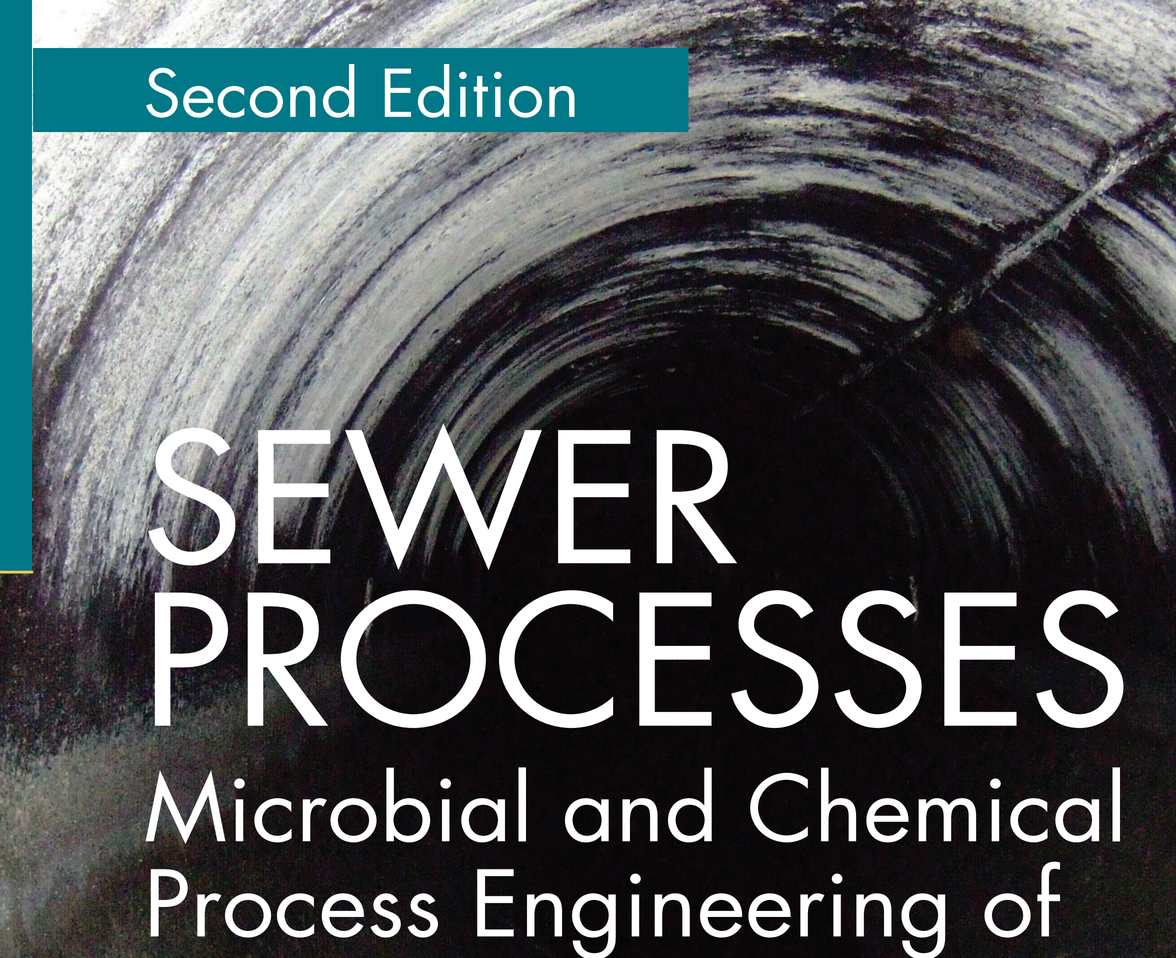

Second Edition

SEWER PROCESSES

Microbial and Chemical Process Engineering of Sewer Networks

Thorkild Hvitved-Jacobsen
Jes Vollertsen
Asbjørn Haaning Nielsen

CRC Press
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Preface

The first edition of this book was published in 2001. Since then, considerable improvements in the fundamental understanding of sewer processes have taken place. Furthermore, the conceptually formulated WATS (Wastewater Aerobic/anaerobic Transformations in Sewers) sewer process model for prediction and assessment of sewer processes and related adverse effects has been extensively upgraded. These developments have required a substantial extension of the text.

As was the case for the first edition, this book serves a dual purpose. First, it will be of use to students in environmental engineering by enabling them to understand sewer networks from a process engineering point of view and to apply this knowledge in quantitative terms. Second, this book is a practical reference intended to help planners, designers, operators, and consultants working with collection systems comprehend and control the adverse effects of sewer processes. Practicing engineers will find the contents of the book directed to solve problems by adding a process dimension to the design and operation of sewer networks.

