artificial recharge

Conjunctive use of surface water and groundwater can sometimes offer an attractive and economical means of solving water supply problems where the exploitation of either resource is approaching or exceeding its optimum yield. The volumes of groundwater naturally replaced during each year are relatively small because of the slow rates of groundwater movement and the limited rate of infiltration. Artificial recharge can be used to reduce the adverse groundwater conditions such as progressive lowering of water levels or saline water intrusion. As shown in Table 3.3, the percentage of population in selected countries relying on groundwater supply ranges from 15 to 98%; the rest is served by surface water sources.

Table 3.3 Percentage of the population supplied by groundwater in selected countries

Country	Population supplied by groundwater (%)
Denmark	98
Portugal	94
Italy	89
Mexico	75
Switzerland	75
Belgium	67
Netherlands	67
Luxemburg	66
Sweden	49
USA	40
United Kingdom	35
Canada	25
Spain	20
Norway	15

3.2.3.2. Supplementary sources of water

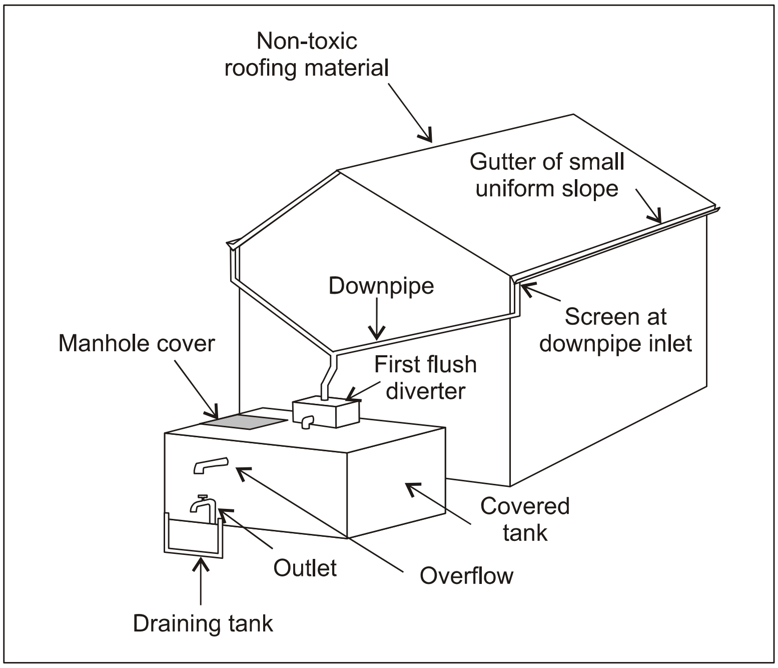
Three supplementary sources of water are of particular importance in urban areas: rainwater harvesting, bottled water and wastewater reclamation and reuse. The first source is addressed in this section, the second one in Section 3.2.6, and the third one in Section 3.4.8.

Rainwater harvesting is a supplementary or even primary water source at the household or small community level, especially in places with relatively high rainfall and limited surface waters (e.g., small islands). Also, the use of roof runoff for irrigation or other uses is becoming of interest in highly developed urban areas, as one of the measures supporting environmental sustainability, by reducing water supply demands for irrigation and reducing urban runoff and its impacts. Roofs of buildings are the most common collecting surfaces. Natural and artificial ground collectors are also used in different places around the world. In designing rainfall harvesting systems the following issues should be considered.

- *Quantity issues*: Rainwater collection systems often suffer from insufficient storage tank volumes or collector areas. Leakage from tanks due to poor design, selection of materials, construction, or a combination of these factors is a major problem of the rainwater collection systems.
- *Quality issues*: The rainwater quality in many parts of the world is good. But, water quality problems may arise within the collection systems. Physical, chemical, and biological pollution of rainwater collection systems occurs where improper construction materials have been used or where maintenance of roofs and other catchment surfaces, gutters, pipes, and tanks is lacking (Falkland, 1991).

Rainwater cisterns or other rainwater collection devices have been used in many parts of the world for centuries. At present, this approach is used widely in Australia and India. In rural areas of Australia, many farms are not connected to water supply systems nor have adequate well water; hence, the rainwater tank has become a symbol of the Australian outback culture. Local councils and urban water authorities are increasingly encouraging these systems in urban areas, and in some cases offering rebates to customers who use rainwater for sub-potable uses. The most feasible reuse of rainwater in urban areas is for garden irrigation, which accounts for 35 to 50% of domestic water use in many large cities of the world. Reuse of rainwater in the garden requires a relatively simple system, with very low environmental risks, and it is therefore encouraged by many water authorities. An example of a rooftop rainwater harvesting system is shown in Fig. 3.2 (Karamouz et al., 2003).

Further savings of potable water can be achieved when rainwater is used for toilet flushing (about 20% of domestic water use), as well as in the laundry, kitchen and bathroom. It can also be used in pools, and for washing cars. In some situations (e.g., in some rural areas), it may be possible to use rainwater for most domestic uses, without relying on the public water supply. In all these cases, strict regulations for reclaimed water quality must be followed and safety systems employed, particularly in connection with drinking water, which should be protected by the so-called "multiple barrier system". In this approach, multiple barriers are used to control microbiological pathogens and contaminants that may enter the water supply system, and thereby ensure clean, safe and reliable drinking water.



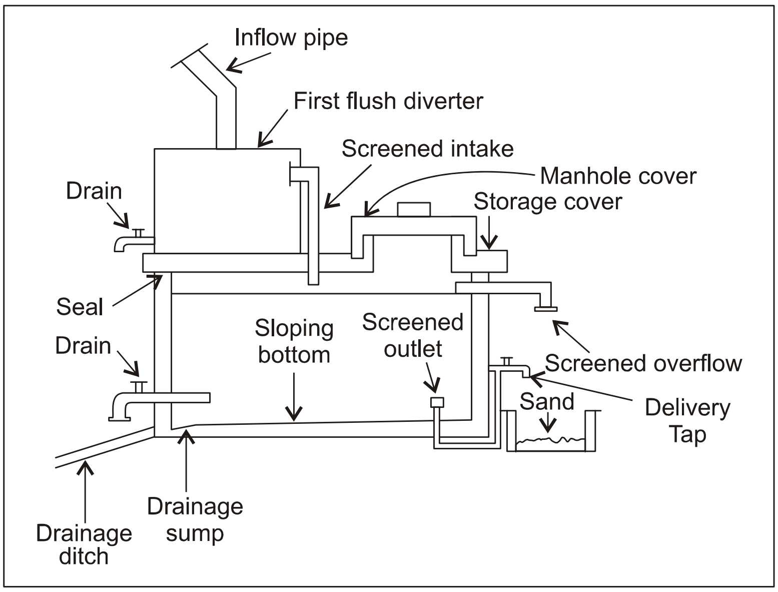


Fig. 3.2 An example of a rainwater collection system (after Karamouz et al., 2003)

3.2.3.3 Water shortage

Urban demands on water supplies are continually increasing as a result of growing urban populations and higher standards of living. When demands exceed the available water, water shortages result, with significant social, political, and economic implications. In general, there are two main reasons for water shortage in urban areas: (a) climatic or hydrologic drought, and (b) inability of the supplier to provide the required water.

Social impacts of water shortage refer to the effects of water deficit on the public health and life styles; such impacts are exacerbated when the equity in water distribution is disturbed. As a part of the long-term planning, urban water suppliers strive to ensure the appropriate level of reliability of water supply meeting the needs of various categories of customers during both normal and dry water years.

The water supply system failure to meet the customer demands is measured by different performance parameters, such as reliability (reflecting the probability that the system will meet demands), resiliency (the speed of returning the system to the fully operational state), and vulnerability (reflecting the consequences of the failure) (Hashimoto et al., 1982).

In comprehensive water supply planning, the following items are considered to mitigate water shortages: (a) Planning horizon, (b) planning criteria (including reliability, cost, and water quality), (c) demand projections, (d) water availability under the current conditions (the minimum water supply is estimated for the driest water year in the planning horizon, all supply opportunities such as recycled water and water transfer are considered, and plans for replacing water resources at risk are assessed), (e) long-term water supply strategy, (f) water quality considerations, (g) treatment and production facilities, and (h) contingency plans (may include water use restrictions and rationing, prioritising competing uses, and utilising alternative sources). Water shortages may lead to conflicts among the stakeholders, which need to be resolved.

3.2.4 Drinking water treatment

Water treatment is generally required to make raw water drinkable. As high quality sources of water are depleted, water utilities are increasingly using lower quality source water requiring more treatment and consuming more water during the treatment. Detailed discussion of water treatment is beyond the scope of this report and can be found elsewhere (Pontius, 1990). Instead, the material presented here focuses just on emerging technologies, desalination, and disinfection.

3.2.4.1 Emerging technologies

Rapid development of microfiltration (membrane filtration) has created new treatment options that were not feasible earlier. One alternative system delivers raw source water, or just primarily treated water, directly to the user, who further treats this water in small, local treatment units near the point of consumption. The main advantages of this system are that the deterioration of the water quality during transport is avoided and each consumer can treat the water to the level specifically needed for their requirements. Needless to say, the water quality does not need to be the same for such purposes as human consumption (drinking water), process water for industry, cooling water, irrigation water, or water for flushing toilets. Small, locally used microfiltration units are rapidly becoming competitive in price. Both conventional central and on-site water treatment systems are illustrated in Figs. 3.3 and 3.4.

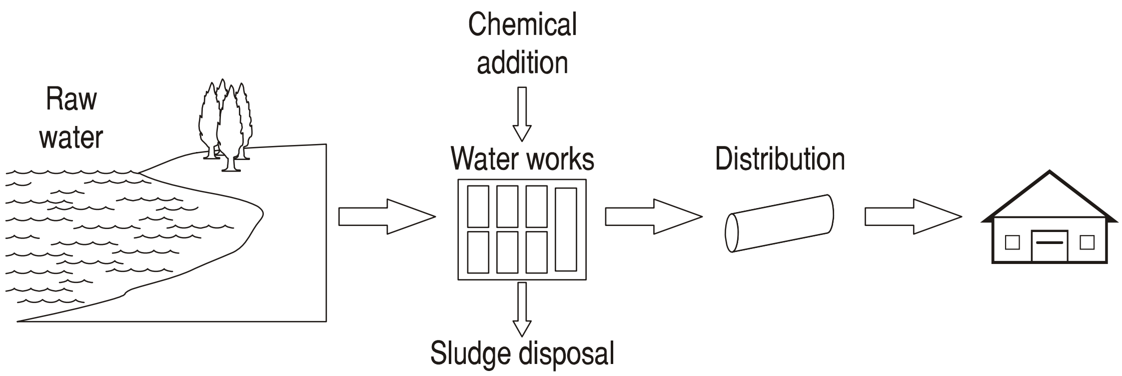


Fig. 3.3 A conventional layout of water treatment and distribution systems

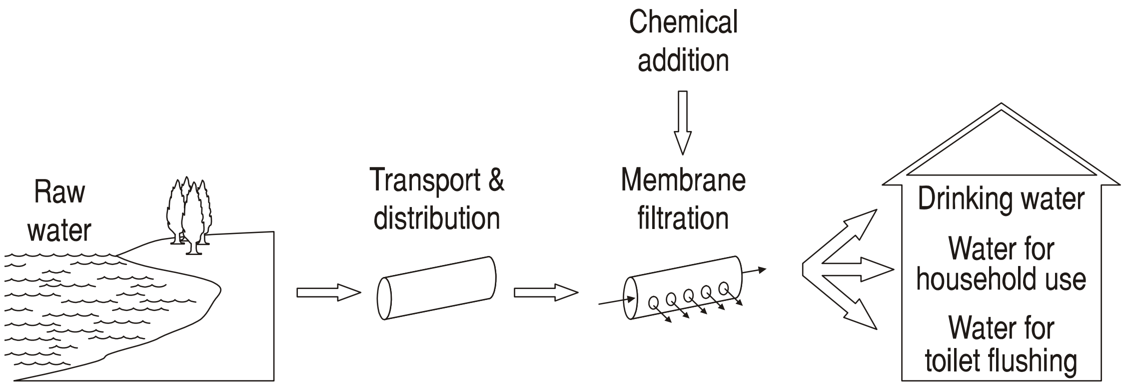


Fig. 3.4 An alternative layout of drinking water distribution and treatment system using small, local membrane filter units

3.2.4.2 Desalination

Among unconventional water supply methods, the use of seawater treated by desalination is the most widely used method. Seawater has a salinity of about 35,000 mg/L that is attributed mostly to sodium chloride. Desalination was first adopted in the early 1960s, using multi-stage flash evaporation (MSF). Several plants using various desalination technologies are currently operating in the USA, Caribbean and Middle East. Desalination technologies have increasingly become cheaper and more reliable, and their current costs may be competitive with those of other high-tech treatment technologies, especially if water sources are sparse or very remote.

The following methods are used for removing dissolved solids:

- *Distillation*: In this method, the water is heated to its boiling point to convert it into steam; the steam is then condensed yielding salt-free water.
- *Reverse Osmosis (RO)*: In this method, the water is forced through a semi-permeable membrane under pressure; the dissolved solids are held back.
- *Electrodialysis*: In this method, ions are separated from the water by attraction through selective ion-permeable membranes using an electrical potential.

Among the above methods, the first two are more common for desalination of seawater; electrodialysis is usually preferred for treating brackish groundwater. During the last decade the development of membrane technologies has been rapid and has resulted in the development of new, cheaper and high-performance membranes. Plants using membrane technologies (reverse osmosis, RO, and electro-dialysis) have been built and the cost of finished water is steadily decreasing. The main advantage of membrane technologies over distillation technologies is that they use much less energy. Often, pre-filtration is used in order to remove hydrocarbons to reduce the fouling of the RO membranes. The cost of reverse osmosis desalination has decreased substantially over the past decade, dropping down to between US$0.25 and US$1.00 per cubic metre. Even then, seawater desalination remains more expensive than most other sources of water supply (where available), but in arid locations close to the sea and far away from suitable surface or groundwater sources, seawater desalination may be the most economical option for an urban water supply. On a household level, small-scale membrane units have been developed and sold in all parts of the world to offices and single households. The cost of such units (typically around US$2,000/unit) is decreasing but still too high for common use. As the technology further improves (particularly for reverse osmosis), these costs may further decrease. In addition to high rates of energy consumption, a major problem at inland desalination plants is the disposal of rejected brine. Evaporation ponds, injection in deep wells, and transfer to the ocean are the common methods depending on the volume of reject brine, site location and geographical and climatic conditions.

3.2.4.3 Disinfection

The introduction of chlorine in disinfection of drinking water in the early 20th century drastically reduced waterborne diseases in western cities. Even today, the struggle to remove pathogens from potable water and deliver a healthy municipal drinking water is of primary concern all over the world. In remote or poor regions of the world, boiling of drinking water will continue to be used for a long time to safeguard against diseases. Alternative disinfection methods have been developed and used, most often by chlorination using hypochlorite, chlorine dioxide and chloramines.

One major drawback of adding chlorine is the formation of carcinogenic by-products during the disinfection process. Among such products, most common are trihalomethanes (THM), haloacetic acids, bromate, and chlorite. Numerous studies have demonstrated that these byproducts may increase the cancer risk (e.g., Batterman et al., 2002; Gibbons and Laha, 1999; Goldman and Murr, 2002; Korn et al., 2002). Consequently, U.S. EPA limits the presence of THM in drinking water to 80 μg/L (Gibbons and Laha, 1999). When considering the risks associated with these substances, one should keep in mind that such risks are much smaller than microbiological risks incurred if water is not disinfected. To avoid the problems associated with chlorination byproducts, other disinfection methods have been introduced, including UV irradiation, ozonation and solar disinfection. In developing countries, the first two methods may not be affordable, but the third has a great potential, because of its simplicity and low costs.

In solar disinfection, solar radiation is used to destroy pathogenic microorganisms which cause waterborne diseases. This process is best suited for treating small quantities of water, usually placed in transparent plastic bottles and exposed to full sunlight for some extended time periods. The actual treatment occurs through solar UV irradiation and increased water temperature, ideally above 50°C, which accelerates bacteria die-off.

UV irradiation and ozonation may require pre-treatment and before discharging disinfected water into the distribution system, some chlorine may have to be added to the treated water to maintain chlorine residuals during transport in the distribution network and prevent growth of bacteria originating from biofilms found in the pipe system. In many countries the residual chlorine concentration at the tap is taken as a measure of safety.

3.2.5 Water distribution systems

Water distribution systems include the entire infrastructure from the treatment plant outlet to the tap. The actual layout of supply mains, arteries, and secondary distribution feeders should be designed to deliver the required fire flows in all built-up parts of the municipality, above and beyond the maximum daily rate usage. Similar considerations must be given to the effects that a break, joint separation, or other main failure could have on the water distribution system operation. In urban areas, most of the water quantity standards relate to the water distribution system, as further discussed below, on the basis of general practices in this field.

In evaluating a water distribution system, pumps should be considered at their effective capacities when discharging at normal operating pressures. The pumping capacity, in conjunction with storage, should be sufficient to maintain the maximum daily use rate plus the maximum required fire-fighting flow with the single most important pump out of service.

Storage is frequently used to equalise pumping rates in the distribution system as well as provide water for fire fighting. In determining the fire flow from storage, it is necessary to calculate the rate of delivery during the specified period. Even though the volume stored may be large, the flow to a hydrant cannot exceed the carrying capacity of the mains, and the residual pressure at the point of use should not be less than 140 kpa (20 psi).

Depending on specific practices, the recommended water pressure in a distribution system is typically 450 to 520 kPa (65 to 75 psi), which is considered adequate for buildings up to ten stories high as well as for automatic sprinkler systems for fire protection in buildings of four to five stories. For a residential service connection, the minimum pressure in the water distribution main should be 280 kPa (40 psi); pressure in excess of 700 kPa (100 psi) is not desirable, and the maximum allowable pressure is 1030 kPa (150 psi). Fire hydrants are installed at spacing of 90-240 m and in locations required for fire fighting.

Although a gravity system delivering water without the use of pumps is desirable from a fire protection standpoint, the reliability of well-designed and properly safeguarded pumping systems can be developed to such a high degree that no distinction is made between the reliability of gravity-fed and pump-fed systems. Electric power should be provided to all pumping stations and treatment facilities by two separate lines from different sources. For more detailed information about the quantitative standards in water distribution systems, the reader is referred to the water distribution text books such as Walski et al. (2003). The use of standby emergency power is also recommended.

3.2.6 Drinking water supply in developing countries

It is estimated that over one-third of the urban water supply systems in Africa, Latin America and Asia operate intermittently. An intermittent water supply is a significant constraint on the availability of water for hygiene and encourages the low-income urban population to turn to alternatives such as water vendors.

Many of the intermittently operating systems do not deliver water more than half the time, and there are large variations in water quality. One way of overcoming the lack of water supply is to construct local water reservoirs, from which water is delivered to outdoor taps or into the households. Problems arise from the facts that these reservoirs are poorly protected against tampering and seldom cleaned. Further, the variations of pressure in the pipe systems may cause intrusion of contaminated water. Considerable risks for spreading of diseases exist in such systems (WHO and UNICEF, 2000).

Among the less developed but commonly used technologies are unprotected wells and springs, vendor-provided water, bottled water and tanker truck provision.

Vendor-provided water is rapidly expanding in many countries and raises many questions concerning water quality and price. It is often argued that for the price of the vendor-provided drinking water, more efficient communal water supply systems could be constructed. However, water vendors today play an important role in many regions of the world.

The bottled water industry is growing quickly all over the world and has become an important market. In developed countries, the price of bottled water is about 1,000 times higher than that of the public water delivered at the tap. Nevertheless the market is growing, influenced by trendy consumers and by people who do not trust the quality of the tap water. In developing countries, bottled water, where affordably priced, may solve acute drinking water problems or problems with low quality water.

Tanker truck provision is common in many regions where the public distribution system does not exist. Typical examples may be small villages or peri-urban areas. Generally (e.g., in India), this water is supplied from public water supplies by contractors.

3.3 URBAN DRAINAGE

Urban drainage serves to reduce the risk of flooding and inconvenience due to surface water ponding, alleviate health hazards, and improve aesthetics of urban areas. Traditionally, drainage development was based on a steady expansion of the drainage infrastructure without consideration of the impacts of drainage discharges on receiving waters and their beneficial uses. Two interconnected urban drainage systems are recognised; the major system serving to alleviate major flooding and the minor system providing convenience by reducing water ponding in urban areas. Drainage systems have evolved throughout the history and existing systems represent a compromise among providing flood protection, improving quality of life, technical abilities, ecological needs, and availability of resources.

Two types of urban sewerage systems exist - combined and separate. The combined system conveys both surface runoff and municipal wastewaters in a single pipe. In dry weather, the entire flow is transported to the sewage treatment plant and treated. In wet weather, as the runoff inflow into the combined sewers increases, the capacity of the collection system is exceeded and the excess flows are allowed to escape from the collection system into the receiving waters in the form of the so-called combined sewer overflows (CSOs), which pollute receiving waters.

In the separate system, surface runoff is transported by storm sewers and discharged, with or without passive treatment, into the receiving waters, and the municipal wastewater is transported by sanitary sewers to the wastewater treatment plant (WWTP) and usually treated prior to discharge into the receiving waters. Both drainage systems exist in many variations.

Urban drainage interacts with other components of the urban water cycle, and particularly with receiving waters. Fast runoff from impervious surfaces, together with hydraulic improvements of urban drainage in the form of street gutters, storm sewers and drains, results in an increased incidence and magnitude of stormwater runoff. The resulting high flows affect the flow regime, sediment regime, habitat conditions and biota in receiving waters. Urban drainage also affects low flows. Reduced infiltration leads to reduced groundwater recharge, lowered groundwater tables and reduced base flows in rivers. Low flows reduce the self-purification capacity of rivers, limit the dilution of polluted influents and consequently are characterised by poor water quality. Where groundwater is withdrawn for urban water supply, aquifers are often overexploited and land subsidence may occur.

Drainage also interacts with other water infrastructures and water resources. For example, cross-connections between storm and sanitary sewers either allow the influx of municipal sewage into separate storm sewers with concomitant pollution of stormwater, or the influx of stormwater into sanitary sewers increases the flow rates, which may exceed the WWTP capacity, result in sewage bypasses, and the pollution of receiving waters. All types of sewers may interact with groundwater, particularly if not watertight. Leaky sewers below the water table suffer from groundwater infiltration and essentially drain groundwater aquifers. Infiltration of groundwater into sanitary sewers increases sewage flows reaching the WWTP and thereby increases the cost of treatment and the risk of sanitary sewer overflows. On the other hand, exfiltration from sanitary sewers pollutes groundwater in urban areas and may impact on sources of drinking water. Sudden increases in wet weather flows in combined sewers produce hydraulic and pollution shocks on the treatment plants and may reduce the treatment efficiency, particularly of biological treatment by shortening the reaction time and reducing the return sludge flow. In addition, the biomass is diminished as sludge is flushed into the final clarifier. All these factors can lead to reduced treatment efficiencies and increased discharge of pollutants into the receiving waters.