Traditionally, books dealing with sewer systems have been devoted to hydraulics and pollutant transport phenomena. In this context, urban drainage and wet weather impacts onto the adjacent environment are in focus. With its concentration on dry weather conditions in the sewer and on the potential adverse effects of in-sewer chemical and microbiological processes, this book is different. It adds a corresponding process-related dimension to the management and engineering of sewers. A well-known example is the generation of hydrogen sulfide and its impacts in terms of concrete corrosion, malodors, and health-related effects. The book provides the reader with knowledge-based information on its formation and fate, and based on this background provides models for prediction and assessment of its occurrence and effects. The general important point is that the sewer is not just a collector and transport system for wastewater but also a chemical and biological reactor with impacts on the system itself, the wastewater treatment plant, and the adjacent environment.

The text offers a fundamental understanding of the chemical and microbiological processes that take place in sewers and quantifies these processes. The process engineering issues of wastewater in sewers are the ultimate objective, and the book provides in this respect the reader with an integrated description of sewer processes in model terms. The text is furthermore useful as an engineering guide to troubleshooting sewer problems.

The organization of the book follows from two perspectives: a general viewpoint with focus on the fundamental principles of chemical and microbiological transformations of wastewater in sewers and a specific viewpoint on the quantitative formulation of sewer processes that is directly applicable for engineers. About 110 figures and 50 tables illustrate the fundamental contents, concepts, and engineering relevance of the text. Furthermore, numerous example problems are included to highlight applications. Chapter 1 offers an overview providing an understanding of the sewer as a process reactor. Chapters 2 and 3 stress chemical and microbiological fundamentals needed to understand the processes in sewers. In Chapter 4, the transfer phenomena between the wastewater phase and the sewer atmosphere are dealt with, particularly in terms of reaeration, odor emission, and impacts of volatile substances. Chapters 5 and 6 investigate the aerobic, anoxic, and anaerobic processes in sewers. Besides hydrogen sulfide-induced corrosion, the major objective of the two chapters is to establish a conceptual understanding of sewer processes and develop corresponding mathematically based formulations. The focal point of Chapter 7 is mitigation directed to control adverse effects of sewer processes, in particular, those related to hydrogen sulfide and volatile organic compounds (VOCs). Chapter 8 deals with the basic characteristics of sewer process modeling and Chapter 9 is on this background devoted to the formulations of the WATS sewer process model. The main subject of Chapter 10 is to quantify and provide information on wastewater compounds and model parameters based on bench scale, pilot scale, and field experiments and directed toward a kinetic description of sewer processes. The text is concluded with Chapter 11 focusing on selected examples on structural and operational measures to improve sewer networks.

The theory and findings of this book have several sources. The first studies on sewer processes were principally carried out 60 to 70 years ago in California, followed by further developments, particularly in Australia, the United Kingdom, and South Africa. The combined scientific and technological understanding acquired through these studies is important and appreciated. The authors of this book have, during the past 30 years, carried out dozens of sewer projects, which have contributed with a conceptually formulated description of sewer processes. This understanding is the basis for the formulation of the WATS sewer process model. The validity of a conceptual understanding of sewer processes has, via the WATS model, been tested through a number of projects in Europe, the Middle East area, North Africa, and the United States.

Thorkild Hvitved-Jacobsen
Jes Vollertsen
Asbjørn Haaning Nielsen
Aalborg University, Denmark
January 2013

Acknowledgments

Today's understanding of the sewer as a chemical and biological reactor is relatively new. The authors acknowledge in particular the innovative works 60 to 70 years ago by C.D. Parker, R.D. Pomeroy, and F.D. Bowlus, who made the first contributions to a solid understanding of sewer processes.

Several people have, during the period this book was being developed, in different ways contributed to its contents and present state. The authors are grateful for the contributions received from their former PhD students, in particular by their work that supported the conceptual description of the in-sewer processes. These PhD students, Per Halkjaer Nielsen, Niels Aagaard Jensen, Kamma Raunkjaer, Hanne Lokkegaard, Jes Vollertsen, and Naoya Tanaka, have all contributed with invaluable results to the first edition of this book. The improvements from the first to the present edition of this book are in several chapters attributable to the work of the following PhD students: Chaturong Yongsiri, Asbjørn Haaning Nielsen, Weixiao Yang, Heidi Ina Madsen, Henriette Stokbro Jensen, and Elise Rudelle. Numerous MS students in Environmental Engineering at Aalborg University have likewise contributed with valuable results. Mary Bjerring Rasmussen and Kristian Kilsgaard Ostertoft are also acknowledged for careful and qualified help to produce the figures for this book.

Last, but not least, the first author of this book is grateful to experience that two of his former PhD students, now Professor Jes Vollertsen and Associate Professor Asbjorn Haaning Nielsen, are continuing the work on sewer processes that started 30 years ago at Aalborg University.

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Web sites: http://www.sewer.dk and http://www.civil.aau.dk.

1 Sewer Systems and Processes

1.1 INTRODUCTION AND PURPOSE

The flows of wastewater originating from households, industries, and runoff from precipitation in urban areas are generally collected and conveyed for treatment and disposal. The systems used for this purpose are named sewer networks or collection systems. A sewer network is thereby defined as the wastewater system located between the sources for generation of wastewater and a wastewater treatment plant, alternatively, a point of discharge into an adjacent receiving water system. A sewer system consists of individual pipes (sewer lines) and a number of installations and structures, such as inlets, manholes, drops, shafts, and pumps, used to facilitate collection and transport. In the European definition, a sewer system is a network of pipelines and ancillary works that convey wastewater from its sources such as a building, roof drainage system, or paved area to the point where it is discharged into a wastewater treatment plant or directly into the adjacent environment (BS EN 752-1, 1996).