Concerning drainage flows, urban water managers are interested in both water quantity and water quality issues, as discussed in the following sections.

3.3.1 Flooding in urban areas

Floods are naturally occurring hydrological events characterised by high discharges and/or water levels leading to inundation of land adjacent to streams, rivers, lakes, or coastal areas. Where such areas are occupied by human settlements, disasters may occur and result in loss of human life and material damages. Two types of floods are distinguished in urban areas – those locally generated by high intensity rainfall, and those generated in larger river catchments and passing through urban areas, where they may inundate flood plains which have been encroached upon. Other floods may occur in coastal areas, in the form of storm surges or tsunamis with catastrophic impacts. Only the first flood type, locally generated, will be addressed here; river floods or flooding of coastal areas are beyond the scope of this report.

Locally generated floods usually result from catchment urbanisation as discussed later in Chapter 4. High catchment imperviousness, hydraulically efficient flow conveyance, and reduced concentration times causing runoff generation by high-intensity rainfall all contribute to high rates of surface runoff and risk of local flooding. In developed countries, these issues have been addressed with various degree of success by applying both non-structural and structural measures incorporated in a master drainage plan. The methodology for urban drainage planning is well developed and described in Geiger et al. (1987). These plans are prepared at two planning levels, short-term (5-10 years) and long-term (25-50 years). A master drainage plan represents a technical layout of the sewerage systems (drainage and sanitation) for the entire urban area as it may further develop within the planning horizon. With respect to drainage, the master plan should be part of a catchment plan and incorporate the whole drainage system including the connections and interactions between the minor and major system components.

The minor system comprises swales, gutters, stormwater sewers, open drains and surface and subsurface storage facilities, and conveys runoff from frequent events with return periods up to 10 years. The minor system reduces the frequency of inconvenience (water ponding) and its failure has minimal implications. The major system consists of natural streams and valleys, as well as large constructed drainage elements, such as large swales, streets, channels and ponds. The major drainage system greatly reduces the risk of loss of life and property damage in urban areas, and consequently, its failure has serious consequences. It is typically designed for a 50-year event, or even a 100-year event (Geiger et al., 1987).

Typical master drainage plans include such points as purpose and background of the study, identification of drainage related problems, definition of study objectives, database for planning, methods for planning and design, identification and investigation of drainage alternatives, impact of the future drainage system, final design of individual structures, and implementation. Much success has been achieved with master drainage planning in developed countries; however, the situation is different in developing countries, where the principles of master drainage planning are rarely followed.

Urbanisation in developing countries occurs too fast and unpredictably, and often progresses from downstream to upstream areas, which increases flood problems (Dunne, 1986). Urbanisation of peri-urban areas is largely unregulated, often without the provision of any infrastructure, many public lands are occupied and developed illegally, and flood-risk areas (flood plains) are occupied by low-income population without any protection. WHO (1988) reported spontaneous housing developments in flood-prone areas of many cities in humid tropics, including Bangkok, Mumbai, Guayaquil, Lagos, Monrovia, Port Moresby and Recife.

Other problems include lack of funding for drainage and other services, lack of solid waste collection (which may end up in and block drainage ditches), no prevention of occupation of flood-prone areas, lack of knowledge on coping with floods, and lack of institutions in charge of flood protection and drainage (Dunne, 1986; Ruiter, 1990). Tucci and Villanueva (2004) suggested solutions including introduction of better drainage policies (which would control flow volumes and peaks), and planned development, in which space is retained for flow management measures. Also in flood plains, non-structural measures should be applied by emphasising green areas, paying for relocation from flood-prone areas, and public education about floods.

3.3.2 Stormwater

Stormwater is mostly rainwater running off impermeable surfaces in urban areas, including roofs, sidewalks, streets and parking lots. It is drained from urban areas by sewers or open channels to avoid local inundation. During this process, stormwater becomes polluted and its discharges into receiving waters cause environmental concerns. A schematics of runoff generation and pollution is shown in Fig. 3.5.

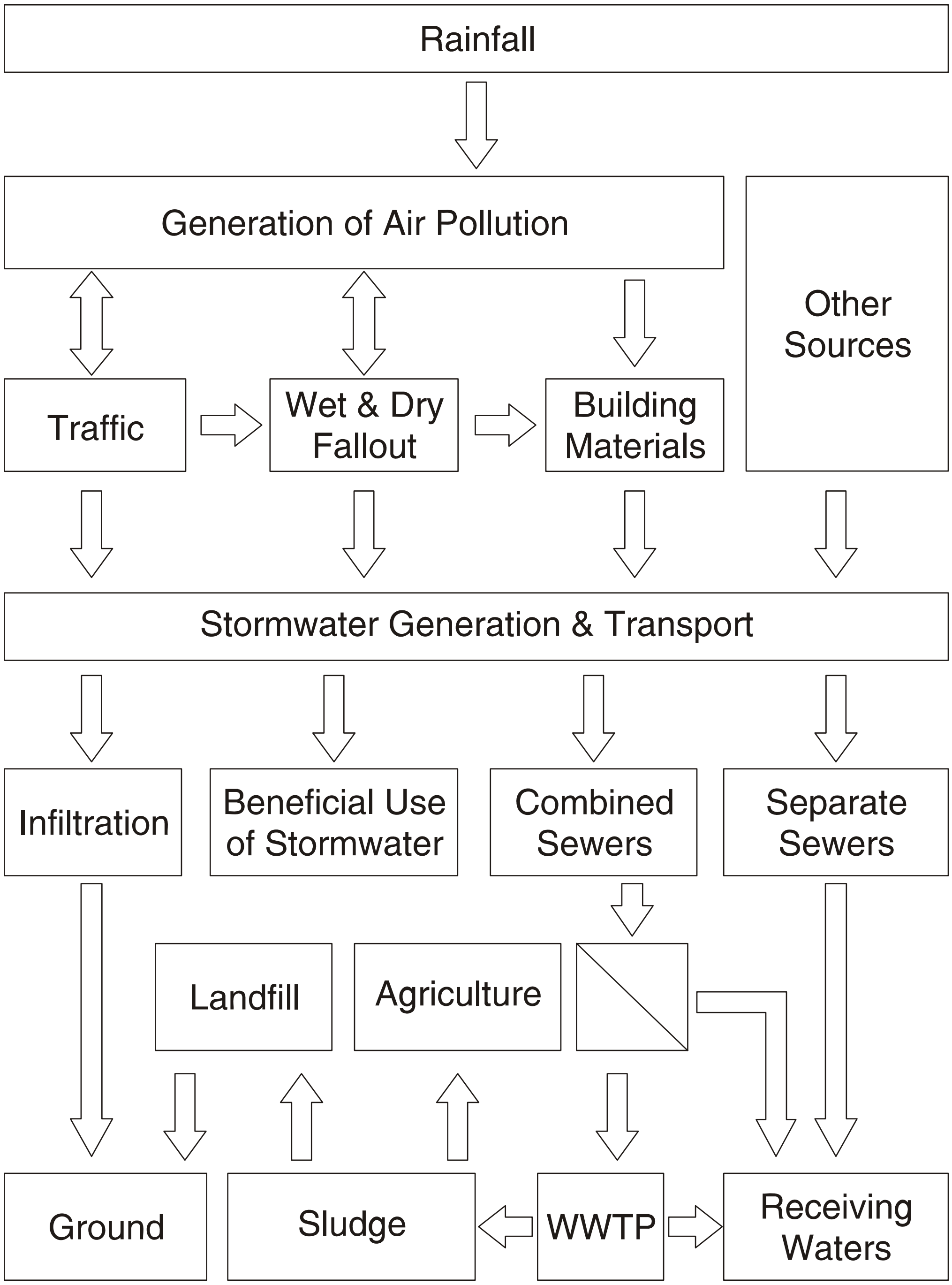


Fig. 3.5 Flows of water and pollutants in stormwater systems

Stormwater may be transported either by combined sewers, together with domestic and industrial wastewaters, or by separate sewers discharging to the nearest stream or lake. In combined sewers, high stormwater inflows exceed the pipe capacity and excess flows have to be diverted by flow regulators as combined sewer overflows (CSOs) to the nearest receiving waters. CSOs contain not only the stormwater, but also untreated wastewater and sewer sludge; their direct discharges into receiving waters cause serious pollution problems.

The stormwater contribution to the wet weather flow reaching the wastewater treatment plant also increases the concentrations of heavy metals and other contaminants in the WWTP effluent and in the sludge (biosolids). This is one of the main reasons why the use of sludge from European WWTPs as a fertiliser in agriculture has been questioned. So, which sewer system is better – the separate system in which polluted stormwater may be discharged directly into the receiving water or the combined system, in which the stormwater is conveyed to the WWTP for treatment, but CSOs occur? There are no general answers to this question, as the definite comparisons of separate and combined systems performance depend on local conditions. The separate sewer system could be improved by implementing separate stormwater treatment plants, but that may be costly and inefficient in view of highly variable infrequent inflows with low concentrations of pollutants. Similarly, the combined systems can be improved by incorporation of CSO pollution abatement.

3.3.2.1 Stormwater characterisation

The literature on urban stormwater quality is very extensive. So far, more than 600 chemicals have been identified in stormwater and this list is growing. Makepeace et al. (1995) identified about 140 important contaminants, which can be found in stormwater and would affect human health (i.e., mostly through contamination of drinking water supply) and aquatic life. This list contains solids, trace metals, chloride, nutrients (N and P), dissolved oxygen, pesticides, polycyclic aromatic hydrocarbons, and indicator bacteria. Typical concentrations of many such constituents were reported in the literature, mostly for developed countries. Summaries of data from two large databases appear in Table 3.4.

Stormwater quality data were also reported for less developed countries, but usually in small data sets. Examples of such data include those from Sao Paulo, Brazil (cited in Tucci, 2001), Johor, Malaysia (Yusop et al., 2004), Bandung, Indonesia (Notodarmojo et al., 2004) and Beijing, China (Che et al., 2004). In general, such data indicate significantly higher concentrations than those in Table 3.4, which may be caused by problems with infrastructure, such as cross-connections between storm and sanitary sewers. In any case, such data suggest that pollution loads conveyed by storm sewers in developing countries are larger than indicated by the literature data published for developed countries.

Table 3.4 Quality of urban runoff and combined sewer overflows: stormwater worldwide data (Duncan, 1999), U.S. NURP stormwater data (U.S. EPA, 1983) and European CSO data (Marsalek et al., 1993).

Chemical constituent	**Units**	**Urban stormwater**		**European CSO data**
		Mean of Duncan's dataset (1999)	U.S. NURP Median site (U.S. EPA, 1983)	(Marsalek et al., 1993)
Total suspended solids (TSS)	mg/L	150	100	50-430
Total phosphorus	mg/L	0.35	0.33	2.2-10
Total nitrogen	mg/L	2.6	-	8-12
Chemical Oxygen Demand, COD	mg/L	80	65	150-400
Biochemical Oxygen Demand, BOD	mg/L	14	9	45-90
Oil and grease	mg/L	8.7	-	-
Total lead (Pb)	mg/L	0.140	0.144	0.01-0.10
Total zinc (Zn)	mg/L	0.240	0.160	0.06-0.40
Total copper (Cu)	mg/L	0.050	0.034	-
Faecal coliforms	FCU/100 mL	8,000	-	10^4-10^7

Elevated pollutant concentrations (compared to the data in Table 3.4) are observed during periods of snowmelt, when the pollutants accumulated in snowpacks are rapidly released and conveyed by storm sewers to the receiving waters (Viklander et al., 2003).

In older separate sewer systems, urban surface runoff is conveyed by storm sewers to the nearest receiving waters without any control or treatment. Only during the last 30 years, has stormwater management been introduced and practised by reducing runoff generation by allowing more rainwater to infiltrate into the ground, balancing runoff flows by storage and providing some form of runoff quality enhancement. Among the main pollutants of concern in stormwater, one could name suspended solids, nutrients (particularly P), heavy metals, hydrocarbons, and faecal bacteria.

3.3.2.2 Stormwater management

As a result of high discharges of stormwater, and pollutant concentrations and loads conveyed by stormwater, and their potential impacts on the environment, alternative techniques have been developed for stormwater management during the last several decades (Azzout et al., 1994; Baptista et al., 2005; Parkinson and Mark, 2005; Schueler, 1987; Urbonas, 1994), including the following:

- infiltration facilities,
- ponds and wetlands,
- swales and ditches,
- oil and sediment separators, and
- real-time control operation systems.

Infiltration may be applied in the so-called percolation basins which are specially designed as underground gravel units. This technology has been used for a very long time particularly on a small scale in rural settlements. Only during the last few decades it has been further developed and used in urban areas on a larger scale. Stormwater infiltration helps keep the groundwater table at a natural level, which promotes good conditions for vegetation and a good microclimate. The construction costs of drainage systems with infiltration facilities are also cheaper than those of conventional systems. Infiltration is also implemented on grass or other permeable surfaces, and in drainage swales and ditches. The use of this measure is steadily growing in many countries.

Ponds and wetlands have become in many countries a common and accepted means of attenuating drainage flows and treating stormwater by removal of suspended solids, heavy metals and, to some extent, nitrogen and phosphorus. The cost of construction and operation of such facilities is often low compared to the environmental benefits. The sediments from ponds may contain high concentrations of heavy metals. However, ponds and wetlands should be considered as stormwater treatment facilities and not as natural water bodies, even if they often provide aesthetic values to the urban area.

Swales and ditches are applied commonly in the upstream reaches of drainage to control runoff flows and provide runoff quality enhancement. Flow control is obtained by stormwater infiltration into the ground, quality enhancement by filtration through the turf, solids deposition in low flow areas, and possible filtration through a soil layer.

Oil and sediment (grit) separators are used to treat heavily polluted stormwater from highways or truck service areas, or where polluted stormwater is discharged into sensitive receiving waters. The efficiency of these units in trapping oil, sediments and chemicals attached to the sediments is often poor, because of under-sized units or lack of flow-limiting devices preventing the washout of trapped materials.

Real-time control operation of sewer systems has been developed during the last two decades and implemented in some Canadian, European, Japanese, and U.S. cities. The applications are often in combined sewer systems and the purpose is mainly to reduce combined sewer overflows and/or overloading of wastewater treatment plants, by the maximum utilisation of the dynamic capacities of the system (Colas et al., 2004).

3.3.2.3 Special considerations for drainage in cold climate

In countries with a cold climate (i.e., occurrence of freezing temperatures over periods of several months) the precipitation falls as snow during a significant part of the year. When the snow is cleared from streets in the cities, it is either brought to local snow dump sites, or to a central deposit site outside the city, or it is dumped into watercourses. When the snow melts, the meltwater runs off in the same way as stormwater. However, the impacts may be more severe due to the following facts:

- Snowmelt may generate high flows, causing surcharging of the sewer systems and possibly flooding in the receiving waters.
- The meltwater often has higher concentrations of heavy metals, sand and salt than stormwater (sand and salts being used for de-icing of urban roads and streets).
- The impacts of urban snowmelt on streams, lakes and ponds may be exacerbated by ice covers of such water bodies and densimetric stratification. High salt

concentrations and oxygen depletion were noted at a number of locations (Marsalek et al., 2003).

Various technologies have been adopted for treating urban meltwater. Examples are ponds, oil and grit separators, and infiltration facilities. They all have to be designed and operated with considerations of the special effects of temperature, ice and snow conditions, and the elevated pollutant concentrations (Viklander et al., 2003).

3.3.3 Combined Sewer Overflows (CSOs)

Even though combined sewer overflows are highly polluted, they are often discharged into nearby receiving waters without much treatment and cause serious pollution. The magnitude of annual CSO discharges depends on the extent of combined sewers (percent of the total), climate, and design policies and practice. The extent of combined sewers varies from country to country, in the range from 20 to 90%. Generally combined sewers are more common in climates with lower annual rainfall; for high rainfalls, the system would be too overloaded and collect a low percentage of total flows. Finally, the overflow setting, typically in multiples of dry weather flow, greatly influences the spilled CSO volume. Typical settings vary from 2 to 6 times dry weather flow (Marsalek et al., 1993).

3.3.3.1 CSO characterisation

The pollution characteristics of CSOs, while somewhat similar to those of stormwater, are strongly affected by domestic sewage and sewer sludge washout from combined sewers. Consequently, CSOs are particularly significant sources of solids, biodegradable organic matter, nutrients, faecal bacteria, and possibly some other chemicals originating from local municipal/industrial sources. During the early phase of runoff, referred to as the first flush, the CSOs characteristics approximate or even exceed pollutant concentrations in raw sanitary sewage. After the first flush, pollutant concentrations in CSOs subside. Their impacts on receiving waters are similar to those described in the preceding section, but much stronger in terms of oxygen depletion, eutrophication and increased productivity, and faecal pollution. It is desirable, therefore, to control CSOs prior to their discharge into the receiving waters.

CSOs are not routinely monitored, except for special studies of local significance. This follows from the diffuse and intermittent nature of these sources, for which large scale monitoring programs would be prohibitively expensive. Nevertheless, over the years, a fair number of studies attempting to assess these sources have been undertaken in a number of municipalities, or regions. A summary of such data from European sources was presented earlier in Table 3.4.

In comparison to stormwater, the pollution strength of CSOs is similar to that of stormwater for TSS, but greater for BOD, indicator bacteria, TN and TP, and generally smaller for unconventional pollutants, including heavy metals, PAHs and organochlorine pesticides.

3.3.3.2 CSO control and treatment

CSOs are caused by excessive inflows of stormwater into the sewer system, so any measure discussed in the preceding section for reducing stormwater runoff and its inflow into combined sewers would also help abate CSOs. Such helpful measures include all lot-level measures, infiltration measures (pits, trenches, basins, porous structures) and porous pavements (Urbonas, 1994). The mitigation of actual overflows is accomplished by various forms of flow storage and treatment; flow storage serves to balance CSO discharges, which may be returned to the treatment plant after the storm, when flows have subsided below the plant capacity (Marsalek et al., 1993).

CSO storage can be created in a number of ways: by maximising the utilisation of storage available in the existing system (e.g., through centrally controlled operation of dynamic flow regulators in real time - Schilling, 1989), as newly constructed storage on-line or off-line (on-line storage includes oversized pipes or tanks; off-line storage includes underground storage tanks or storage and conveyance tunnels), or even in the receiving waters (the so-called flow balancing systems created by suspending plastic curtains from floating pontoons, in a protected embayment in the receiving waters) (WPCF, 1989). Some storage facilities are designed for treatment, more or less by sedimentation, which can be further enhanced by installing inclined plates. Stored flows are returned to the wastewater treatment plant, which must be redesigned/ upgraded for these increased volumes. Without such an upgrade, the plant may become overloaded, its treatment effectiveness impaired and the benefits of CSO storage would be defeated.

CSO storage tanks have become a common design feature in many European sewerage systems, and are increasingly being used in North America. In this approach, an additional "storage" volume for flow and pollutant load retention is included in the form of an oversized sewer pipe or storage chamber, which is incorporated into the sewerage at the points of overflow. Tanks are normally either on-line (continually in operation) or off-line (to which flow is diverted during high-flow periods via a diversion structure).

CSO treatment takes place either at the central plant, together with municipal sewage, or can be done in satellite plants dedicated to this purpose. Various processes have been proposed or implemented for the treatment of CSOs, including settling (plain, inclined plate and chemically aided), hydrodynamic separation, screening, filtration, dissolved air flotation, and the Actiflo™ process with coagulation and ballasted settling (Zukovs and Marsalek, 2004). Furthermore, the treated effluents may be disinfected, either by conventional chlorination (sometimes followed by dechlorination), or by UV irradiation (WPCF, 1989).

Treatment technologies are available to achieve almost any level of CSO treatment, but proper cost/benefit considerations are crucial for achieving the optimal level of CSO pollution abatement, within the given fiscal constraints. Reductions in treatment capacities are obtained by flow balancing of inflows by storage (Marsalek et al., 1993). From the maintenance point of view, the operators (municipalities) prefer relatively simple treatment systems, with more or less automatic operation, and minimum maintenance requirements.

The most cost-effective CSO abatement schemes deal with the entire urban area (and all system components) and represent combinations of various source controls, storage and treatment measures, allowing various degrees of control and treatment, depending on the event frequency of occurrence (Marsalek et al., 1993). More frequent events should be fully contained and treated; less frequent events may be still fully or partly contained and treated to a lower degree, and finally, infrequent events would still cause overflows, but of reduced volumes and could receive some pre-treatment prior to their discharge into the receiving waters.

The complexities of combined sewer systems, and the dynamics of flow, storage, loads and treatment processes, make it particularly desirable to control the sewerage/treatment/ receiving water systems in real time. Real time control (RTC) was found particularly useful in systems with operation problems varying in type, space and time, and with some idle capacity (Schilling, 1989). The best developed types of RTC are those for wastewater quantity and the associated modelling. The remaining challenges include RTC of quality of wastewater and receiving waters, and reliable hardware Colas et al., 2004). It was suggested that in typical wastewater systems with no control (i.e., control by gravity only), approximately 50% of the system capacity remained unused during wet weather. By applying RTC, about half of this potential could be realized (Schilling, 1989).

3.4 WASTEWATER AND SANITATION

Urban populations require access to adequate sanitation and disposal of generated solid and liquid wastes. Such objectives are achieved by wastewater management and sanitation.

3.4.1 Problem definition

According to the "Global Water Supply and Sanitation Assessment 2000 Report" (WHO and UNICEF, 2000) the proportion of the world's population with access to excreta disposal facilities increased from 55% in 1990 to 60% in 2000. At the beginning of 2000, 2.4 billion people lacked access to improved sanitation. The majority of these people lived in Asia and Africa; for example, less than one-half of the Asian population had access to improved sanitation. In developing countries, the percentage of the population served by wastewater treatment hardly reaches 15% (U.S. EPA, 1992) and such treatment almost always consists of a primary or inefficient secondary level treatment. Effluents are frequently destined for agricultural irrigation or discharged into soils, rivers or lakes, ultimately reaching the sea. Agricultural reuse of treated wastewater effluents is the most common option in arid and semi-arid areas because of the lack of water, but also because farmers know that sewage increases productivity because of its nitrogen, phosphorus and organic matter content. Nevertheless, this practice also considerably increases health risks.

The global sanitation coverage with "improved sanitation" is estimated to be around 60%. The coverage in urban areas is significantly higher than in rural areas, ranging from 78% in Asia to 100% in North America. These numbers must be considered unreliable, due to the vague definition of urban areas and to the fact that the term "improved sanitation" includes not only connections to public sewers but also connections to septic systems, pour-flush latrines, simple pit latrines, and ventilated, improved pit latrines.

Water quality in receiving waters is affected mainly by wastewater discharges, solid wastes and wet-weather flow pollution. Impacts of such discharges depend on the type of pollutant, the relative magnitude of the discharge vs. the receiving waters, and the self-purification capacity of receiving waters.

In developed countries, even though the wastewater is treated at a secondary level, treated effluents still pollute.

3.4.2 Technological development

Some milestones in the development of modern, centralised wastewater systems are summarised below (Wolfe, 2000).

Around 3,500 BC, brick stone stormwater drain systems were constructed in streets of Mesopotamia. In Babylonia manholes and clay piping were used to connect in-house bathrooms to street sewers around 3,000 BC. In Rome the famous cloacas were constructed starting 600 BC (Cloaca Maxima). The construction of sewers in Paris started in the 14th century. An underground sewer for draining cellars and carrying away wastewater was constructed in Boston, around 1700. The City of Hamburg is credited with having built the first city sewerage system around 1840. Sewage pumps were introduced around 1880, followed by the development of screens and grit chambers to remove solid matter. The modern WC (water closet) was developed by Thomas Twyford in 1885.

Wastewater treatment technologies were successively developed from the end of the 19th century. Among the important developments were contact beds (1890), trickling filter (1901), sludge digestion (1912), activated sludge process (1913), and surface aeration (1920). Biological as well as chemical treatment systems have been steadily improved and installed, removing solids, organic matter, and nutrients from the wastewater. A schematic of such a conventional system is shown in Fig. 3.6. At the beginning of the 21st century much interest is being paid to combinations of biological treatment and different kinds of microfiltration (membrane technology). The protection of the environment from harmful discharges of wastewater is governed by laws and directives, such as, for example, the European Union Waste Water Treatment Directive 91/271/EEC (CEC, 1991), and many national regulations.

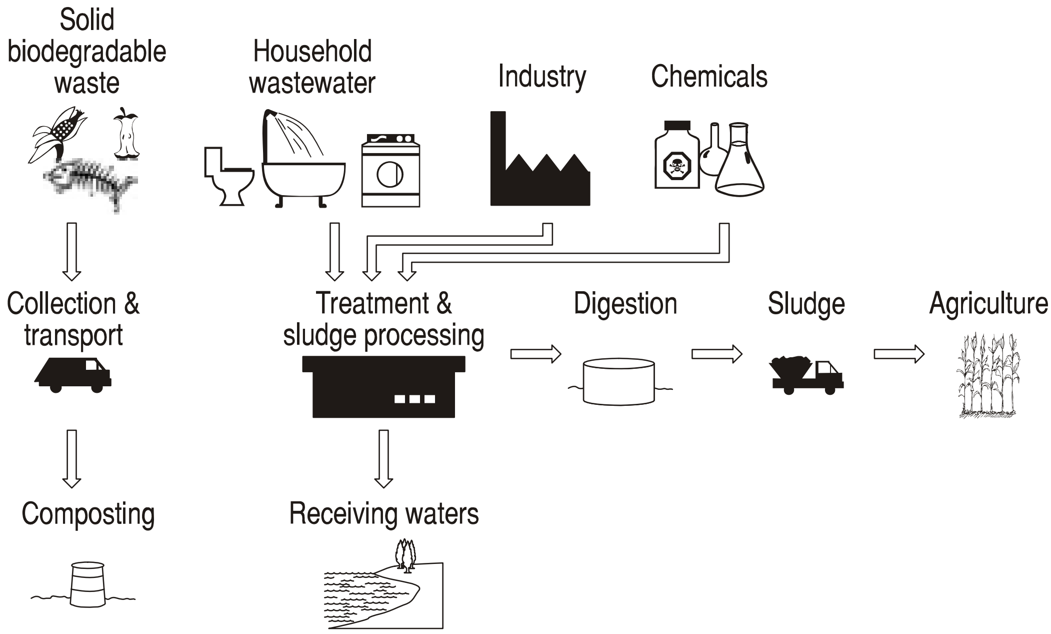


Fig. 3.6 A conventional system for managing wastewater and organic waste

3.4.3 Ecological sanitation

There is a fundamental connection between the present state in water supply, sanitation, solid (organic) waste management and agricultural development worldwide. While sustainable provision of water and sanitation for a growing population is in itself a formidable challenge, the new target is to develop technologies and management strategies that can make organic residuals from human settlements useful in rural and urban agriculture for production of food. Traditional methods used in water resources development and in provision of sanitation were, and still are, unable to satisfy the fast growing needs of developing countries.

In other words, a strong coordination between urban and rural components for nutrient and biomass recycling is required, particularly in a sustainable society. After consumption, the question is how to deal with urine and faeces and utilise them in the recycling of nutrients and biomass. One solution is a separation of urine from other household wastewater. This process is called ecological sanitation – a dry toilet with separation of urine and faeces at the source (Winblad and Simpson-Hebert, 1998). The separated urine can then be transferred to the nutrient processing plants, where nitrogen and phosphorus are recovered and transformed into chemical fertilisers.

If the urine and faeces are collected and used in agriculture, the remaining wastewater is called greywater, which is easier to treat by conventional wastewater treatment processes. Pipe systems are not necessary for collecting greywater and open channels are still acceptable for minimum conditions. The collected greywater can be treated locally and discharged to surface waters in the vicinity of the collection points (Maksimovic and Tejada-Guibert, 2001). The nutrient content of greywater is comparable to waters that by different standards are regarded as "clean" (Gunther, 2000). However, concerns about pharmaceuticals and personal care products and therapeutics in greywater exist and need to be considered in greywater reclamation and reuse. Also sludge revalorisation causes some concerns due to associated health risks, particularly in developing countries. Spreading diarrheic diseases can be a health concern unless the pathogen content in the ecosanitation sludge is greatly reduced (Jiménez et al., 2006). That is why EcoSanRes (2005) and Schönning and Stenström (2005) recommend that, even if treated, ecosanitation black matter (faeces) should be handled safely and not used to fertilise vegetables, fruit or root crops that will be consumed raw.

A greywater reuse system should be able to receive the effluent from one or more households during all seasons of the year. Where garden soils of low permeability become saturated by winter rainfall, there should be opportunities to divert excess water to sewers or to arrange an alternative disposal. The reuse system needs to protect public health, protect the environment, meet community aspirations and be cost-effective (Anda et al., 1996).

Esrey et al. (2001) summarised the basic characteristics of ecological sanitation systems as follows:

- *Prevent disease* - must be capable of destroying or isolating faecal pathogens;
- *Protect the environment* - must prevent pollution and conserve valuable water resources;
- *Return nutrients* - must return plant nutrients to the soil;
- *Culturally acceptable* - must be aesthetically inoffensive and consistent with cultural and social values;
- *Reliable* - must be easy to construct and robust enough to be easily maintained in a local context;
- *Convenient* - must meet the needs of all household members considering gender, age and social status; and,
- *Affordable* - must be financially accessible to all households in the community.

3.4.4 Basic demands on wastewater management systems

Basic demands to be met by an urban wastewater management system are pollution control, public health protection, avoidance of flooding, and recycling of nutrients.

Pollution control aims to protect the receiving waters, including creeks, streams, rivers, lakes and the sea, against discharges of wastewater that may cause eutrophication, oxygen depletion, toxicity and other negative impacts that decrease the biological diversity or impair beneficial uses of the receiving waters for such purposes as e.g., drinking water supply for downstream settlements. Pollution control is one of the major reasons for the construction of wastewater treatment plants (WWTPs).

Public health protection has historically been the major driving force behind the construction of WWTPs. In western countries as well as in developing countries the application of wastewater treatment has resulted in drastic improvements in the health standards of people living in affected areas. In particular, the introduction of disinfection has been successful, as further elaborated below.

Flooding in urban areas, which is caused either by locally generated floods or by floods generated in the upstream catchment was discussed earlier in Section 3.3.1. Local (pluvial) flooding can be exacerbated by poorly designed and functioning sewer systems. Flood damages caused by local flooding are often less severe in drainage systems using open channels, ditches or swales for flow conveyance, rather than underground sewers.

Recycling of nutrients has been included in the basic demands since the sustainability requirements were formulated at United Nations sponsored meetings in Oslo, Rio, and Johannesburg. The nutrient contents of domestic wastewater may be valuable as fertiliser in agriculture (or aquaculture). Associated problems are the contamination of the sludge with heavy metals and certain organic substances.

Additional demands on wastewater systems are that they should be affordable, accepted by the public and convenient.

Affordable wastewater systems provide such services, which the users are able to pay for. The distribution of service costs is essential, the rates should be equitable and fair to all connected. The consumers must be willing to pay the costs. As a general guideline, the World Bank recommends that the cost of water and sanitation should not exceed 5% of total family income.

The services provided must also be *accepted* by the consumers, regarding the service delivery, water quality and prices. The water and wastewater systems must be socially and culturally acceptable to the consumers. Different traditions exist in each country or region. For example, in some cultures, dry sanitation is not acceptable.

The systems must also be convenient to use. The carrying of drinking water or wastewater products has strong gender implications and should be avoided in sustainable systems.

3.4.5. Wastewater characterisation

Municipal sewage is a mixture of domestic, commercial and industrial wastewaters. In developed countries, industrial wastewaters are pre-treated prior to discharge into municipal sewers; in developing countries, industrial wastes are often not treated at all. In spite of this, the impact of industrial discharges in developing countries is smaller than in developed ones, because of a lower level of industrialisation. Typical composition of municipal sewage is described in Table 3.5.

Table 3.5 Typical composition of sewage (after Metcalf and Eddy, 2003)

Parameter	Concentration		
	Minimum	Average	Maximum
Total solids (mg/L)	350	720	1,200
Dissolved solids, total (mg/L)	250	500	850
Fixed solids (mg/L)	145	300	525
Volatile solids (mg/L)	105	200	325
Total suspended solids (mg/L)	100	220	350
Fixed solids (mg/L)	20	55	75
Volatile solids (mg/L)	80	165	275
Settleable solids (mL/L)	5	10	20
Biochemical Oxygen Demand, BOD_5 (mg/L)	110	220	400
Chemical Oxygen Demand, COD (mg/L)	250	500	1,000
Total Organic Carbon (mg C/L)	80	160	290
Total nitrogen (mg N/L)	20	40	85
Organic nitrogen (mg N/L)	8	15	35
Free ammonia (mg N/L)	12	25	50
Total phosphorus (mg/L)	4	8	15
Grease and oil (mg/L)	20	100	150
Alkalinity (mg $CaCO_3$/L)	510	100	200

As shown in Table 3.6, pathogen concentrations in developing countries wastewater are much higher than those in wastewater in developed countries.

Table 3.6 Pathogen concentration in wastewater from developing and developed countries (Chávez et al., 2002)

Microorganism	Developed countries	Developing countries
Salmonella (MPN/100 mL)	10^3-10^4	10^6-10^9
Enteric viruses (PFU/100 mL)	10^2-10^4	10^4-10^6
Helminth ova (HO/L)	1-9	6-800
Protozoa cysts (organisms/L)	28	10^3

Characteristics of industrial wastewaters vary greatly, depending on the type of industry. To protect receiving waters from industrial pollutants, it is important to develop efficient pre-treatment programs in order to have influents to wastewater treatment plant with "relatively controlled" characteristics. Without such pre-treatment, industrial pollutants might pass through conventional wastewater treatment plants without much abatement and cause damage in receiving waters.

3.4.6 Wastewater systems without separation of wastewaters at the source

Systems without separation of wastewaters at the source manage the total mixture of wastewaters, including blackwater and greywater. In terms of system architecture, they can be designed as conventional centralised systems, or less common distributed systems.

3.4.6.1 Centralised systems

Currently, most cities in all parts of the world have a centralised sewerage system with some kind of treatment. Exceptions are the poorest cities and unofficial "squatter" settlements in peri-urban areas in Africa, Asia and Latin America. They all have the same basic features: collection of the wastewater in or near the houses, transport by gravity sewers or pressure sewers to a treatment plant, and discharges to the receiving waters by longer or shorter outfalls. In many of the old sewer systems, domestic and industrial wastewater is mixed with stormwater in combined sewers. In principle, wastewater collection and treatment systems are similar in all large cities of the world. The degree of use of modern technologies may vary, depending on financial resources and political will.

However, it is reported from many developing countries that although they have access to central sewer systems and sewage treatment, the facilities do not operate properly and in some places not at all due to the lack of management, maintenance, funding and training.

Currently, the interest in research and technology advancement involves:

- further development and refinement of biological methods for nutrient removal from wastewater and the recovery of nutrients,
- the use of membrane technology for wastewater treatment,
- development of anaerobic methods for sludge digestion and treatment,
- incineration of sewage sludge (biosolids), and
- control of new chemicals of concern, including endocrine disruptors, pharmaceuticals (including antibiotics), and personal care and therapeutic products.

3.4.6.2 Distributed (local) systems

Conventional (centralised) sewerage systems are common in the central parts of most large cities, but the approaches to wastewater management are quite different in small towns or in the peri-urban areas on the outskirts of cities. Open canals are commonly used to transport human wastes and discharge them to receiving waters without treatment. Such systems are a severe threat to public health since the water in receiving streams, rivers or canals may be used further downstream for cleaning and washing, or even as a drinking water source. In densely populated areas, polluted rivers cause the same kind of a threat.

In some parts of the world, simplified and cheaper solutions are sought for the management of wastewater on a smaller scale. Examples of such technologies are listed below:

- *Wastewater infiltration.* After sedimentation, the wastewater is infiltrated into the soil in a constructed filter plant, seeping down to the groundwater. The reduction of organic matter, nutrients and bacteria may not reach the standards of a high-tech WWTP, but may be a significant improvement compared to the existing conditions. This technology should not be used for industrial effluents or for wastewaters having high contents of dissolved substances (heavy metals, organic toxic compounds, pharmaceutical residues, etc.). Also, wastewater infiltration should not be used where the affected groundwater is used as a source of drinking water.
- *Constructed wetlands.* The term “wetlands” is commonly used for many technologies: simple open ponds, several ponds in a series with or without vegetation, reed-beds with horizontal or vertical flow, and some others. In the developed countries wetlands are most commonly used as a polishing step after a WWTP, mainly for nutrient removal. The microorganisms in the wetland nitrify and denitrify the nitrogen to a certain degree, depending on the size of the wetland, the type of vegetation and the ambient temperature. In the Nordic countries, the uses of wetlands are increasing as a low-cost, natural technology, but the efficiency of the treatment is low during the winter. The major drawback of this technology is that it requires a large space.
- *Biological ponds.* These have been used for a very long time and their performance has been improved considerably. Further improvements of their performance, especially in cold climates, have been achieved and demonstrated by addition of precipitation chemicals.
- *The Living Machine.* In few places in North America, domestic wastewater is transported to hydroponics plant beds in a greenhouse and subject to treatment, while at the same time, the nutrients in the wastewater are used for cultivating

various green plants. Experimental facilities based on a similar concept also operate in Europe (Todd and Todd, 1993).

3.4.7 Systems with separation of wastewaters at the source

Originating in Sweden in the 1990s, the idea of separating domestic and other wastewaters at the source has been developed and tested in a small scale. Since then, this concept has spread and facilities exist in many other European countries, including Denmark, Germany, Switzerland and The Netherlands, although in all cases at a small scale. Several ongoing research projects deal with the refinement of these systems. The separation systems have also been applied in many places in developing countries, especially in rural areas where they may substitute for pit latrines or no sanitation at all.

The advantages of ecological sanitation in rural areas in developing countries are striking: the hygienic conditions are improved compared to simpler solutions, water is only used for cleaning purposes, and the wastewater products, urine and/or excreta, can be used as fertilisers after some minimum period of storage. Characteristics of various domestic wastewater sources are listed in Table 3.7. Although the chemical characteristics of various household wastes in developed and developing countries are similar, the biological characteristics greatly differ. For example, with reference to developing countries, the helminth ova content in untreated faeces may be as high as 3000 ova/g total solids (Strauss et al., 2003) and in treated ones from 0 to almost 600 ova/g total solids (Jiménez et al., 2005). A similar point was also emphasised in section 3.4.5.

The use of separation systems in densely populated areas has been discussed but not proven in reality. Opponents argue that the cost for redesigning the sewerage systems in houses and in the streets will be huge, and that the transport of collected urine and/or excreta will cause additional costs, nuisance and air pollution in the cities. Advocates argue on the other hand that the cost/benefits of the system are favourable when compared to the conventional system, particularly after accounting for the recycling of nutrients and the use of natural resources. It would seem that the separation system may be feasible in peri-urban areas and "informal" settlements where sewerage systems still do not exist and the extension of the central system to the outlying parts of the city would be too costly or almost impossible due to the lack of space and financial resources.

Table 3.7 Composition of urine, faeces, greywater, household wastewater and compostable household waste in Sweden (in kg/person equivalent/year) (Jönsson et al., 2005)

Parameter	Urine	Faeces, incl. toilet paper	Greywater total	Household wastewater	Compostable household waste
TSS	7	19	26	53	25
VSS	3	17	15	35	21
COD_{tot}	3	23	23	49	34
BOD_7	2	12	12	27	12
N_{tot}	4.0	0.5	0.6	5.1	0.6
P_{tot}	0.33	0.18	0.25	0.76	0.10
S_{tot}	0.26	0.06	0.17	0.48	0.05
K_{tot}	0.88	0.33	0.29	1.49	0.23

A schematic of blackwater separation is shown in Fig. 3.7.

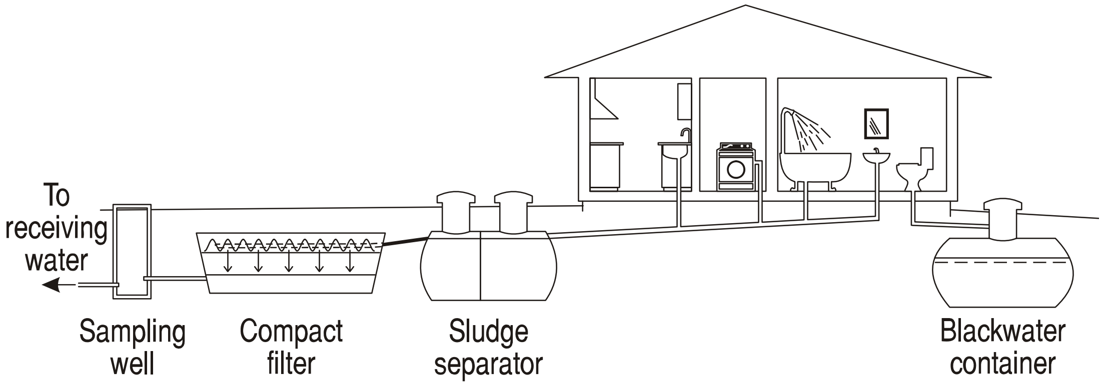


Fig. 3.7 Blackwater separation

3.4.8 Water and wastewater reuse

Water scarcity in many parts of the world causes stress on water supplies, which occurs when the demand for water exceeds the available amount during certain periods or when poor quality restricts the use of water. Water stress causes deterioration of fresh water resources in terms of quantity (aquifer over-exploitation, dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.) (EEA, 1999). In urban areas this has emphasised the need for developing other kinds of water resources, such as desalination of seawater, collection of rainwater and reclamation of used water.

The reuse of treated wastewater has been practiced in many countries over a long time, mostly for recharge of over-exploited aquifers by infiltration. Moreover, the reuse of untreated wastewater is also practiced in some regions of the world due to the lack of water and economic resources to treat wastewater before reuse. It is estimated that at least 21 million ha are irrigated with treated, diluted, partly-treated or untreated wastewater (Jiménez and Asano, 2004). In some urban areas, wastewater has been used for agricultural irrigation. The "urban agriculture" is practiced in urban and peri-urban areas of arid or humid tropic countries due to wastewater availability, local demand for fresh produce and the need to support people living on the verge of poverty. Wastewater flowing in open channels is used to irrigate very small plots of land where trees, fodder or any other crops that can be brought to the market in small quantities (flowers and vegetables) or be used as part of the family diet are grown (Cockram and Feldman, 1996; Ensink et al., 2004a). One-tenth or more of the world's population consumes crops irrigated with wastewater (Smit and Nasr, 1992). The use of wastewater can vary considerably from one region to another; for example, in Hanoi, Vietnam, up to 80% of vegetables locally produced are irrigated with wastewater (Ensink et al., 2004b).

More recently, direct use of treated stormwater and wastewater has been introduced in some countries in most regions of the world. On a small scale, reuse of stormwater and greywater has been applied in some European countries (The Netherlands, UK, and Denmark) for garden irrigation and for flushing of toilets. In some cases, certain drawbacks have been observed; most are due to cross-connections with the drinking water supply system, causing risk of spreading waterborne diseases. In 2003 the use of treated greywater was prohibited in the Netherlands for this particular reason.

In other parts of the world, the need for developing complementary water resources has forced water authorities to go one step further by applying high-tech treatment and delivering reclaimed water to the customers for various uses. Some examples are given below.

Various types of waters, including reclaimed wastewater, are used in aquaculture to produce fish and grow aquatic crops. Some guidance can be obtained from WHO guidelines (WHO, 1989), which are currently under review.

3.4.8.1 NEWater in Singapore

In February 2003, Singapore started to replenish about 1 percent of its total daily water consumption with reclaimed wastewater, which was named NEWater. NEWater is mixed and blended with raw water in the reservoirs before undergoing conventional treatment at the waterworks for supply to the public for potable use. The amount will be increased progressively to about 2.5% of total daily water consumption by 2011. Singapore suffers from a water shortage and buys more than half of its water demand from neighbouring Malaysia under decades-old treaties, which will start expiring in 2011. The water trade has caused many arguments between the two nations over pricing and other issues. The wastewater used is the product from a multiple barrier water reclamation process. Treatment steps are conventional wastewater treatment, microfiltration, reverse osmosis and finally ultraviolet disinfection. The quality of the reclaimed water fulfils all requirements and is in most aspects better than the raw source water currently used (more information can be obtained from Public Utilities Board and the Ministry of the Environment and Water Resources, Singapore, www.pub.gov.sg/NEWater/).

3.4 8.2 Shinjuku water recycling centre, Tokyo, Japan

The water recycling centre in the Shinjuku district of Tokyo, distributes advanced treated wastewater for toilet flushing in high rise office buildings in the districts of Shinjuku and Nakano-Sakaue. The reclaimed water is supplied from the Ochiai wastewater treatment plant (WWTP), located 2 km from the water-recycling centre. The treatment process applied in reclamation includes conventional secondary wastewater treatment (primary sedimentation, activated sludge process and secondary sedimentation) supplemented by rapid sand filtration. At present, the water recycling system operates in 26 high-rise buildings. Differentiated fees for water supply were implemented to support the choice of recycled water, rather than municipal drinking water, for toilet flushing (Asano et al., 1996).

3.4.8.3 Wetlands with fish production in Calcutta, India

The City of Calcutta, India has ancient wetland traditions, and the existing techniques are used for direct recycling of nutrients in the city, which is one of the largest in the world. The sewage system in central Calcutta was constructed in the 1870s, and is completely inadequate today. Some parts of the city constructed in later stages of the city development have no sewers at all. There is also frequent flooding during the monsoon period. Currently, there is one wastewater treatment plant operating in Calcutta, and two more plants are under construction.

Most of the wastewater in Calcutta remains untreated today, and will remain untreated when the ongoing project is completed. However, some of the untreated wastewater is diverted into Calcutta's wetlands, which are part of the largest aquaculture area in the world. Wastewater is pumped directly to huge wetlands where fish are cultivated and sold on the market. Use of wetlands has a centuries old tradition in India. In the 1980s, systematic follow-up studies of the wetlands were initiated, under the auspices of the newly established Institute for Wetland Management and Ecological Design (IWMED). The area is enormous, corresponding to 12,000 ha, and produces one sixth of all the fish consumed in Calcutta (Ghosh, 1999).

3.4.8.4 Reuse of (untreated) sewage for agricultural irrigation in the Mezquital Valley (Mexico City sewage disposal)

Mexico is a country with apparent water sufficiency at the national level. However, two thirds of the territory suffers from a lack of water. Frequently, municipal wastewater is used for irrigation. In 1995, a total of 102 m^3/s of wastewater was used to irrigate about 257,000 ha in the country. An example of this practice is Mexico City sewage, which has been used to irrigate the Mezquital Valley, north of the city, since 1896; 52 m^3/s of wastewater without any treatment has been used to irrigate several crops and has permitted the economic development of the region. This is the largest and oldest scheme of agricultural irrigation using urban wastewater in the world (Mara and Cairncross, 1989). As a result of this practice, the water table of the aquifer underlying the irrigation zone has been rising. The unplanned artificial recharge is about 25 m^3/s and springs with capacities of 100 to 600 L/s started appearing 35 years ago (Jiménez and Chávez, 2004). This "reclaimed water", treated only with chlorine, is being used to supply 300,000 inhabitants of the region for human consumption. Several studies have shown that the water meets potable norms and another 288 parameters from WHO human consumption guidelines, including toxicological tests (Jiménez et al., 2001). Also, this wastewater is enriched in nutrients, as confirmed by increased yields of agricultural crops (see Table 3.8).

Table 3.8 Yield increase as a result of irrigation with wastewater in the Mezquital Valley, Mexico (Jiménez et al., 2005)

Crop	**Yield** (tonnes / ha)		**Increase**
	Wastewater	Fresh Water	(%)
Maize corn	5.0	2.0	150
Barley	4.0	2.0	100
Tomato	35.0	18.0	94
Oats for forage	22.0	12.0	83
Alfalfa	120.0	70.0	71
Chili	12.0	7.0	70
Wheat	3.0	1.8	67

3.4.8.5 Reuse of stormwater and greywater in Sydney, Australia

Serious water shortages in Sydney, Australia during summer prompted Sydney Water to encourage the reuse of stormwater and greywater, besides the ongoing intensive water saving and conservation campaigns. The use of reclaimed water for garden irrigation is encouraged, either by using treated greywater or stormwater collected in separate tanks. Advice to house owners can be found on the website www.sydneywater.com.

Sydney Water also introduced the distribution of reclaimed water. One example is the Rouse Hill Development area. These homes have two water supply systems, reclaimed water and drinking water. To ensure that the drinking water is not confused with the recycled water it is delivered by a separate distribution system. The reclaimed water taps, pipe-work and plumbing fittings are coloured lilac for easy identification. Reclaimed water is passed through a complex treatment train including ozonation, microfiltration and chlorination, in addition to the customary high level of treatment. The reclaimed water is subject to strict guidelines that limit its use to toilet flushing and outdoor purposes, such as car washing and garden irrigation (NSW Health, 2000).

Chapter 4

Impacts of Urbanisation on the Environment

4.1 OVERVIEW

Urbanisation affects many resources and components of the environment in urban areas and beyond. Even though the discussion in this report focuses on water, brief discussions of some connected issues, or other environmental compartments interacting with urban water, cannot be avoided. Thus, for the sake of completeness, the discussion covers, in various degrees of detail, impacts of urban areas on the atmosphere, surface waters, wetlands, soils, groundwater and biota.

Urban areas produce air pollution and release heat into the atmosphere. In turn, air pollution of local or remote origin may be a significant source of pollutants found in wet and dry urban precipitation and in urban waters. Heat releases in urban areas lead to the so-called heat island phenomenon with elevated air temperatures, which then affect local climate and snowmelt.

The soil-water interface is important with respect to soil erosion, leaching of chemicals from soils into water, and on-land disposal of residue from stormwater or wastewater treatment. These interactions may affect both the water and the soil.

Most of the published literature on the effects of urbanisation addressed impacts on surface waters, which may include streams, rivers, impoundments, reservoirs, lakes, estuaries and near-shore zones of seas and oceans. The transition from aquatic to terrestrial ecosystems is provided by fresh or salt water wetlands, which are discussed separately from surface waters.

During the past 10-20 years, a great deal of attention has been paid to urban groundwater, which is affected by urbanisation with respect to both quantity and quality. Depending on local circumstances, urbanisation affects aquifers and groundwater tables through either reduced recharge (increased runoff) or increased recharge (leaking water mains, leaking sewers, stormwater infiltration), and pollution by infiltrating effluents or accidental spills.

Finally, changes in the urban environmental compartments greatly affect the urban biota, particularly the fish and wildlife, with respect to health, abundance and biodiversity.

Each of the urban environmental compartments can be subject to various types of impacts, which occur in the urban environment in various combinations and magnitude. For convenience, it is useful to discuss these impacts under such headings as physical, chemical, and microbiological, but the overall effect is generally caused by the combined impacts of the earlier named categories. Considering the great diversity of topics discussed in this chapter, some guidance to following the material in this chapter is offered in Table 4.1, which provides classification of urbanisation impacts on environmental compartments and illustrates this classification by the examples listed in the table.

Table 4.1 Classifications and examples of impacts

Type of Impact	Environmental Compartment Atmosphere	Surface Waters	Wetlands	Soil	Ground-water	Biota
Physical	Heat island, increased precipitation downwind, dry deposition	Increased surface runoff and flooding, higher water temperature	Changes in water balance	Increased erosion, changes in physical structure	Lower or higher water table	Loss of habitat, benthic organism burial
Chemical	Acid or toxic rain	Pollution of streams and lakes	Pollution	Soil pollution	DNAPL contamination	Toxic effects, loss of biodiversity
Micro-biological	Small risk of exposure during sludge handling	Faecal pollution of beaches or drinking water sources	Changes in bacterial ecology	Changes in bacterial ecology due to sludge application	Polluted drinking water	Risk of biotic impacts (diseases)
Combined	Smog	Loss of biodiversity, impairment of beneficial uses	Loss of biodiversity, impacts on biota	Landfills	Degraded aquifers	Loss of abundance, loss of biodiversity

4.2 GENERAL CHARACTERISATION OF URBANISATION EFFECTS

The process of urbanisation changes the landscape as well as material and energy fluxes in the urban areas, thereby affecting the urban environment. Changes in landscape and runoff conveyance are particularly important with respect to surface runoff and its characteristics. Other changes are caused by construction of urban infrastructures, increased water consumption in urban areas, and releases of solids, chemicals, microorganisms, and waste heat. Water leaves urban areas in the form of urban wastewater effluents, (UWWE), which include stormwater, CSOs and municipal wastewaters. Such types of effluents differ in their physical, chemical and microbiological characteristics; consequently, their effects also differ and will be discussed separately within a common framework of impacts. Because of the dynamic nature of UWWE discharges and the associated pollutant levels, loads and effects, the temporal and spatial scales of individual effects are also important (Lijklema et al., 1989). Some effects manifest themselves instantaneously; others may become apparent only after periods of many years. With respect to spatial scales, the magnitude of discharges and the number of outfalls vis-à-vis the type and size of receiving waters are also of great importance. Further discussion of these factors follows.

4.2.1 Increased ground imperviousness

Perhaps the most visible consequence of urbanisation is the increase in the extent of the impervious ground cover that strongly limits the possibility of water infiltration. High imperviousness is particularly noticeable in downtown areas, where it reaches almost 100%. In many countries, the rapid increase in catchment imperviousness is a relatively recent phenomenon; in France, for example, the area of the impervious surface has increased tenfold between 1955 and 1965.

Increased imperviousness affects runoff in several ways. Firstly, it increases runoff volumes. This effect is often cited when explaining urban floods. However, if the runoff volume increase plays an important role for frequent storm events, or even for the events corresponding to the return periods considered in the design of minor drainage systems (generally about 10 years), it is not the most important factor for extreme events.

Indeed, the infiltration capacity of the majority of pervious soils, in the absence of a dense forest cover, or except for sandy grounds, is much lower than the rainfall intensities than can be observed during exceptional rainstorms. Thus, in this type of a situation, permeable soils often yield specific runoff volumes (volume of runoff per unit area), which approach those of the impermeable soils. For example, during an extreme flood on the Yzeron River in the Lyon area in April 1989, the runoff coefficient of the rural part of the catchment was estimated at 50% and the corresponding value for the urban part was 60%.

Another significant consequence of increasing ground imperviousness is the lack of recharge of groundwater aquifers (Leopold, 1968). This phenomenon can be accentuated when water is withdrawn from the same aquifer for urban water supply. More importantly, besides the direct effect of depletion of the water resource, the lowering of the water table is likely to cause land subsidence, which in some cases can reach several metres, as reported for example in the Mexico City (Figueroa Vega, 1984). Such extreme subsidence then affects the stability of buildings. For example, during the drought spell in France in the early 1990s, the allowances paid by the insurance companies for damages to buildings (cracks, fissures, etc.) were ten times higher than the monetary losses in agriculture. However, in certain cases, exfiltration from urban water infrastructures (drinking water mains, sewers and stormwater management measures) can partially compensate the deficit in rainwater infiltration. For example, in an urban agglomeration of 50 km^2, with imperviousness of 50% and water consumption of 100,000 m^3 per day, the water supply distribution network losses (leakage) of 20% are equivalent to a groundwater recharge by infiltration of 300 mm of rainfall per year. Similar values were reported by Lerner (2004).

4.2.2 Changes in runoff conveyance networks

As the urbanising area develops, there are profound changes in runoff conveyance, by replacing natural channels and streambeds with man-made channels and sewers. In general, these changes increase the hydraulic efficiency of runoff conveyance by increasing the speed of runoff. This process starts with overland flow in headwaters of the catchment and progresses to the receiving streams and rivers, which are canalised to increase their hydraulic capacity and protect their beds against erosion. Finally, the general drainage pattern of the catchment is also affected by transportation corridors required in urban areas.

4.2.2.1 Construction of runoff conveyance networks

In urban areas, a natural drainage network, which may be temporary and comprising sinuous waterways partly blocked by vegetation, is replaced with an artificial conveyance network, which is often oversized in the upstream parts and characterised by a straight layout to limit its length, and laid on significant slopes to decrease drain sizes (and thus reduce costs) and improve its self-cleansing. The same process also takes place in peri-urban areas, with respect to the drainage of soils and the canalisation of the brooks, creeks and ditches. This canalisation, which is generally presented as an effective means of preventing flooding, often has its origin in the occupation of the flood zone (i.e., a major stream bed) by buildings or roads. However such major stream beds constitute a natural part of the flood plain, and thus play a role in regulating the flows transported to the downstream reaches. The increase in runoff speed and the resulting shortening of the catchment response time contribute to higher runoff peaks through two mechanisms: (a) faster transport processes, and (b) greater intensities of the critical rainfall, which apply to the shortened response times.

4.2.2.2 Canalisation of urban streams and rivers

For various reasons, urbanisation usually leads to modification of river courses, by damming, widening and training. Little brooks are gradually canalised, covered and buried. Most important watercourses are enclosed between high embankments, which completely isolate them from the city. In many cities, after centuries of progressing urbanisation, urban rivers are now regarded only as "virtual sewers". The results of this state of affairs are twofold.

- Urban rivers are gradually forgotten by the citizens who only perceive their harmful effects.
- Urban rivers are enclosed in a too narrow “corset” and thereby have lost any "natural" possibility of spilling onto natural flood plains in the case of floods.

Consequences can be catastrophic; the city, which is appropriately protected as long as the water levels remain below the top of the embankments or dams, is suddenly inundated when the flow increases, or these protective structures fail. No longer accustomed to the presence of water, the city then reveals and manifests its increased vulnerability by incurring damages of sensitive equipment located underground (telephone switchboards, electric transformers, pumping stations, etc.), damages to subways and in underground car garages, loss of important supplies of vulnerable goods on ground floors, sweeping away of cars by floodwaters (because of their buoyancy), inexperience of urban dwellers in coping with floods, etc. All the above factors help transform the crisis into a catastrophe.

From an ecological point of view, the anthropogenic changes and river training also have important consequences. A river is indeed a “living” entity, which must be considered in all its temporal and spatial dimensions. From the spatial point of view the river equilibrium depends on many conditions:

- upstream-downstream continuity (longitudinal dimension),
- habitat diversity (nature of the banks, width of the bed, speed of flow, depth of the river, etc.),
- connections between the major stream bed and hydraulically connected water bodies (lateral dimension), and
- flow exchange between rivers and aquifers (vertical dimension).

Construction of embankments and dams, bed dredging, canalisation, and construction of new underground structures and foundations, all impoverish the river habitat and decrease its capacity to be regenerated.

Temporal dynamics of rivers must also be considered. The succession of high and low water stages, either episodic or cyclic (temporal dimension) is necessary for river equilibrium. For that reason, the training and regulation of watercourses, building dams to reduce floods and/or to maintain low flows, can be extremely harmful.

4.2.2.3 Interfering transport infrastructures

The third important consequence of urbanisation is the construction or expansion of transportation corridors (motorways, railways, etc.). These projects often involve large earthworks; the resulting infrastructures can be either very high, compared to the original ground elevations, or very low in the form of deep cuts. As a consequence, these earthworks superimpose a relief on the natural one, which, particularly in flat terrain, can considerably modify the surface runoff and drainage patterns in two ways, both of which contribute to increased flood risk:

(a) When the linear infrastructure is laid perpendicularly to the slope and the natural direction of flow of water, transportation corridors constitute physical barriers (dams) that force the runoff towards the provided flow openings (culverts), which are generally superimposed on natural and obvious waterways (brooks, main thalwegs of streams, etc.). Earthworks even can, in certain cases, significantly modify the delineation of the catchments themselves.

(b) When the linear infrastructures are laid in the direction of the slope, they become constructed channels, sometimes with steep slopes, often rectilinear, and always characterised by low flow roughness compared to natural waterways.

4.2.3 Increased water consumption

By definition, urbanisation results in a population increase, and in most cases, an improvement of sanitation. Both have the same consequence: an increased consumption of water. This consequence is not always obvious, since urban water demand is usually much lower than agricultural water needs. For economic reasons, the water needed is typically withdrawn from the closest source (a river or aquifer); the pressure on such a water resource can become excessive and result in the lowering of the groundwater table or a severe reduction of low flows. A detailed discussion of this issue was provided in Chapters 2 and 3.

4.2.4 Time scales of urbanisation effects

Concerning time scales, two types of UWWE effects are recognised, acute and cumulative (Harremoes, 1988). Acute effects are almost instantaneous and may be caused, for example, by flow (flooding), and discharges of biodegradable matter (impact on dissolved oxygen levels), toxic chemicals (acute toxicity), and faecal bacteria (impacts on recreation). In the case of acute effects, the frequency and duration of occurrence of pollutant levels are important. Transport processes in the receiving waters, including effluent mixing and dispersion, and pollutant decay, are all important and influence the resulting ambient concentrations. The frequency of acute effects is related to the frequency of rain and snowmelt events. The duration of such effects exceeds the duration of rainfall and snowmelt events by the duration of the so-called 'wet weather after-effects' (the persistence of the wet-weather disturbance) which varies from a few hours in well-flushed or stable receiving water systems to more than one day in water bodies with limited circulation (Tsanis et al., 1995).

Cumulative effects (sometimes called chronic effects) generally result from a gradual build-up of pollutants or stresses in the receiving waters and manifest themselves only after such accumulations exceed a critical threshold, as may be the case of nutrients and toxicants released from accumulated sediment, or geomorphologic changes in urban streams. For pollutants causing cumulative effects, short time-scale dynamics is unimportant and the main interest consists in loads integrated over extended time periods (generally years or decades).

4.2.5 Spatial scales and types of receiving waters

UWWE effects on surface waters also depend on the magnitude of effluent discharges and the type and physical characteristics of the receiving waters. All receiving water bodies can cope with some input loads without a serious impairment of their integrity, but problems arise when this capacity is exceeded. With reference to UWWE discharges, the receiving surface waters range from creeks and streams, rivers, lakes or reservoirs of various sizes, to estuaries and oceans.

The UWWE effects are most serious in small urban creeks with wet-weather inflows vastly exceeding the creek flow and minimal dilution of effluent discharges. Small streams can be severely impacted by cumulative effects of elevated discharges, and incoming discharges of chemicals, pathogens and heat. The morphology of such streams may change dramatically and these changes contribute to physical habitat destruction. In rivers, the mixing and dispersion of UWWE pollutants are important processes that reduce pollutant concentrations outside of the mixing zones. Acute effects are generally less common than in streams/creeks because of large input dilution and the riverine self-purification capacity. Typical urban runoff flows may be too small to affect the stream geomorphology, which is governed by the streamflow regime.

UWWE effects on lakes and reservoirs depend on the size of such water bodies. The most impacted are small impoundments in urban areas (e.g., stormwater ponds), particularly by faecal bacteria, nutrients, and contaminated sediment. The large influx of sediments also destroys the physical habitat. In the case of large lakes (e.g., the Great Lakes in Canada and the United States), UWWE discharges typically affect only the near-shore waters in the vicinity of urban areas and their sewer outfalls. Finally, potential effects of UWWE on ocean waters are minimal; however, municipal effluents, in general, do impact on harbours, estuaries and coastal waters.

Characteristics of the urban area and the receiving waters determine the spatial scales of UWWE effects. Stormwater outfalls are dispersed in large numbers throughout urban areas, with hundreds or thousands of outfalls. CSO outfall points are consolidated to fewer locations. Finally, sewage effluents, which are also called point sources of pollution, are discharged typically at one or few locations along the river, usually downstream of the urban area, or via outfalls, which may extend deep into a lake or ocean. Such arrangements reduce sewage effluent impacts on urban waters. On the other hand, pollutant transport in the receiving waters further increases the spatial extent of UWWE effects.

Spatial and temporal scales of various processes in receiving waters are shown in Fig. 4.1 (Lijklema et al., 1989).

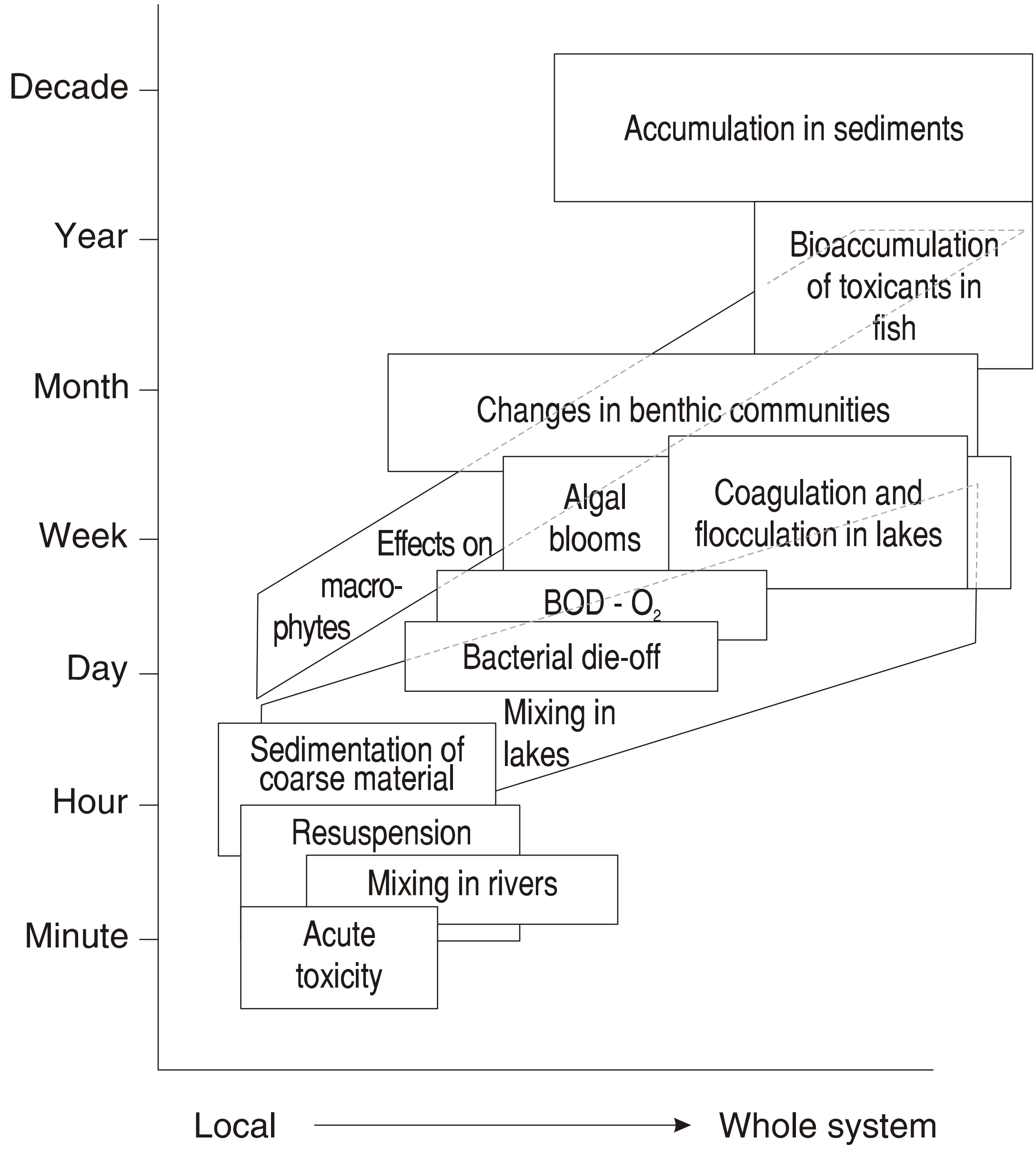


Fig. 4.1 Relation between the rates of processes and spatial and temporal scale of effects (after Lijklema et al., 1989)

4.3 URBANISATION EFFECTS ON THE ATMOSPHERE

Urban areas and land use activities result in many types of effects on the atmosphere. A full discussion of such effects is outside the scope of this report focusing on water issues, and consequently, only the issues relevant to urban water are briefly introduced below. The most obvious connections between the urban atmosphere and water include elevated temperatures affecting urban precipitation and snowmelt, and air pollution contributing to wet and dry deposition in urban areas, pollution of precipitation, and increased precipitation due to the presence of condensation nuclei.

4.3.1 Thermal effects (urban heat island phenomenon)

Urban areas are known to attain higher air temperatures than the surrounding rural areas, because of differences in thermal balances. Higher temperatures in cities (by 4-6°C, Geiger et al., 1987) result from several factors, including: (a) net solar energy gains, which are not moderated by evaporative cooling (low presence of water surfaces or vegetation subject to evapotranspiration), (b) waste heat from buildings and means of transportation (this may represent up to one third of solar energy input), and (c) "canyon structure" of tall buildings trapping solar energy and reducing infrared heat losses. This phenomenon may be somewhat mitigated by strong winds, and it may increase cloudiness and precipitation in the city, as a thermal circulation sets up between the city and surrounding region (Myer, 1991).

4.3.2 Urban air pollution

Air transport of pollutants through the atmosphere occurs in two forms, as short-range or long-range transport, with the former being common and intense in urban areas. The air pollution originates in urban and industrial areas from gaseous emissions, volatilisation of toxic compounds from water and soil, and particles from land use activities and wind erosion. The transport of pollutants in the atmosphere, with respect to the direction and distance travelled, and concentration levels can be described as a pollution plume, with the highest concentrations near the emission source. The dispersion of pollutants in the atmosphere depends to a large extent on the height of the mixing layer, wind velocity and the atmospheric temperature. Only certain pollutants are routinely measured in the atmosphere, including sulphur dioxide, nitrogen oxides, suspended particles, carbon monoxide and ozone. The acid rain precursors, oxides of nitrogen and sulphur, and particles are relatively easily transferred to water and soils; other constituents, because of their solubility and instability, may not be readily transferable to other environmental media. Typical sources of air pollution include traffic, heating, industrial operations, paints, gasoline evaporation and gas leaks. A detailed assessment of air pollution in 20 megacities of the world was provided by UNEP and WHO (1992).

Air pollution contributes to pollution of urban precipitation in the form of acid or polluted rain. SO_x and NO_x combine with atmospheric water to produce H_2SO_4 and HNO_3 acids. Various forms of precipitation, such as rain, snow, dew, fog, sleet or hail, transport these acids into soils and water bodies. Acid rain can be generated and deposited locally, but it can also be transported hundreds or thousands of kilometres by wind, and affect large areas. Acid rain in urban areas corrodes metallic surfaces and damages urban infrastructure, buildings, historical monuments, and plants, and also affects water bodies and soils with low alkalinity or capacity to control pH changes (Henry and Heinke, 1989). In vegetated areas, it weakens trees and other plants, and in soils, it limits the nutrient availability to plants and extracts aluminium from soils, which impairs soil structure and permeability. Acid rain may also leach metals from soils, and such dissolved metals may be toxic to aquatic biota. Acidic deposition accumulates in snowpacks and is suddenly released during the final snowmelt, causing an acidic shock in receiving streams, resulting in fish kills.

Besides inorganic acids, organic acids, which are toxic to biota at certain levels, are also commonly found in the air and marginally contribute to the acid rain phenomenon. Of these, formic, acetic and propionic acids are more common in water, as they are highly soluble. Hydrocarbons are also transferred from the air to water and soils by atmospheric deposition. They originate from combustion or volatilisation of fuels, and the use of paints and solvents. Observations in Mexico City indicate that annual air emissions include 20,000 tonnes of particles smaller than 10 microns, 22,500 tonnes of SO_2, 1,800,000 tonnes of CO_2, 206,000 tonnes of NO_x and 465,000 tonnes of hydrocarbons (Molina and Molina, 2002). Nitrogen compounds in the atmosphere contribute to the eutrophication of lakes as well as to increasing nitrate concentrations in groundwater.

Air in cities contains solid particles of diverse sizes and origins. Such particles are scavenged by rain and transported into soils and surface waters. The composition of particles is of great concern, because they frequently absorb metals, toxic organic compounds and gases. For example, fine particles produced by diesel vehicles have been shown to contain 1,3-benzene and butadiene, which are both well-known carcinogenic compounds (Fernandez-Breaumontz, 1988). Besides water quality effects (and human health effects), the presence of particulate in the atmosphere contributes to increased precipitation, because such particles serve as condensation nuclei in formation of rainfall droplet. Increased precipitation (by 5-30%) downwind from urban areas was reported by Geiger et al. (1987).

4.3.3 Combined impacts

From the human health point of view, a particularly dangerous form of air pollution is smog, which describes a noxious mixture of air pollutants (fine particulate and gases) held in stagnant masses of air over urban areas, particularly during thermal inversion. This phenomenon was first observed and the term smog coined in London, U.K., where a combination of fog and smoke created serious air pollution problems resulting in thousands of additional deaths during smog spells. The two key components of smog are airborne particles and ground-level ozone. Airborne particles are solids or minute droplets of liquid that are suspended in the air for days or even weeks. Ground-level ozone is produced by photochemical reaction between nitrogen oxides (NO_x) and volatile organic compounds (VOC) (UNEP and WHO, 1992).

4.4 URBANISATION EFFECTS ON SURFACE WATERS

Urbanisation strongly impacts on surface waters, particularly in the case of streams, small rivers, impoundments, lakes, estuaries and coastal waters. The physical setting and explanations of such effects were introduced in Section 4.2; a more detailed discussion of various types of effects follows.

4.4.1 Physical effects

4.4.1.1 Urbanisation effects on flows

The process of urbanisation results in high catchment imperviousness (increased volume of runoff), fast runoff (increased speed of runoff) and quick catchment response to critical rainfall of reduced duration, all of which contribute to increased runoff flows, as demonstrated in Figs. 2.2 and 2.3 displaying attributes of predevelopment and post-development runoff hydrographs.

While the first two reasons for runoff peak increase after urbanisation (i.e., increased volume and speed of runoff) are well understood, the third reason, the reduced catchment response time, making the catchment more sensitive (responsive) to rain events of shorter duration and higher intensity, and therefore producing higher specific runoff rates, is less obvious and deserves further discussion. Theoretically, for a given homogeneous catchment, the critical rainfall producing the greatest runoff is that whose duration, t_d, is equal to the time of concentration of the catchment, t_c. Indeed, if the duration is shorter, ($t_d < t_c$), the whole catchment area does not contribute fully at the same time to the flow at the catchment outlet. On the other hand, for a given return period, the shorter the rain duration, the higher its average intensity. For that reason, shorter response times result in shorter times of concentration, and greater intensities of the critical rainfall. This phenomenon undoubtedly plays the most important role among the factors discussed. Numerical simulations show that a reduction in the catchment response time by 20-50% leads to corresponding peak flows increased by a factor ranging from 5 to 50.

Water balances of impoundments and lakes receiving urban runoff are also affected, with generally higher inflows during the wet seasons and lower inflows in summer.

Environmental effects of increased flows include flooding (addressed in Section 3.3.1), sediment and habitat washout (Borchardt and Statzner, 1990), and morphological changes (Schueler, 1987).

4.4.1.2 Urbanisation effects on sediment regime: erosion and siltation

Among the effects of increased runoff flows and their durations are secondary effects on sediment erosion, transport, increased concentrations of suspended solids and sediment deposition (siltation) in slowly moving stream reaches. Soil erosion is intensified in urbanising areas as a result of two factors: the stripping of natural protective vegetative covers from the soil surface during construction and increased runoff flows, which cause sheet erosion, scouring in unlined channels and transport of eroded material to the downstream areas (Horner et al., 1994). Wolman and Schick (1962) reported that sediment yields from natural catchments were as low as 100 t/km^2/year, but increased more than 100 times during urbanisation. After completion of the urban development and the establishment and consolidation of surface covers, the sediment yields drop to the predevelopment, or even lower, values (Marsalek, 1992). Thus, excessive soil erosion in urban areas is a transient process, which should be mitigated by implementation of erosion and sediment control programs.

Excessive erosion causes ecological damages by sweeping away habitats and expanding stream channels (both width and depth) either gradually, or as a result of a single severe storm resulting in rapid downcutting, or channel incision (Booth, 1990; Urbonas and Benik, 1995). Eroded soils contribute to increased concentrations of suspended solids, which cause a number of direct and indirect environmental effects. These effects include those associated with reduced sunlight penetration (interference with photosynthesis); blanketing of gravel substrates where fish spawn and rear their young, and where algal and invertebrate food sources live; filling up pools where fish feed, take refuge from predators and rest; damaging fish gills and other sensitive tissues; reducing visibility for catching food and avoiding predators; transporting various pollutants; and, contributing to loss of riparian vegetation (with the concomitant loss of shade and refuge) and large woody debris forming a part of aquatic habitat (Horner et al., 1994). Another cause of stream siltation is the large load of suspended solids carried by treated and untreated sewage effluents and discharged to the receiving waters.

Sediment conveyed by urban runoff is deposited in receiving impoundments and lakes, where it causes similar effects as in streams, particularly with respect to siltation and increased concentrations of suspended solids in the water column

Erosion and siltation impacts can manifest themselves on various time scales; a single large rainfall/runoff event can cause significant impacts, but generally long-term impacts are more important. Ecological impacts include those related to critical species and dispersal and migration; and, practically all beneficial water uses are affected (water supply, bathing, recreation, fishing, industrial water supply and irrigation) (Lijklema et al., 1993).

4.4.1.3 Modification of the thermal regime of receiving waters

The urban environment contains numerous sources of heat, which increase the temperature of surface runoff. This warming of runoff is particularly strong during the summer months, when rainwater comes into contact with hot impervious surfaces (pavements, roofs) or is exposed to solar radiation in storage facilities (Van Buren et al., 2000), and stream discharges are low. The resulting stormwater temperatures may exceed those in the receiving waters by up to 10°C (Schueler, 1987) and contribute to long-term changes in the receiving water temperature as the development of the basin progresses. Additional waste heat is conveyed by wastewater treatment plant (WWTP) effluents, which are generally discharged at a single point.

Aquatic organisms have characteristic temperature preferences and tolerance limits. As catchment development progresses and thermal enhancement takes place, the original cold-water fishery may be succeeded by a warm-water fishery, cold-water algal species (mainly diatoms) may be replaced by warm-water filamentous green and blue-green species, and cold-water invertebrates (where they exist) are also adversely affected (Galli, 1991). Ecological impacts of thermal enhancement include those related to energy dynamics, food web, genetic diversity, and dispersal and migration. The most impacted beneficial water use is fishing (Lijklema et al., 1993).

4.4.1.4 Density stratification of receiving water bodies

Density stratification of urban receiving waters may be caused either by dissolved solids or by temperature. Large quantities of total dissolved solids may be found in urban stormwater in cold climate regions, where large quantities of chloride are conveyed by runoff and snowmelt as a result of road salting (Marsalek, 2003b). Such loads then lead to densimetric stratification of urban lakes and impoundments (Judd, 1970; Marsalek, 1997), with a concomitant impediment of vertical mixing and oxygenation of bottom layers of such water bodies. Stratification can be also of thermal origin, as observed in natural water bodies and further described in Section 4.4.5.2.

Furthermore, high concentrations of chloride contribute to increased mobility of heavy metals (Novotny et al., 1998) and occurrence of toxic effects (Rokosh et al., 1997; Marsalek et al., 1999a), with the resulting loss of biodiversity (Crowther and Hynes, 1977). The ecological impacts include those on the food web, genetic diversity and ecosystem development. The affected beneficial water uses include water supply, fishing and irrigation (Lijklema et al., 1993).

4.4.1.5 Combined physical effects

In most regions of the world, very few river basins remain unaffected by anthropogenic influences. The general deforestation of land, changes in terrain slopes to allow agricultural cultivation, and damming of creeks and rivers for energy production, irrigation or navigation, have strongly modified hydrological behaviour of the affected streams and rivers. Thus, the popular references to achieving a "natural" state (or renaturalisation) of catchments, in a vast majority of cases, represent a certain Utopia. In practice, the actual reference to the “natural” state is of a historical character and often corresponds to an equilibrium state, actual or hypothetical, which was reached in the catchment in a not-too-distant past, so that the collective memory preserved its trace. All water bodies, and particularly those in urban areas, are always in a state of permanent evolution. Thus, the concept of equilibrium indicated here does not correspond to a stable and invariable state, but to a certain stage of slow and partly controlled evolution, striving to preserve the physical (water resource, floods, solid transport), biological (nature of the ecosystems) and sociological (beneficial uses of the water body) balances. Yet, urbanisation still affects the behaviour of catchments, and it is necessary to describe the different kinds of effects that can be observed in order to be able to mitigate the most disastrous ones. Further complexity and uncertainty may be introduced into this analysis by climate change, which may affect all aspects of the hydrological cycle.

The various types of impacts of urbanisation on the hydrological cycle are not independent; in fact, they act synergistically, as shown in Fig. 4.2. The ultimate result is a somewhat paradoxical situation. In urban areas, where the requirements on water resources, with respect to water quantity, quality and security, are the strongest, the risks of flooding are the highest and the aquatic environment and its ecosystems are the most degraded.

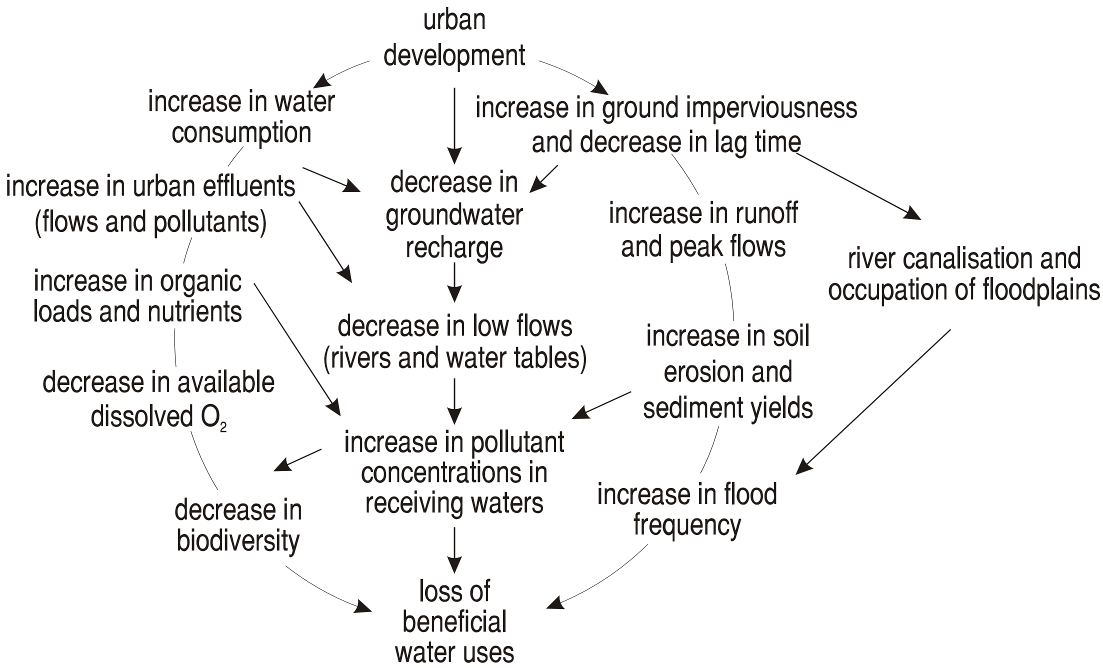


Fig. 4.2 Impacts of urbanisation on the aquatic environment (after Chocat, 1997)

4.4.2 Chemical effects

In this section, environmental and ecological problems caused by the pollution of urban wastewater effluents are examined. The individual types of effluents, stormwater, CSOs and municipal wastewater, were characterised in Chapter 3 (sections 3.3.2.1, 3.3.3.1 and 3.4.5, respectively). The discussion presented in this chapter focuses on their chemical effects in receiving waters.

4.4.2.1 Dissolved oxygen (DO) reduction

Reduction in DO and the concomitant biomass accumulation are typically caused by discharges of oxygen demanding substances, characterised by biochemical oxygen demand (BOD), chemical oxygen demand (COD) and ammonia. Oxygen demanding substances are conveyed in relatively high concentrations by wastewater treatment plant (WWTP) effluents (Chambers et al., 1997) and CSOs (Harremoes, 1988); stormwater sources are much less important. However, DO depletion can occur in summer months in shallow stormwater ponds, or in ice-covered stormwater ponds during the winter months (Marsalek, 1997). Environmental effects occur on two time scales - short-term effects are caused by dissolved BOD/COD and ammonia, and intermediate-term effects that may be caused by sediment oxygen demand (Hvitved-Jacobsen, 1982). These impacts cause ecological effects and affect water uses; ecological effects include those on biodiversity and critical species; the affected water uses include water supply, bathing, fishing and industrial water supply (Lijklema et al., 1993).

4.4.2.2 Nutrient enrichment and eutrophication

Nutrient enrichment and eutrophication of receiving waters is typically caused by nitrogen and phosphorus additions to receiving waters by WWTP effluents, CSOs and stormwater. Among these sources, WWTP effluents, particularly if inadequately treated, are the most important. Excess nutrients can increase the growth of primary producers (algae and rooted aquatic plants) to levels that impair the ecosystem by changes in energy dynamics and food web structure, changes in the composition of algal community from one-celled diatoms to filamentous green forms, followed by blue-green forms, changes in habitat and loss of species (Chambers et al., 1997). Eutrophication degrades lake ecosystems in a number of ways, including reduced food supplies to herbivores, reduced water clarity, and at the end of the bloom, algal decomposition which causes high oxygen demands leading to oxygen deficiency, particularly in the bottom layers. These effects typically manifest themselves over longer time scales, (seasonal or even longer) (Harremoes, 1988). The affected beneficial water uses include water supply, bathing, recreation, fishing, industrial water supply, and irrigation (Lijklema et al., 1993). The prevention of urban lake or reservoir eutrophication usually requires control of nutrient sources, including WWTP effluents, stormwater and CSOs (Schueler, 1987), and upstream agricultural sources (where they exist).

4.4.2.3 Toxicity

All the three types of UWWEs may cause toxic effects in receiving waters by elevated levels of ammonia, total residual chlorine, cyanide, sulphides, phenols, surfactants, chlorides, metals, and trace organic contaminants (e.g., organochlorine pesticides). Ambient conditions in the receiving waters, such as temperature, pH, hardness, alkalinity and DO may modify toxicity of chemicals, and interactions of chemicals in receiving waters may increase the risk of toxicity. With reference to WWTP effluents, extensive literature on this topic indicates that toxicity is usually attributed to ammonia, total residual chlorine (where used in disinfection), cyanide, sulphides, phenols, surfactants and some heavy metals (Cu, Zn, Cr and Ni). Ambient factors and pollutant interactions modify toxicity in receiving waters and impede generalisations (Chambers et al., 1997).

The understanding of toxicity of CSOs and stormwater is incomplete, but generally, their toxicity is attributed to ammonia, toxic metals, hydrocarbons (particularly polycyclic aromatic hydrocarbons, PAHs), and pesticides (Hall and Anderson, 1988; Dutka et al., 1994a,b). Toxicity of urban runoff is measured by bioassays, but conjunctive determination of causes (i.e., pollutants and their forms) is lagging behind (Marsalek et al., 1999a,b). Results from selected studies are summarised below.

Hall and Anderson (1988) used *Daphnia pulex* to investigate stormwater toxicity caused by trace metals in runoff from various urban land use. Toxicity varied greatly and was attributed to several metals (copper, lead, iron and zinc). Dutka et al. (1994a,b) reported toxicity assessment of water and sediment from four stormwater ponds in the Toronto area. A large number of samples of pore water and solvent extracts tested positive for the presence of promutagens; a limited search for sources of toxicity pointed towards ammonia and pesticides. Marsalek et al. (1999a,b) studied urban runoff toxicity at 14 urban sites, including two sites receiving runoff from major multi-lane divided highways (> 100,000 vehicles/day). About two-fifths of all data did not show any toxic responses, one-fifth indicated severe toxicity, one-fifth confirmed toxicity, and one-fifth potential toxicity. The highest occurrence of severe toxicity was found at sites receiving highway runoff.

In comparisons of CSOs and stormwater toxicity (Marsalek and Rochfort, 1999), CSOs displayed lower acute toxicity (only 7% of samples were moderately toxic), and none of the samples was severely toxic. The frequency of genotoxicity detection in CSOs was higher than acute toxicity detection (15% of samples were at least moderately genotoxic) and up to two-thirds of all CSO samples showed chronic toxic effects, depending on the toxicity test applied.

In receiving waters, the observed effects of stormwater and CSO toxicity may be offset by mixing and dilution with less polluted ambient water. Toxicity measurements were found effective in screening and comparing sources of toxicants, but their effectiveness in prediction of control performance and the assessment of chronic toxicity has not yet been demonstrated (Marsalek et al., 1999b).

Ecological impacts of ammonia and trace organic contaminants (toxicants) include those on the food web, biodiversity, and critical species; in the case of metals, such a list could be further expanded for ecosystem development. In the short term, the only beneficial water use significantly affected is fishing (Lijklema et al., 1993); in the long term, the receiving water ecosystem is downgraded.

4.4.3 Microbiological effects

Microbiological contamination of urban waters is one of the most severe impacts of urbanisation, because it adversely affects the health of urban dwellers. Such a contamination is directly related to the level of waste management and sanitation in urban areas. In developed countries, this level is fairly advanced and the associated effects on human health are limited. However, the situation is much different in developing countries, where large populations lack access to improved sanitation. The main sources of microbial contamination of urban waters are human wastes. The microbial agents causing waterborne illness were described, for example, by Leclerc et al. (2002).

4.4.3.1 Waterborne pathogens

There are four groups of organisms affecting human health and commonly found in water: viruses, bacteria, protozoa and helminths. The first three are microscopic, while the latter measure from millimetres to metres, but in water, travel as microscopic eggs. Table 4.2 contains a list of those, which are likely to be found in sewage. Their presence and concentrations depend basically on local conditions.

Viruses exist in different forms and sizes (from 0.01 to 0.3 μm) and reproduce only within infected cells. There are more than 140 enteric types of viruses causing infections or diseases. Unlike bacteria, pathogenic viruses are not found in the faeces of healthy humans, but only in those of infected individuals. The enteroviruses of greatest concern are polio, echo, coxsackie, Norwalk, rotavirus, reovirus, calicivirus, adenovirus and hepatitis A. Viruses are more resistant to disinfection and environmental conditions than most bacteria and are very difficult to detect using conventional laboratory techniques. Rotavirus is the most important cause of infantile gastroenteritis, causing 500-1,000 million annual episodes of diarrhea in children under five years in Africa, Asia and Latin America, and up to 3.5 million deaths (Jawetz et al., 1996).

Bacteria are unicellular microorganisms measuring between 0.1 and 7 μm and occurring in diverse forms - spherical, oval, helicoid, filamentous or rods. Bacteria are ubiquitous in the environment and occur in many varieties, some of which are innocuous to man. Some of them colonise the human intestines, like faecal coliforms, and are evacuated in human faeces in great quantities (more than 10^{12} per gram). Bacteria that pose the greatest health risk are the enteric bacteria that live in or can inhabit human intestines. Such bacteria are adapted to living in an environment rich in organic matter at 37°C, and consequently have difficulty surviving in other environmental conditions. The main pathogenic bacteria transmitted through water are listed in Table 4.2.

Protozoa are parasites often associated with diarrhea. They are unicellular, measure between 2 to 60 μm and are found in two forms: trofozoite and cyst. Infection is acquired by mature cyst ingestion, which is resistant to gastric juice. In the small intestine the cyst transforms itself into a trofozoite and settles down. Trofozoites can once again form cysts and be eliminated in the human faeces whether or not the person displays the symptoms. Like viruses, protozoa do not reproduce in the environment; nevertheless, they are able to survive in it for weeks, months or years, depending on the environmental conditions (Bausum et al., 1983). Protozoa are transmitted via polluted food or water. Table 4.3 lists the main characteristics of diverse protozoa.

Table 4.2 Main pathogenic bacteria transmitted through water (after Craun, 1988; Sansonetti, 1991; Thomas et al., 1992; Hopkins et al., 1993; Lima and Lima, 1993; Nachamkin, 1993; Jawetz et al., 1996; Johnson et al., 1997)

Bacterium	Characteristics	Illness
Escherichia coli	Some breeds are pathogens	Intestinal infections
Campylobacter jejuni	The main cause of gastroenteritis in Europe (rather than *Salmonella*); originates from non-chlorinated water sources.	Diarrhea in humans and animals (more frequent), usually affects children and young people, incubation period 2-5 days.
Salmonella	Widespread; one of the most important pathogens affecting both man and animals due to amount of serotypes that exist, very common in water and food in developing countries	Salmonellosis or typhoid fever causes acute gastroenteritis with diarrhea, abdominal cramps, fever, nausea, vomit, headaches and, in severe cases, death; frequency varies annually and differs from one country to another; the infective dose varies from 10^5 - 10^8 although it can be produced in low immunity individuals at 10^2 for *Salmonella typhi*.
Shigella	Does not survive well in the environment; a large amount of serotypes exists (more than 40), but *S. sonnei* and *S. flexeneri* account for 90% of the isolates from raw wastewater.	Bacillary Shigellosis or dysentery causes fever, nausea, vomit, abdominal pain, migraine and faeces emission with blood and mucous; highly infectious; more virulent in old people and children; the infective dose is 10^3 microorganisms
Mycobacterium tuberculosis	Cause diseases in people who swim in contaminated water.	Gastrointestinal alterations.
Vibrio cholerae	Normally present in the aquatic environment; its presence depends on water temperature and salinity. *Vibrio cholerae* is not very common in developed countries but frequent in developing countries; humans are the only well-known hosts and the most frequent way of transmission is the ingestion of polluted water or of produce irrigated by polluted water.	Gastroenteritis; usually affects children; causes very abundant liquid diarrhea, with important hydroelectrolytic losses and severe dehydration, associated with vomiting.
Helicobacter pylori	The means of transmission not well known; unsanitary conditions and consumption of polluted vegetables are possible means; more sensitive to chlorine than Faecal coliforms.	Causes gastritis, duodenal ulcer (peptic), gastric ulcers and carcinoma.

Table 4.3 Main protozoa transmitted through water (after Salas et al., 1990; Gray, 1994; Goldstein et al., 1996; Tellez et al., 1997; WHO, 1997; Cifuentes et al., 2002)

Protozoan	Characteristics	Illness
Entamoeba histolytica	10% of the world population suffers from amoebas (500 million infected people); 40 to 50 million cases and up to 100,000 deaths occur per year (the second cause of mortality by parasites after malaria); 96% of all cases occur in poor countries, particularly on the Indian subcontinent, in Western Africa, the Far East and Central America	Invade the large intestine, occasionally penetrate the intestinal mucous and lodge in other organs; responsible for amoebic and hepatic dysentry. The prevalence depends on cultural habits, age, sanitary conditions and socioeconomic conditions. In developed countries, this disease occurs mainly among immigrants.
Cryptosporidium	Widely distributed in the environment; infects farm animals and pets. It was recently (1976) discovered to be a human pathogen. Infected people carry it for life and can be reinfected.	Cryptosporidiosis causes stomach cramps, nausea, dehydration and headaches. The infective dose is 1-10 cysts. Different population segments and different cultures react in different ways.
Giardia	Giardiasis is endemic with 10% prevalence in developed countries and 20% in developing ones; the total number of cases is 1,100 million per year, 87% of which is in developing countries. This incidence has been increasing in recent years (WHO, 1997); water may not be the main transmission mechanism.	Very liquid, odorous and explosive diarrhea, stomach and intestine gases, nausea and loss of appetite. The incubation period is 1-4 weeks. It particularly affects undernourished children under five.

Helminths are pluricellular organisms. Generally, free-life larvae are not pathogenic, but those in wastewater are pathogenic and associated with suspended solids. Helminths contribute to poor nutrition, anaemia and delay growth. There are different species of helminth ova, whose relative frequency depends on regional conditions, with *Ascaris* commonly found in wastewaters. For example, in Mexico City's wastewater, 90% of helminth ova were attributed to *Ascaris* (Jiménez and Chávez, 1998).

The ova measure between 20 and 100 μm and are resistant to diverse environmental conditions as well as conventional disinfectants (chlorine, ozone and UV light). They can be removed from wastewater by sedimentation, coagulation-flocculation (Jiménez et al., 2001), stabilisation lagoons (WHO, 1989), wetlands and filtration (Jiménez et al., 2001). They are also inactivated by high temperatures, and dry and acid conditions (Barrios-Pérez, 2003).

Helminthiasis affects 25% to 33% of the population in developing countries (Wani and Chrungoo, 1992; Bratton and Nesse, 1993), whereas in developed countries less than 1.5% are affected (WHO, 1997). Ascariasis is endemic in Africa, Central and South America, Asia and the Far East, especially in regions where poverty, congested living conditions and bad sanitary conditions predominate. In such situations, incidence of helminths can be found in 90% of population (Schulman, 1987; Bratton and Nesse, 1993). In the United States, ascariasis is common, but of the 4 million infected people, most are immigrants (Bratton and Nesse, 1993). In this sector, the prevalence rate is 20-60% (Salas et al., 1990). Basic statistics concerning helminthiasis are summarised in Table 4.4.

In developed countries, microbiological pollution effects on human health and biomass are primarily associated with CSOs, and to a lesser degree, with stormwater. The effects on public health are related to swimming beaches, the effects on biomass include contamination of shell fish and closure of harvesting areas.

Table 4.4 Infected people and annual cases and deaths caused by Helminthiasis (after Salas et al., 1990; WHO, 1997)

Parasitosis	**Number of infected** (million)	**Annual cases** (million)	**Annual deaths** (thousand)
Amibiasis	500	40 to 50	40 to 100
Giardiasis	200	0.5	-
Ascariasis	800 to 1 000	1	20
Uncinariasis	700 to 900	1.5	50 to 60
Tricocefalosis	500	0.1	-

Stormwater, CSOs and non-disinfected (or poorly-disinfected) WWTP effluents convey high loads of faecal bacteria, which are typically described by concentrations and fluxes of indicator bacteria, such as *Escherichia coli* (EC). Various public health authorities have established recreational water quality guidelines, which among other parameters, specify the permissible levels of indicator bacteria. For example, the current Province of Ontario (Canada) limit, calculated as a geometric mean of no less than five samples, is 100 EC/100 mL. While the determination of microbial pollution in the receiving waters is a routine task, the potential public health risks are not well understood (lack of epidemiological data). Furthermore, these effects manifest themselves instantaneously, though their measurement (involving laboratory incubation) introduces time delays into the process of detection, and the assessment of compliance with the existing water quality guidelines is defined as a geometric average of a number of individual measurements collected over extended time periods, which contradicts the instantaneous nature of impacts of this parameter.

Recognising that typical concentrations of *E. coli* in CSOs may reach up to 10^6/100 mL and in stormwater up to 10^5/100 mL, these sources can cause bacterial contamination and exceedance of the recreational water quality guideline in receiving waters. Such exceedances occur during wet weather and usually persist for a significant time period afterwards (depending on bacteria die-off and their transport in the receiving waters), often lasting 24 to 48 hours after the end of storm (Tsanis et al., 1995). Thus, the beaches impacted by urban stormwater and CSOs may have to be closed for periods of several days – comprising the storm duration and the persistence of after-effects.

Many beaches in urban areas are frequently closed during and immediately after rainfall events, because of faecal bacteria contamination caused by stormwater and CSO discharges (Dutka and Marsalek, 1993; Marsalek et al., 1994; Tsanis et al., 1995). Urban runoff, in the form of CSOs or stormwater, is a significant source of faecal pollution caused by pet populations, urban wildlife (particularly birds), cross-connections between storm and sanitary sewers, lack of sanitation, deficient solid waste collection and disposal, accumulation of sediments in sewers and receiving waters, rodent habitation in sewers, land wash and growth of bacteria in nutrient rich standing waters (Olivieri et al., 1989).

4.4.3.2 Indicators of microbiological pollution

Because of inherent difficulties with measuring pathogens, microbiological indicators are generally used instead. An ideal microbiological indicator should meet the following conditions: (a) be present exclusively when there is faecal contamination, (b) have equal or greater capacity to survive than the pathogens, (c) not easily reproduce in the environment, and (d) be measurable in environmental samples. Even though no indicator fulfils perfectly all of these conditions, faecal coliforms or *E. coli* are currently used as indicators in freshwater, and enterococci in marine waters. However, these microorganisms are not adequate indicators of the presence of viruses, protozoan and helminth ova, but only of bacteria. In countries with widespread waterborne diseases, selection of an indicator is a complicated process and generally it is recommended to use a combination of organisms.

There is a great variety of viruses and thus it is impossible to measure them all. A virus indicator would be helpful. The use of bacteriophage viruses as indicators was proposed, because they can be easily detected. However, bacteriophages are viruses that infect bacteria but have not been related to human viruses. Attempts to use the coliphage group have been made, because of their relatively high concentrations in wastewater and simple and fast (24 h) detection technique. Nevertheless, coliphages do not mimic enterovirus behaviour and further research is needed.

Protozoon cysts and helminth ova are very resistant to disinfection and diverse environmental conditions. Currently, any protozoon is considered a good indicator, but the applicable analytical procedures are very complex. For helminths, generally *Ascaris* eggs are measured; however, in this case, given the type of technique (visual counting), it does not make much sense to speak of an indicator but to measure all the species of concern in a certain region, since it entails virtually the same effort, time, cost and training.

Ecological impacts of microbiological pollution include those on energy dynamics, food web, and ecosystem development. The impacted beneficial water uses include water supply, bathing, and fishing (Lijklema et al., 1993).

4.4.4 Combined effects on surface waters

Urban wastewater effluents, including WWTP effluents, stormwater and CSO discharges, often in combination with other stressors, cause numerous biological effects through combination of five factors: (a) flow regime changes, (b) impairment of habitat structure, (c) biotic interactions, (d) changes in energy (food) sources, and (e) chemical variables (water pollution). The effects of these factors are measured by the biological community performance, as shown schematically in Fig. 4.3.

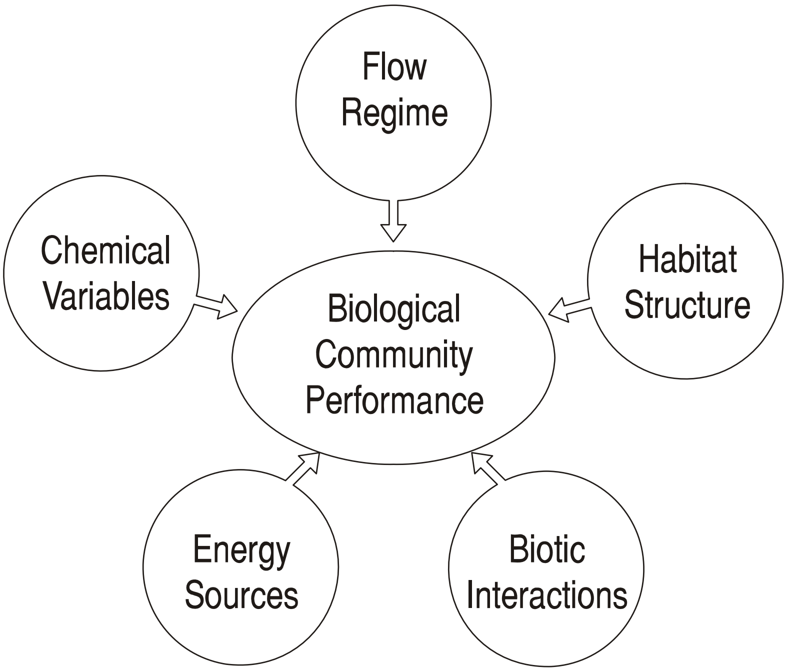


Fig. 4.3 Combined effects on biological community performance

4.4.5 Examples of urbanisation effects on specific types of receiving waters

The effects of urbanisation on streams, rivers, lakes and reservoirs are presented in this section.

4.4.5.1 Rivers

River characteristics are highly diverse, depending on the catchment characteristics, climate, pollution sources, flow velocities, etc. Generally, river flows are highly variable in time (annual and cyclic variation) and space, based on topography, climatic and basin conditions. In general, strong vertical mixing occurs in rivers due to currents and turbulence, but full lateral mixing may require a fair distance (about 100 times the bed width). For that reason, water quality in rivers is highly variable in time and space and cannot be adequately represented by mean conditions. Rivers serve for transporting pollutants, especially the persistent ones, from the point of pollutant entry to the point of discharge into other rivers, aquifers, wetlands, reservoirs, lakes, estuaries, and marine waters. Therefore, upstream uses must consider downstream uses.

The natural variability of water quality in a river depends on the combination of diverse environmental factors (Meybeck and Helmer, 1989) including the presence of highly soluble minerals, the thickness of the substrate above the bedrock, the ratio of the annual precipitation volume of the river catchment the annual river streamflow, the presence of peatbogs, wetlands and marshes, and contributions of nitrogen, phosphorus, silicon, calcium, magnesium, sodium and potassium from soil erosion.

Urban areas affect the water quality in rivers through discharges of wastewaters, and thereby modify temperature, suspended solids, organic matter, turbidity and faecal pollution indicators in rivers, as shown in Table 4.5. Self-purification processes taking place in rivers and regulating soluble compounds in riverine water include flow turbulence, evaporation, absorption to sediments, primary production, and organic matter oxidation (Chapman, 1992). Turbulence contributes to volatilisation of chemicals and higher dissolved oxygen levels. Evaporation may increase pH, electrical conductivity, and precipitation of soluble materials. Sediment absorption can result in reduced concentrations of nutrients, dissolved organic carbon, soluble metals and organic micropollutants. Primary production may increase precipitates, reduce nutrients by consumption, and increase DO and dissolved organic carbon (DOC). Finally, organic matter oxidation in the water column or anoxic sediment reduces pH, increases dissolved nutrients, reduces DO and DOC, and potentially increases soluble metal concentrations by de-sorption (Chapman, 1992).

Table 4.5 Changes in river characteristics due to sewage discharges

Disturbance	Description
Physical characteristics	Suspended solids and turbidity increase; temperature increases if there are cooling water discharges.
Faecal pollution	Mainly in cities of developing countries, particularly in those with fast growth. Faecal coliform counts can be as high as 10^6 MPN[1]/100 mL.
Organic matter	Raw wastewaters as well as treated wastewater (to a lesser extent) produce dissolved oxygen demand and nitrogen release in rivers. The effect is directly related to the ratio of the polluting discharge to river discharge. Disturbances can be observed from some kilometres to up to 100 km from the discharge point. Turbulence helps to re-oxygenate the riverine water.
Eutrophication	Between 1950 and 1960, first reports of eutrophication in lakes and reservoirs were made; later, in the 1970s, the same problem was reported for rivers.
Increase in salinity	Treated sewage, as well as mining and industrial discharges, contain salts, which increase the salinity of water supplies, especially in arid and semi-arid areas with high rates of evaporation.

[1] MPN – most probable number

Dissolved oxygen. All rivers possess self-purification capacity for biodegrading organic matter through aerobic oxidation. Thus, this process depends on the concentration of dissolved oxygen and can be represented by the oxygen sag curve shown in Fig. 4.4. In this curve, four zones can be distinguished.

- The degradation zone, where the discharge enters the river, is characterised by visible signs of pollution (floating solids), turbidity is high and dissolved oxygen begins to diminish due to the presence of oxygen consuming bacteria.
- The decomposition zone, where dissolved oxygen is very low (sometimes practically absent), contains no superior aquatic fauna. Water is black, emanates odour, and a great amount of sediment deposits on the river bed.
- The recovery zone, where DO increases, and microorganisms are present in small numbers (facultative anaerobic or strict aerobic), contains superior forms of biota (small larvae, worms and fish).
- The clean water zone, whose appearance is similar to the river upstream of the discharge point, is characterised by no floating solids, clear water, DO near saturation, superior microorganisms and other forms of biota. Fish are generally more abundant than upstream of the discharge point.

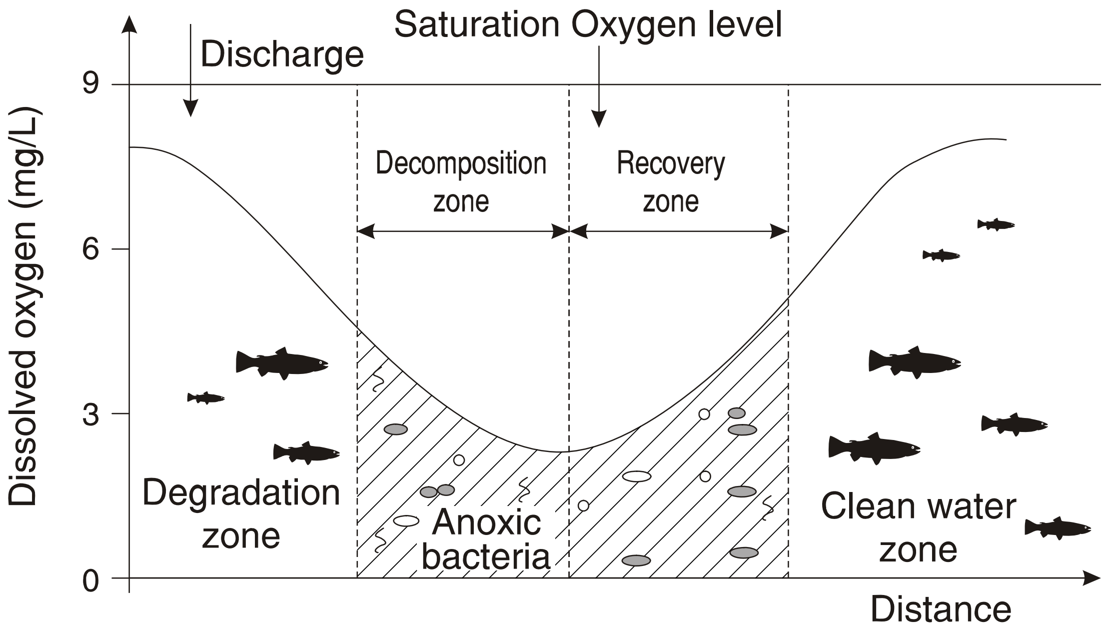


Fig. 4.4 Dissolved oxygen sag curve

The sag curve form is a function of the pollution load, the quality of the receiving water, temperature, and the pollution discharge to river flow ratio. Temperature plays an important role in the sag curve because in warmer water oxygen dissolves in smaller quantities than in cold water, although biological activity and therefore oxygen demand increase. Mixing is another important factor since it promotes oxygen transfer and dilution.

Nutrients. Excess nutrients may cause eutrophication in rivers, particularly where rivers are impounded with retention times greater than one month. Impoundments also increase water evaporation and dramatically modify the composition of aquatic organisms. Oxygen content is reduced, the pH is modified and ammonia is released (NH_3), which are the conditions dramatically impacting on fish. In very slow river flows, an excess of phytoplankton caused by eutrophication causes taste and odour problems in drinking water. For a detailed discussion of water quality changes in river impoundments, see Chapman (1992).

Other effects encountered in rivers include increased salinity (total dissolved solids, TDS), acidification, and higher concentrations of trace elements and nitrates. Sewage, industrial and mining wastewater discharges as well as winter runoff in cold climate countries (where salt is used in winter maintenance) increase Cl^- and Na^+, SO_4^{2-} and CO_3^{2-} content in rivers. Other reasons for increased TDS in rivers may be soil erosion and water evaporation. Where such waters are used for water supply, higher costs of treatment are encountered for removing TDS.

Acidic waters may enter rivers as a result of mining and industrial discharges, and atmospheric deposition. This may change the pH of the riverine water, where the buffer capacity is low, as encountered in areas with non-carbonated detritic rocks (sandstones) or crystalline rocks (granites or gneisses). Acidification of rivers diminishes water biota and reduces its diversity. Acidification also increases metal dissolution, possibly producing toxic effects and limiting uses of such water.

Trace elements are discharged into rivers from various industrial operations, urban runoff, pesticide applications (copper), atmospheric deposition, and sanitary landfill leachates. Most of such chemicals (metals and organic compounds) are adsorbed to particles at normal pH and redox potential conditions. Trace metals consequently accumulate in sediments, from which they can be released if pH or redox potential conditions change. Bacteria also can solubilize metals (Hg, As, and Pb) in sediments and transform them into volatile organometallic compounds. Thus, sediments play an important role in water pollution and decontamination.

Finally, in some rivers, nitrates may reach high values, as a result of polluted domestic and industrial discharges. Anoxic conditions may be created in rivers and cause nitrogen released from river beds into the water column by denitrification. When oxidized nitrogen reaches 10 mg N/L in river water, it becomes unsafe for human consumption.

4.4.5.2 Lakes and reservoirs

Lakes and reservoirs are characterised by long hydraulic residence times and relatively low capacity for decontamination. Lakes located near urban areas are often used for water supply, recreation and as receiving waters for urban effluents. Thus, a delicate balance among the various water uses must be achieved. Lakes are typically thermally stratified, with the highest density water located at the lake bottom (hypolimnion) and lower density water found in the upper layer (epilimnion). The epilimnion is completely mixed by wind and waves; the hypolimnion is cooler than the epilimnion. There is a clear physical separation between both layers, known as a thermocline, of which thickness typically varies from 10 to 20 m. In shallow lakes, stratification does not occur because of wind induced mixing (Chapman, 1992). As temperature changes during the year, many lakes undergo alternating periods of vertical mixing and stratification. As mentioned in section 4.4.1.4, stratification can be also caused by dissolved solids (particularly chloride), which impede vertical mixing. One of the main characteristics of lakes and reservoirs is a significant water loss through evaporation.

The main water quality problems in encountered in lakes and reservoirs are summarised in Table 4.6.

Table 4.6 Main water quality problems in lakes and reservoirs

Process	Cause	Effects on water quality
Acidification	Atmospheric deposition of acidity.	Decrease in pH, increased concentrations of heavy metals, loss of biota.
Increased salinity	Water balance modifications, soil leaching, industrial and municipal discharges	Increased TDS, increased treatment cost if dissolved solids exceed 1,500-2,000 mg/L.
Eutrophication	Excess of nutrients	Increased algae and plant production; consumption of the hypolimnion oxygen; release of Fe, Mn, NH_4 and metals from the hypolimnion; loss of diversity in the higher trophic levels; favourable conditions for reproduction of mosquitoes and spread of shistosomiasis.
Pathogen contamination	Sewage discharges	Spread of disease including infection by bacteria, virus, protozoa and helminth ova.
Increased toxicity	Industrial and municipal discharges	Increased concentrations of trace organic and metal toxicants; introduction of endocrine disruptors; toxic effects through bioaccumulation and biomagnification; and, fish tumours and loss of biota.

Acidification is one of the most important problems observed in lakes in temperate climates. It results from acidic depositions caused by air pollution and occurs in lakes with low alkalinity, hardness, conductivity, and dissolved solids. Normally, these conditions are found in lakes located in zones with noncarbonated soils (crystalline rocks or quartz sandstones) in temperate climates.

Increase in the salinity of lake waters is a natural process that occurs to a greater extent in rivers and lakes with high evaporation rates. Saline inflows into lakes accelerate this process and limit possible water uses.

Eutrophication is a natural process of water body “aging” and can be accelerated by contamination. Eutrophying lakes pass through four stages: oligotrophic, mesotrophic, eutrophic and hipereutrophic. Oligotrophic lakes are characterised by low nutrient concentrations and little biological productivity. When the nutrient content is increased by soil leaching and polluted inflows, flora and fauna also increase in lakes. If large amounts of nutrients are added, especially nitrogen and phosphorus, algae and aquatic plants begin to abnormally proliferate, covering the lake surface and preventing sunlight and oxygen from entering the water. Normal life in lakes is then altered. Under these conditions, during the day, primary production exceeds the detritus bacterial decomposition of algae. Oxygen content can reach 200% of saturation and pH values of 10 or more in the early afternoon. At night this situation is reversed; oxygen drops to 50% of saturation and pH diminishes to below 8.5. If in addition, the lake also receives biodegradable organic contaminants, it is difficult to achieve oxygen saturation during the day. The flora die due to the lack of sunlight and sediments turn anaerobic due to decomposition. The normal life of lakes is disturbed and the lake is said to be eutrophied. After some time, sediment accumulation and the high rate of evapotranspiration caused by surface plants dry up the lake and transform it into a marsh. Other factors related to the development of aquatic plants during eutrophication are discussed in section 4.8.3.2. Common lake changes caused by eutrophication include:

- loss of biodiversity and displacement of native species,
- obstruction/blockage of channels and drains in irrigation zones and feed channels of hydroelectric plants, when connected to eutrophic lakes,
- restrictions on tourist, recreational and fishing activities, and
- reduction in the useful life of the lake.

Reservoirs behave similarly to lakes. Constructed reservoirs require some aging to develop the characteristics of natural lakes. As these reservoirs usually serve many purposes, including water supply, flood control and hydroelectric power generation, their levels greatly and frequently fluctuate. Water withdrawals alter the natural thermal stratification. Perhaps the most significant effect of damming a river is the transformation from flowing to stagnant water, with a concomitant reduction in self-purification capacity and promotion of eutrophication. More detailed description of the effects of dam construction on rivers can be found in Chapman (1992).

4.5 URBANISATION EFFECTS ON WETLANDS

Wetlands represent 6% of the terrestrial surface on Earth and occur in all types of climates, from the tropics to the tundra. The term wetland describes a great variety of specific ecosystems such as bogs, bottomlands, fens, floodplains, mangroves, marshes, mires, moors, muskegs, beaches, peatlands, pocosins, potholes, reedswamps, sloughs, wet meadows, and wet prairies (Mays, 1996). Wetland ecosystems represent the transition between terrestrial and aquatic systems and are inundated, or characterised by high water tables (at or near the land surface) during much of the year. The general importance of wetlands can be inferred from the list of their functions and values presented in Table 4.7.

Plants and animals that inhabit wetlands are uniquely adapted to live under conditions of intermittent flooding, the lack of oxygen (anoxia), and harsh (often toxic) conditions characterised by presence of reduced species of chemicals (sulphurs rather than sulphates). These characteristics make wetlands suitable for treating wastewater; constructed wetlands have been used for enhancing stormwater quality, and treating CSOs and wastewater. Constructed wetlands are designed to mimic the characteristics of natural wetlands, but are typically strongly affected by accumulation of solids and chemicals resulting from the treatment of urban effluents. Such wetlands, with either surface or subsurface flow, were recommended for stormwater quality enhancement, with good guidance available for their design (MOE, 2003) and their effectiveness in removal of suspended solids and some other constituents well documented (U.S. NURP), (U.S. EPA, 1983). As constructed wetlands become colonised by wildlife, concerns were raised about the quality of habitat in such wetlands in view of accumulation of polluted sediment, chloride and other pollutants (Bishop et al., 2000a,b).

One of the key functions of wetlands is their capacity to store, transform, and recycle nutrients. In addition, they provide effective treatment of sewage and urban runoff. Wetlands retain 60-90% of incoming suspended solids, 80% of eroded runoff materials and adsorb heavy metals (Mays, 1996), and also remove pathogens (Table 4.8). Nevertheless, the treatment efficiency of wetlands greatly varies, depending on climatic conditions, the season of the year, the type of wetland and the hydraulic residence time. Furthermore, when treatment capacity is exceeded, odour is produced. Wetlands may also encourage the breeding of mosquitoes, which sometimes serve as disease vectors (e.g., West Nile virus) and require implementation of mosquito control programs.

Table 4.7 Attributes, functions and values of wetland ecosystems (Richardson and McCarthy, 1994)

Wetland functions

1. Hydrological flux and storage
- a. Aquifer recharge by wetlands, conveyance of flows
- b. Water storage and flow regulation
- c. Regional stream hydrology (discharge and recharge control)
- d. Regional climate control (evapotranspiration export, large scale atmospheric releases of H^{2-})

2. Biological productivity
- a. Net primary productivity
- b. Carbon storage
- c. Carbon fixation
- d. Secondary productivity

3. Biogeochemical cycling and storage
- a. Nutrient source or sink in landscape
- b. C, N, S, P etc. transformations (oxidation/reduction reactions)
- c. Denitrification
- d. Sediments and organic matter storage

4. Decomposition
- a. Carbon release (global climate impacts)
- b. Detritus output for aquatic organisms (downstream energy source)
- c. Mineralization and release of N, S, C, etc.

5. Community/wildlife habitat
- a. Habitat for critical species (unique and endangered)
- b. Habitat for algae, bacteria, fungi, fish, shellfish, wildlife and wetland plants.
- c. Biodiversity enhancement

Wetland values

1. Flood control, conveyance and storage (1,2) *
2. Sediment control (filter wastes) (3,2)
3. Wastewater treatment system (3,2)
4. Nutrient removal from agricultural runoff and wastewaters (3,2)
5. Recreation (5,1)
6. Open space (1,2,5)
7. Visual/cultural amenity (1,5)
8. Hunting (water fowl, beavers, muskrats) (5,2)
9. Preservation of flora and fauna (endemic, refuge) (5)
10. Timber production (2,1)
11. Shrub crops (cranberry and blueberry) (2,1)
12. Production of medical supplies (streptomycin) (5,4)
13. Education and research (1-5)
14. Erosion control (1,2,3)
15. Food production (shrimp, fish, ducks) (2,5)
16. Archaeological, historical and cultural resources (2)
17. Habitat of threatened, rare, and endangered species (5)
18. Water quality enhancement (3,1,4)
19. Water supply (1)
20. Global carbon storage (4,2)

* Wetland values are directly related to wetland functions (1-5) or those functions that can be adversely affected by the overexploitation of values. The function numbers are ranked in the descending order of importance.

Table 4.8 Removal of pathogens in wetlands

Microorganism	Removal (%)	Reference
Faecal coliforms	90 to 99	Perfler and Haberl, 1993; Hiley, 1995; Rivera et al., 1995; Karpiscak et al., 1996; Rivera et al., 1997
MS-2 Coliphages	67 to 84	Gersburg et al., 1989
Cryptosporidium	53 to 87	Karpiscak et al., 1996
Giardia	58 to 98	Karpiscak et al., 1996
Acanthamoeba astronyxis, *A. polyphaga* and *A. rhysodes*	60 to 100	Ramirez et al., 1993
Entamoeba coli, *E. histolytica*, *E. nana* and *Iodamoeba butschlii*	100	Rivera et al., 1995
Ascaris lumbricoides eggs	100	Rivera et al., 1995

Other reported applications of wetlands include the treatment of municipal wastewater, septage, acid mine drainage, ash pond seepage, and pulp mill effluents (Metcalf and Eddy, 2003). To operate such treatment systems effectively, implementation of pre-treatment and good maintenance are essential. Maintenance operations include removal and disposal of deposited sediment with associated contaminants, occasional harvesting of vegetation, clearing of drainage channels and similar measures.

Ecological problems encountered in constructed wetlands are similar to those found in natural wetlands receiving polluted urban effluents; accumulation of pollutants from such sources will affect the operation and integrity of wetland systems.

4.6 URBANISATION EFFECTS ON SOILS

The interactions between soils and various components of the urban hydrological cycle occur in urban areas through such processes as soil erosion, leaching from contaminated soils, water infiltration/percolation and on-land sludge (biosolids) disposal.

4.6.1 Erosion

Two types of soil erosion occur in urbanising catchments – stream bed erosion described earlier in Section 4.4.1.2 and sheet erosion (detachment of soil particles by rain drops) occurring mostly on large tracts of soils stripped of vegetation cover and subject to intense soil erosion. Soil losses due to erosion can be described by the Universal Soil Loss Equation (USLE) developed by Wishmeier and Smith (1965) in the following form:

$$q = R\ K\ L\ S\ C$$

where q is the erosion rate (tonnes/ha) from a site, R is the rainfall erosivity (tonnes/ha), also called rainfall energy factor, K is the soil erodibility (dimensionless)(Wishmeier et al., 1971), L (m) and S (%) are the length and slope of the site, and C is an erosion control factor (dimensionless). Eroded soil is transported by runoff into storm or combined sewers, and in the second case, to the sewage treatment plant. Thus, erosion leads to a loss of a resource (topsoil) and at the same time, it causes operational problems in sewers and sewage treatment plants. To mitigate these problems, excessive soil erosion needs to be prevented by implementing erosion and sediment control programs in all construction activities. Where sediment deposition in sewers impairs the system hydraulic capacity, sediments may have to be removed by mechanical or hydraulic means, often at significant costs. Furthermore, the removed sediment may be contaminated and may require special conditions for safe disposal. Some of these issues are documented by an example of sewer sediment problems in Mexico City, where about 40% of sewer sediments originate from soil erosion and the rest is wastewater sludge.

Sediments removed from the Mexico City sewer system. A recent study (Jiménez et al., 2004b) of sediments removed from the Mexico City sewer system reveals the magnitude of the problem that erosion, solid wastes, and water and wastewater sludge from treatment plants can represent for a city. The city has about 19 million people and is served by a combined sewer system discharging annually 1,700x10^6 m^3 of sewage, of which 70% is municipal wastewater and 26% is stormwater. The sewer systems must be cleaned each year to prevent flooding in the city. About 2.8x10^6 m^3 of sediments are generated annually, but only 30% is extracted because of budget limitations. These sediments originate in discharges of sludge from 27 wastewater treatment plants, soil erosion, uncollected municipal solid wastes and sedimentation of suspended solids contained in wastewater. It has been estimated that at least 40% of these sediments are contributed by erosion soil losses in natural conservation areas in the City. About 22% of the City territory is subject to erosion soil losses at a rate of 500-3,500 t/ha/year. The removed sediments are disposed at the only available landfill near the city, with a limited capacity. The capacity for dealing with this problem is only now being developed. The composition of removed sediments varies greatly; some are too contaminated and require special disposal, others can be used in landfills compensating for land subsidence, or for soil conditioning, landfill cover, or in nurseries.

4.6.2 Transport of pollutants in soils

Numerous sources of soil pollutants can be found in urban areas - industries, storage tanks, petrochemical facilities, landfills, natural resource extraction, garbage dumps, hazardous waste confinement sites, factories, oil transport pipes and small businesses. Locating polluted soils in cities is a complex problem, but determining the physical, chemical and biological aspects of such contamination is even more difficult.

Soil contamination begins in the unsaturated zone, where the pollutants may exist in four phases (Matthew, 1994): (a) as a gas in the soil pores; (b) adsorbed or adhered to solid surfaces; (c) dissolved in water (hydrosoluble compounds); and, (d) dissolved in other liquids (hydrophobic compounds). Pollutant transport occurs in the gaseous and liquid phases (water and liquids); from the gaseous phase, pollutants are transported by volatilisation to the atmosphere, while those in liquid phases move deeper into soils by diverse mechanisms. The magnitude of their infiltration and the mechanism used depends on the polluting agent and soil properties. For the polluting agent, its solubility, vapour pressure density, viscosity, persistence and hydrophobicity are the driving forces. For soils, geology, mineralogical composition, distance to the aquifer, organic matter content and hydrology are the intervening factors.

Liquids that are lighter than water and hydrophobic, like hydrocarbons, first spread laterally to form a layer that floats over the phreatic level. From here, vertical migration occurs until capillarity forces retain the pollutant, or, the insoluble fraction is exhausted. Phreatic level fluctuations caused by seasonal variations, pumping or intentional or non-intentional recharge enhance the transport and mixing of pollutants. Vertical transport continues through the unsaturated soil zone by capillary and gravity forces until arriving at the capillarity strip or at a zone of low permeability. There, the hydrophobic compound forms a layer that extends and thickens until a sufficient load is reached to penetrate through the capillarity strip to the phreatic level. As the density of many hydrophobic solvents (like chlorinated ones) is greater than that of the water, the polluting agent continues sinking until it reaches an impermeable layer. In this place it forms deposits of the polluting agents that are difficult to detect and recover.

Soluble compounds, including metal compounds, also migrate vertically but along with water and/or by diffusion. Since metals tend to adhere to soil particles, their transport with water is possible only in an acidic environment, and in soils containing low concentrations of organic matter and calcium. Because the water soluble compounds are well distributed in the groundwater, they do not accumulate in some places like the hydrophobic compounds. For that reason, remediation of soluble compounds requires pumping and treating groundwater, while in the case of hydrophobic compounds, remediation implies soil extraction or *in situ* treatment (or remediation).

For all chemical compounds there is a direct relation between soil permeability and its potential to pollute groundwater. For that reason, sandy and gravelly soils are more sensitive to pollution than clay soils. Furthermore, chemical transport depends on other phenomena that delay or accelerate the chemical movement, including photochemical reactions, biological assimilation, oxidation-reduction reactions, ion exchange, complexation, precipitation, and aerobic and anaerobic degradation.

4.6.3 Changes in water quality during percolation through soils

Apart from being a possible source of water pollution, soils can also have the opposite effect on water, because they may enhance the quality of infiltrating water. Soils may remove suspended solids, nutrients, metals, organic compounds and pathogens from the percolating water through filtration, biological degradation, ion exchange and pathogen dieoff. These processes are sometimes used as a wastewater treatment method also known as SAT (Soil Aquifer Treatment). Treatment is achieved by combining inundation and dry cycles to maintain aerobic conditions in soils; if the soil percolation rate, and hydraulic and mass loads in the influent are limited. To avoid pollution of the aquifer, a certain depth to the saturated zone must also be maintained.

Reuse of treated or untreated wastewater for agricultural irrigations is in fact a low cost treatment alternative (Bouwer et al., 1980). In developed countries, this treatment process is controlled; however, in developing countries, it is mostly fortuitous. Wastewater treatment is achieved by the great amount of carbon and nitrogen consumption that the terrestrial ecosystem exerts (Bouwer and Rice, 1984), significantly in excess of that in a water body. It should be noted that even in unfavourable conditions in certain types of soils, there is always some improvement in the quality of water percolating through such soils (Oron, 2001). Soils remove more than 90% of suspended solids, 80% of organic carbon, 70% of total nitrogen, and almost 50% of phosphorus from percolating wastewater (Bouwer and Rice, 1984). The passage of treated wastewater through the vadose zone (at least 3 m thick) removes persistent organic residuals and pathogens (Wilson et al., 1995; Fujita et al., 1996; Quanrud et al., 1996). Due to the high infiltration rates (30 to 110 m/year) used in some types of SAT systems most of the infiltrating water reaches the aquifer and therefore the application of effluents on soils may be viewed as a recharge method that increases the groundwater availability (Lance and Gerba, 1980). Also, SAT systems were found to be efficient in treating and reclaiming urban stormwater (Oron, 2001).

Two aspects must be watched during effluent infiltration: organic recalcitrants and viruses. Viruses can migrate long distances in soils; vertical distances of up to 67 m and horizontal distances of 408 m were reported. Table 4.9 describes some of the phenomena that occur during virus transport in soils.

Table 4.9 Processes or characteristics affecting virus transport in soils and groundwater

Process or characteristic	Effect
Adsorption	Increases virus survival and slows down its transport; depends on ionic forces, pH, humidity and salinity.
Virus aggregation	Makes viruses more resistant.
Temperature	Represents the determining factor in inactivating viruses, in comparison to the effects of pH, sulphates, iron, hardness and dissolved solid content.
Microbial activity	Eliminates viruses.
Soil moisture	Absence of water inactivates viruses; saturated soils support virus transport.
pH	Affects adhesion and activity properties based on the type of virus.
Dissolved salts	Iron and aluminium salts inactivate viruses and slow down transport.
Organic matter	Prevents absorption.
Hydraulic conditions	Transport is increased with flow.
Types of viruses	Each species behaves and is transported differently.
Soil properties	In soil with coarse texture, there is greater mobility than in karstic fine textured soils; clay retains viruses.

Sources: Drewry and Eliassen, 1968; Nestor and Costin, 1971; Berg, 1973; Bixby and O'Brien, 1979; Gerba and Bitton, 1984; Yates et al., 1985.

4.6.4 Effects of sludge disposal on soils

Wastewater treatment produces treated water and a solid residual, which is called sludge, or biosolids. The latter term refers to well treated and processed sludge that can be recycled, for example, by disposal on agricultural land. Sludge may contain all the constituents removed from wastewater as well as those added during treatment. In many countries, sludge is poorly managed and often disposed, without any treatment, onto soils or into water bodies. In other cases, sludge is disposed in lagoons, landfills or at uncontrolled sites. Better quality sludge is used to control land degradation or improve agricultural soil characteristics. Experience shows that more hazardous practices are more common in developing countries rather than in developed ones.

4.6.4.1 Sludge production

Reliable information on sludge production is available more or less just for the United States and the European Union. In 1998, sludge production was estimated in the U.S. as 7 million dry tonnes (U.S. EPA, 1999), which is comparable to the total quantity generated in the European Union in 1992, 7.4 million dry tonnes.

4.6.4.2 Sludge quality

The environmental impact of sludge disposal on soils depends on its composition, type of treatment and the disposal method. The chemical composition of sludge is not well known, due to its variability and the lack of research. It depends more on the sludge origin than on the wastewater treatment process. Chemical compounds occur in sludge as precipitates (sulphides, oxides or bicarbonates) or are adsorbed to, or chelated with, organic matter. Six classes of chemical compounds are distinguished: (a) metals and cyanides (b) volatile organic compounds, (c) semi-volatile organic compounds, (d) pesticides and PCBs, (e) organic matter and nutrients; and, (f) others. In general, in developing countries, toxic compounds are present in lower quantities than in developed countries, unless there is a strong input of specific industrial wastewaters (such as, e.g., tannery wastewaters). Concerning heavy metals, the limited data available from Brazil, Chile, China, Mexico and South Africa indicate trace metal concentrations well below the international standards, without any treatment (Jiménez et al*.,* 2004a).

Sludge contains a lot of microorganisms. Pathogen content is the main concern since sludge is often spread through direct hand contact in the developing world, where health protection is relatively low. The difference between microbial counts in sludge in developed and developing countries is very important. Orders of magnitude vary from 10^5-10^6 to 10^7-10^{10} MPN (most probable number)/g of solids for faecal coliforms, 10^3-10^7 MNP/g of solids for *Salmonella typhi*, 10^2-10^4 cysts/g of solids for *Giardia lamblia* cysts, and from < 1 to 177 ova/g of solids for viable helminth ova, respectively (Jiménez et al*.,* 2004a).

4.6.4.3 Biosolids (sludge) application on land

Biosolids (well treated sewage sludge) can be reused for diverse purposes, including applications on agricultural land, or production of construction materials (e.g., bricks). Applications on land include agricultural, forestry and soil restoration uses. Table 4.10 shows the rates at which biosolids are applied and compares them with the rate of confinement in landfills.

Table 4.10 Typical rates of biosolids applications (U.S. EPA, 1997)

Final disposal method	**Frequency of application or final disposal**	**Disposal rate** (t/ha)	
		Range	Typical
Agricultural use	Annual	2 – 60	10
Forests	Once, thrice or five times per year	8 – 200	40
Soil remediation or restoration	Once	6 – 400	100
Confinement in landfills	Annual	200 – 800	300

Biosolids are applied on (a) sites with no public access, like agricultural fields (land grass and culture soils), forests, restoration sites (mining and construction sites), airports and highway corridors; and (b) sites with public access, such as, public parks, greenhouses, golf courses, prairies, gardens and cemeteries.

Applications of biosolids in agriculture are very important for reducing the cost of fertilisation, controlling soil degradation by erosion, improving soil characteristics, and increasing agricultural productivity. At the same time, there are some risks involved due to concentrations of heavy metals and trace organics, and disease vector attraction. These are all important issues, which however, are outside of the scope of this report. More information on this subject can be found in Girovich (1996).

4.6.4.4 Sludge disposal

Other methods of sludge disposal include landfills, lagooning, incineration and dumping into the sea. The last two options are prohibited in some jurisdictions, but still used in others due to the lack of disposal space. Land disposal can be designed as a monofill (sludge only), or sludge is sent to a local landfill where it competes for space with solid wastes. Ponds and lagoons are also sometimes used as disposal sites. The lack of space for land disposal is an increasing problem in some cities. Since many of them are no longer permitted to use local landfills, they have to look for other disposal alternatives. Final disposals for a number of European countries are shown in Table 4.11 (Lue-Hing et al., 1992). Hogg (2002) reported the costs of sludge handling in the range from $105 to $350/tonne, for a semi-solid sludge application on land and monoincineration, respectively. Further increases of costs of sludge disposal are expected in the future.

Table 4.11 Final sludge disposal methods in some European countries (Lue-Hing et al., 1992)

Country	**Final destination** (%)			
	Agriculture	Landfills	Incineration	Sea dumping
Germany	25	65	10	0
Spain	61	10	0	29
France	27	53	20	0
Greece	10	90	0	0
England	51	16	5	28
Portugal	80	12	0	8

4.6.4.5 New chemicals of concern in sludge

Municipal sludge contains various toxic chemicals, which may cause a variety of environmental effects. The discussion of such effects is beyond the scope of this report, but one emerging challenge is briefly listed - endocrine disrupters (EDS). EDSs are compounds that interfere with animal hormonal activity and are present in municipal, industrial and sewage discharges (Chambers et al., 1997). They may damage reproductive organs and alter reproductive functions. In human beings, the main concerns about endocrine disrupters are their similarity to feminine and masculine hormones (estrogens and androgens); nevertheless, little is known about their actual effects. Endocrine disrupters are difficult to detect because they appear in extremely low concentrations in water (in the order of ppb); and, the traditional parameters used to measure pollution, including toxicity tests, do not provide useful information as to their presence. Yet even very low concentrations of EDSs (in ppb) may be sufficient to cause environmental effects (Chambers et al., 1997). It is currently known that many xenobiotic compounds, such as DDTs, DDEs, chlorinated pesticides, certain pharmaceuticals and musk compounds are also endocrine disruptors because they mimic estrogen. Also, some natural compounds, such as 17-β estradiol and estrone are hormones produced by microorganisms and plants. Matsui et al. (2000) measured the content of compounds similar to estrogen in raw and treated wastewater, reporting values of 50-150 ng/L before and 1-13 ng/L after treatment. Further research of these new chemicals of concern, their effects, and means of mitigation is needed.

4.7 URBAN IMPACTS ON GROUNDWATER

Two types of urban effluent discharges reach the groundwater – non-intentional (accidental) and intentional. Non-intentional discharges are much more significant than expected. Typical examples of such discharges include infiltration of liquids from storage tanks and lagoons, sewage reuse in agriculture or landscape irrigation, landfill leaching, and infiltration of polluted water from channels and rivers and cemeteries.

4.7.1 Unintentional discharges into groundwater aquifers

Foster et al. (2002) concluded that (a) a high number of urban human activities may potentially pollute aquifers through non-intentional recharge, but only a few are responsible for the most severe problems, (b) the severity of the pollution caused is not directly proportional to the source size, because extended discharges from small operations (e.g., machine shops) can cause great impacts, (c) the larger and more complex industries pose lower risks of accidental or intentional spills, because of monitoring and quality control programs, and (d) the concentration of pollutants in groundwater depends on the pollutant dispersion and persistence, more than on the type of pollution source.

Fortuitously, the soil vadose zone retains a large part of the pollutants depending on the type of chemical compound (concentration, volatility and density), geological properties of the soil material (physical heterogeneity and hydraulic characteristics), reactions involved (sorption, ion exchange, precipitation, oxidation, reduction and biological transformation), and the hydrological conditions (retention time, flow pattern and evaporation). Water quality modifications by passage through soils were discussed in more detail in section 4.6.3, whereas the following section focuses on sources of aquifer pollution.

Any landfill, controlled or not, can be a source of aquifer contamination. Most of such contamination comes from old landfills or garbage dumps, which were built without adequate guidelines and before hazardous waste segregation was introduced. Particularly in developing countries, landfills built from 1950 to 1970 are not equipped with geomembranes and are sources of leachates. Such problems are worse in humid regions, where rain generates larger amounts of leachates. The situation is not much better in arid climates where leachates may be smaller in volume, but may possess higher concentrations of contaminants. The potential impacts of sanitary landfills on aquifers can be estimated from the type of solid wastes deposited and rainfall amounts (Nicholson et al., 1983).

Tanks and lagoons are used to treat, evaporate or store liquid wastes (municipal, industrial and mining drainage) or store water in flood control, particularly in developing countries. Generally, such storage facilities are less than 5 m deep and their hydraulic residence times vary from 1 to 100 days. Even if some of these structures are initially waterproof, almost all develop some leakage, the magnitude of which depends on the type and quality of construction and the quality of maintenance. The total volume of leakage was estimated at 10 to 20 mm/d by various authors (Miller and Scalf, 1974; Geake and Foster, 1986).

Other sources of groundwater contaminants are confinement sites of hazardous wastes. Various trace metals and organics may leak from these sites and enter aquifers (NRC, 1994).

Given the rapid population growth and the lack of sewers in urban areas in most developing countries, wastewater may leak from septic tanks, latrines, sewers, wells or be directly discharged into soils (Lewis et al., 1986). Such leaks contribute to aquifer recharge and pollution. For example, Capella (2002) estimated that sewage leakage into the Mexico City aquifer amounts to 1 m^3/s and Foster (2001) estimated that, in extreme cases, such leakage can be equivalent to 500 mm of rain/year in highly populated areas of developed nations. Thus, in areas with limited or non-existent drainage and population density higher than 100 persons/ha, there is a high risk of groundwater pollution. This risk diminishes and is of local significance only in predominantly residential areas with high density drainage (Foster, 2001).

Pollutants commonly associated with sewage leakage (exfiltration) include biodegradable organic matter, nitrogen compounds, phosphorus, microorganisms (including those causing typhoid, tuberculosis, cholera and hepatitis), suspended solids and trace organic compounds. Among them, nitrates are the most mobile and persistent, which is why they are normally detected in polluted aquifers.

Underground tanks are used for storing various liquids, but most often gasoline. Usually, leaks develop due to corrosion and poor connections, and there is a close correlation between the frequency and size of the leaks and the age the tank (Kostecki and Calabrese, 1989; Cheremisinoff, 1992). In general, tanks that are more than 20 years old are very likely to leak, especially if not appropriately maintained. Leakage problems can be significantly reduced with better design, construction, operation and maintenance. Tank leaks can be controlled using cathodic protection or double-wall steel or plastic reinforced with fibreglass tanks.

Fuel stations tanks cause many cases of groundwater contamination (Fetter, 1988). For example, in the United States, they account for at least one out of 30 leaks (Bedient et al., 1994). This pollution problem is exacerbated by the fact that gasoline tanks are widely distributed in cities, reflecting the local fuel demand rather than the need for environmentally suitable locations. Even though these leaks are usually small, they occur over long periods of time and produce pollution plumes of great extent. To avoid such pollution, leaks should be detected by standard procedures and the tanks should be sealed. Additional risks occur when pumping stations are coupled with service stations, where significant amounts of organic solvents may be spilled on soils.

The conveyance of contaminated water in open channels and rivers is frequently a source of aquifer pollution and recharge. The significance of such an impact depends on seeping flow volume and quality, and can be determined only by monitoring each case.

Industrial activities can seriously pollute subsoil and groundwater depending on the type, volume and the way of handling liquid and solid wastes. Such risks are particularly significant in industries using more than 100 kg of toxics per day (hydrocarbons, organic synthetic solvents, heavy metals, etc). The pollutants involved are related to the type of the industry as discussed by Foster et al. (2002).

In many cities and surrounding urban areas, small industries and service operations (mechanical factories, dry cleaning services, etc.) handle toxic substances like chlorinated solvents, aromatic hydrocarbons, pesticides, etc. It is important to control their wastes (liquid and solids), since they frequently store or discharge such wastes into soils instead of recycling or disposal at appropriate confinement sites. Nevertheless, it is difficult to control small industries and services, because they often move, relocate or operate intermittently. Without proper regulations, it may be difficult to exert such controls.

The burial sites of humans and animals represent sources of microbiological contamination of aquifers, although to a small extent. To avoid this problem, watertight caskets must be used, but they may not be affordable in poor countries.

4.7.2 Intentional discharges into groundwater aquifers

In urban areas with intensive soil use, aquifers may be used as water storage facilities, also called Aquifer Storage Recovery systems, ASR. This is possible because any aquifer is essentially a water reservoir, from which water can be withdrawn when required. Stored water can be of diverse quality, depending on its intended use (Table 4.12). The first systems of this nature began operating in the US in 1968. Some of the water stored is saline and considered of low quality due to the presence (in some cases of natural origin) of nitrates, barium, hydrogen sulphide, iron and manganese (Pyne, 1995).

For designing ASRs, a well defined methodology has been established and addresses design, construction and operation. Water quality improvements during water injection depend on the combination of soil filtration properties and the method of water recharge (Bouwer, 1989). Aquifers can be recharged by infiltration through soils or direct injection. The latter requires the water of quality better than that applied through soil infiltration to avoid well blockage and entry of pollutants into the subsoil and aquifer. The injected water must match the drinking water standards, or at least be of the same quality as that of the aquifer (Crook et al., 1995).

Table 4.12 Objectives of Aquifer Storage Recovery Systems (ASR) (adapted from Bouwer, 1989; Pyne, 1995; Oron, 2001)

Objectives	
• Temporary water storage during various seasons of the year	• Control of nutrient leaching
• Long-term storage	• Enhancing water well production
• Storage for emergencies or as strategic reserves	• Retarding water supply system expansion
• Daily storage	• Storing reclaimed water
• Reduction of disinfection by-products	• Soil treatment
• Restoration of the phreatic levels	• Refining water quality
• Pressure and flow maintenance in the distribution network	• Stabilising aggressive waters
• Improvement of the water quality	• Hydraulic control of pollution plumes
• Prevention of saline intrusion	• Water temperature maintenance to support fisheries
• Water supply for agriculture	• Reducing environmental effects caused by spills
	• Compensating salinity leaching from soils

Some critical considerations of ASR applications in conjunction with reclaimed water include (Oron, 2001):

- the risk of introducing recalcitrant pollutants into aquifers and soils, if there is no pre-treatment of non-residential discharges to the drainage system,
- the leaching of dangerous pollutants originating in households, and
- the dilemma of disinfecting the effluent prior to recharge knowing that this kills native soil microorganisms useful in water treatment.

4.7.3 Impacts on aquifers

In many countries, groundwater represents the main source of water supply (Table 3.3). In spite of this fact, many aquifers around the world are currently being overexploited and polluted. Aquifers are characterised by stable flow patterns, in terms of flow speed and direction. Velocities often vary from 10^{-10} to 10^{-3} m/s and depend to a great extent on the soil porosity and permeability. As a consequence, mixing is impaired in soils. Bedient et al. (1994) listed 30 potential sources of aquifer pollutants divided into six categories. Among these, the most frequent pollution source in cities were storage tanks, septic tanks, leaks from sewerage systems, hazardous and municipal landfills, and polluted soils used to store materials.

Based on a literature review, van Eyck et al. (2001) established that potentially harmful contaminants of groundwater include metals, pharmaceuticals, estrogens (natural and synthetic), surfactants, solvents and musks. This selection emphasises the risk posed by endocrine disrupters, such as nonylphenol (an intermediate product in nonylphenol ethoxylate surfactant biodegradation), 17-β estradiol (natural human oestrogen) as well as polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofuran, which can be formed by thermal desorption of chlorinated organic compounds.

4.8 URBAN IMPACTS ON BIOTA – LOSS OF BIODIVERSITY

Many urban areas have developed on shores of lakes and rivers and have affected the pre-development biota and entire ecosystems. Also, the urban water cycle may disturb nearby or distant aquatic environments and such disturbances may cause loss of species or changes in their enzymatic or metabolic systems that alter their way of living. Each organism responds in a different way to the environmental modifications, which is the reason for using biological indicators, including biological communities, for assessing the state of aquatic ecosystems.

4.8.1 General structure of water bodies and their biota

Each water body has its own biocenosis, defined as a set of organisms, plants and animals living in harmony, within a specific biotope described by physical and chemical characteristics of the environment. Aquatic ecosystems are physically made up of three zones: water body including its bottom (aquatic zone), the transition zone between water and earth (amphibious zone), and the terrestrial zone. Each zone is characterised by specific conditions that determine the structure of biological communities.

In water bodies, photosynthetic organisms that depend on dissolved nutrients and solar light to produce organic matter are called primary producers, and represent a food source for zooplankton and small fish that constitute secondary producers, which in turn represent a food source for superior animals like fish, which are called tertiary producers. When all these organisms die, predators are responsible for their degradation and decomposition. All these organisms make up a nutritional chain.

4.8.2 Properties of the water bodies affecting flora and fauna

Organisms require certain times to develop and reproduce. In moving water with short hydraulic residence times, there may not be enough time for reproduction and organisms may disappear. For normal development, the biota needs dissolved oxygen. Where DO levels are insufficient, even intermittently and for short time periods, there is a rapid decrease in aquatic communities, particularly fish. Dissolution of oxygen in rivers depends on the water movement, temperature and oxygen consumption by living organisms. Organic matter, N and P, are the main sources of nutrients for plankton and benthos in water bodies. Such nutrients must be available in the right amounts to ensure normal and balanced development of aquatic biota. Finally, toxics are compounds that alter the abundance, diversity and function of organisms. In general, aquatic organisms response to toxics is slower than to the lack of oxygen or sunlight, because they need to undergo a sufficient exposure before showing any effects. Nevertheless, the response can be magnified by the presence of other compounds, which favour absorption through nutritional chains. Since all the water body characteristics discussed in this section (hydraulic residence time, DO, N and P, and toxics) are changed by urbanisation, flora and fauna in such impacted streams will change as well.

4.8.3 Effects of alterations of urban water bodies on biota

The urban water cycle leads to alterations in urban water bodies, which in turn alter aquatic biota. Such changes are discussed here for two types of water bodies, rivers and lakes.

4.8.3.1 Rivers

The biotope and the biocenosis of a river may vary along the river course as it moves from headwaters to the point of its discharge. These variations depend on a number of factors, including climatic and geological conditions as well as the season of the year. In rivers, the main biological community is fish. This community has successfully adapted to colonizing flowing water by possessing the following characteristics: (a) growth and reproduction patterns compatible with short hydraulic residence times; (b) use of spaces that serve as a refuge; and, (c) the ability to swim against the current. However, fish are very sensitive to physicochemical conditions in rivers and when these are modified, fish are directly or indirectly affected.

Urbanisation affects river flow by withdrawals of water and discharges of urban effluents. Flow velocity has direct and indirect influences on biota. If velocity changes are permanent, a new adapted ecosystem evolves and may differ from the original one, depending on the magnitude of alterations. If the modification consists in withdrawing water, then a minimum flow called ecological flow needs to be respected, below which no development of the native flora and fauna can exist. Rivers with increasing flows also affect amphibious zones, which are often vegetated by reeds. High flows can cause erosion and make rivers so deep that the inhabitants of the amphibious zones cannot develop. Also, when the water level in the river rises, the terrestrial zone is affected.

Rivers are also susceptible to eutrophication like lakes, but to a lesser extent because their water is moving. Table 4.13 lists the main effects of eutrophication on rivers.

River bed rugosity as well as river flow patterns determine the habitat for living organisms. The river bed undergoes constant changes resulting from erosion and deposition of material by sedimentation or precipitation. These changes are magnified to a great extent by human activities involving canalising rivers or building structures to impound water. Erosion produces habitat losses followed by an impaired performance of biological communities. In addition, water movement creates turbulence and material suspension preventing sunlight penetration and photosynthetic functions. In such conditions, primary producers, the base of nutritional chains, can disappear.

Table 4.13 Effects of eutrophication on rivers

River zone	Effects
Headwaters with currents in the shade	None
Headwaters with currents exposed to the sun(1)	Macrophytes and periphyton growth is promoted, including filamentous algae
Medium to large rivers(2)	Growth of periphyton and/or macrophytes is promoted
Wide rivers(3)	Growth of plankton and macrophytes
Stagnating pools in medium size rivers	Ample growth of plankton and floating macrophytes.

(1) Average width < 1 m,
(2) Average width > 1 m < 20 m, average depth < 2 m,
(3) Average width > 20 m, average depth > 2 m

Water temperature influences physiological processes. In flowing waters, a slight elevation of temperature may be beneficial for accelerating processes and organism development over short retention times typical for such waters. Nevertheless, if the riverine temperature is increased above an acceptable level, for example, by discharges of cooling waters or warm runoff, reactions stop and the organisms die.

Pelagic communities. Pelagic communities are those that swim or float in rivers. Among them, only phytoplankton is able to produce large populations during the short hydraulic residence times typical for rivers, due to their high growth rates. Sunlight intensity, high temperatures, and low turbidity favour phytoplankton growth. This phenomenon also occurs where water is impounded by means of dams or other barriers that increase hydraulic residence times.

Benthic species. Benthic species are invertebrate organisms that live in, on, or near the bottom sediments deposited on riverbeds. Benthic communities are sensitive to water and sediment quality changes and, consequently, are frequently used as water quality indicators.

Macrophytes can be also classified as benthic species, because they attach their roots to bottom sediments. Some macrophytes remain completely submerged while others are emergent. Since the macrophytes require light and nutrients, the changes in their composition and abundance reflect well the level of eutrophication or physical characteristics of the riverbed. Macrophytes constitute an important refuge for small invertebrates, fish, fry and eggs.

4.8.3.2 Lakes and reservoirs

Pollutants fractionate among the various lake compartments, including water, sediment or organisms, depending on their chemical characteristics. Once a lake is contaminated, the pollutants follow diverse chemical, biological and physical pathways. The soluble compounds (hydrophilic) are transported with water and mixed in lake water during the hydraulic residence time. Phenomena like density stratification or turnover may help disperse pollutants. Non-soluble pollutants, mostly trace organic compounds and trace metals, are adsorbed to sediments. The distribution and removal of these chemicals is closely related to the sediment behaviour.

Bioaccumulation and biomagnification are important factors that influence pollution effects. There is evidence suggesting that these mechanisms produce high concentrations of PAHs (polycyclic aromatic hydrocarbons) and carcinogens in fish inhabiting waters in or near urban areas (Black, 1983). Similar effects were reported for metals.

A summary of the effects of eutrophication on biota is presented in Table 4.14. The main modification of biota caused by eutrophication is the proliferation of several kinds of aquatic weeds. Most common are water hyacinths (*Eichhornia crassipes)*, hydrilla (*Hydrilla verticillata)*, cattail (*Typha* sp.) and duckweed (*Lemna* sp.). Water hyacinths grow in a great variety of habitats - from continental pools, marshes, drains, channels, lakes, and dam reservoirs to slowly flowing rivers, and adapt to a wide variety of environmental conditions. They can survive for long periods even in oligotrophic waters, but optimal growth takes place in eutrophic conditions. *Hydrilla* is probably native to the warmer regions of Asia and has spread to warm regions of the world. *Typha* sp. is an herbaceous plant that appears throughout North America, Europe and Asia, mainly in the temperate, subtropical and tropical zones. It lives along the borders of reservoirs, channels, pools and marshes, and grows densely in humid habitats or in fresh or brackish waters up to 1 m deep. *Lemna* sp. is an aquatic plant that floats on the surface of lakes, pools and bogs. Its fast vegetative propagation in the aquatic environment causes high evapotranspiration rates and therefore important water losses that can be excessive in shallow water bodies.

Table 4.14 Biota status in lakes with different trophic levels

Trophic status
Oligotrophic - primary productivity and associated biomass is low due to low nutrients (N and P) concentrations. Fish fauna is of high quality and value. Oxygen in the water column is near the saturation point.
Mesotrophic - fish are of intermediate quality due to oxygen deficiencies in the hypolimnion. Stratification occurs in summer.
Eutrophic - there is a significant production of biomass as a result of high nutrient concentrations. Low water transparency affects plants development. Communities of fish are of low value. The water quality eliminates or impairs many uses of water. During summer stratification, oxygen concentration in hypolimnion can be very low ($<$ 1 mg/L).
Hypereutrophic - excessive concentrations of biomass and nutrients. Fish communities are of very low quality. Possible uses of water are very limited. Anoxic conditions exist, or there is an evident lack of oxygen in the hypolimnion during summer stratification.
Distrophic - organic matter content is high (mainly humic and fulvic acids) and fish practically do not exist.

The control of aquatic weeds consists of reducing their concentration to an acceptable level per unit area (it is impossible to eliminate them completely). Four techniques are used for such purposes: (a) biological control, (b) physical or mechanical control, (c) chemical control, and (d) manipulation of habitat.

Acidification of lakes contributes to leaching of bottom sediments and hydroxylation of iron oxides, manganese and aluminium as well as other toxic metals. Aluminium dissolution occurs at a pH < 4.5 and its presence is toxic to fish because it deposits as aluminium oxide on gills and causes asphyxia.

When water is withdrawn from the surface layer of reservoirs at a rate higher than the heating capacity, there is a net loss of epilimnion and primary producers are affected. However, if withdrawal is from the bottom, the cold water of the hypolimnion is withdrawn and lake water quality is improved, if no compounds are released from sediments. Water withdrawn from the bottom stratas always has a poorer chemical quality (less oxygen content and more suspended solids) than surface water, so bottom withdrawals are generally avoided.

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