The efficient, safe, and cost-effective collection and transport of wastewater and runoff water have been identified as key criteria to be observed. In this context, the word "safe" means that public health, welfare, and environmental protection have high priority. The demand for solutions toward more sustainable water management in the cities is furthermore a challenge.

A sewer network is subject to great variability in terms of its performance. During dry weather periods, the flow rates reflect the behavior of the community in the upper part of a sewer system, often with a flow rate variability of about a factor of 10 over day and night. In sewer pipes receiving both municipal wastewater and urban stormwater runoff, i.e., the combined sewer networks, the flow rates during extreme rainfall events are often increased by a factor of 100–1000 compared with the average dry weather flow. It is clear that efforts in both research and practice have been devoted to developing systems and procedures for the design of collection systems and their operation under varying conditions. During the past 20 to 30 years, emphasis has been placed on drainage phenomena in terms of flow conditions for the sewer network and integrated solutions comprising the treatment plant performance and receiving water impacts during wet weather periods. Urban drainage has thereby been an important issue in both research and practice.

The focus of this book is on the dry weather aspects of the sewer network and, in this respect, its design and performance from a microbial and chemical process standpoint. Wastewater includes substances with a pronounced chemical and biological reactivity, and the sewer network is therefore—in addition to being a collection and conveyance system—also a reactor for transformation of wastewater. In this respect, the point is that several substances from this transformation have a severe impact on the sewer network and its surroundings. Concrete corrosion, odor nuisance, human health impacts, and effects on a treatment plant located downstream are important examples.

During wet weather conditions, quite different problems related to the pollution and process performance of the sewer network arise, and the impacts on the adjacent environment are potentially severe. The authors of this book are aware of this situation. In their book, *Urban and Highway Stormwater Pollution: Concepts and Engineering*, Hvitved-Jacobsen et al. (2010) pose a "wet-weather parallel" to the present book.

Because of the basic requirements of wastewater collection and conveyance, sewer networks are traditionally dealt with from a physical point of view, i.e., the hydraulics and sewer solids transport processes are addressed. From this point of view, design and operational principles have been developed, to a great extent supported by numerical procedures and an ever-increasing capacity of computers. Under wet weather conditions, the hydraulics and solids transport phenomena in a sewer play a central role. Because of dilution and reduced residence time of wastewater and runoff water in the sewer, the chemical and microbiological processes in the network itself are often of minor importance. Not surprisingly, interests devoted to urban drainage have focused on the physical behavior of the sewer, "sometimes"—although at an increasing rate—taking into account the chemical and biological impact of wastewater and runoff water discharged to the receiving environment.

In contrast, under dry weather conditions, which may occur more than 95% of the time, chemical and biological sewer processes may exert pronounced effects on the sewer performance and on the interaction between the sewer and subsequent treatment processes. Possibly, because researchers' and operators' interests have been devoted to wet weather conditions, the dry-weather biological and chemical performance of a sewer, i.e., the sewer as a "chemical and biological reactor," have been of minor concern. Or, at least, it has not been dealt with in terms of a detailed understanding of the chemical and biological processes and their quantification based on the underlying fundamental phenomena. In this respect, it is interesting—but also a bit depressing to note—that sewers and treatment plants have been very differently managed. It is, however, apparent that the sewer cannot be neglected as a chemical and biological process system. These processes may exert severe impacts on the sewer itself, the treatment plant, the environment, and the humans in direct or indirect contact with the sewer.

Textbooks dealing with collection systems have normally been devoted to planning, design, operation, and maintenance focusing on the physical processes. This book is different, in that it will primarily be concerned with chemical and biological processes in sewers under dry weather conditions, and will emphasize and quantify the microbiological aspects. There are several examples that illustrate the importance of these sewer processes and call for their control and consideration in practice. The impact of sulfide (hydrogen sulfide) produced under anaerobic conditions in wastewater is probably the most widely known example. Sulfide is a serious health hazard for humans and is a malodorous compound that may also create severe corrosion problems in the sewer network. On the other hand, anaerobic conditions may produce and preserve those easily biodegradable substrates that enhance advanced wastewater treatment in terms of improved conditions for denitrification—nitrogen removal—and biological phosphorus removal. In an aerobic sewer, removal of these easily biodegradable organic substances and production of less biodegradable particles (e.g., microorganisms) may occur. Aerobic conditions may, therefore, improve conditions for in-sewer treatment of the wastewater and result in a positive interaction with subsequent mechanical and physicochemical treatment processes. These few examples show that a sewer is not just a collection and conveyance system but also a process reactor that must be considered an integral part of the entire urban wastewater system.

In conventional design and management practice, treatment of wastewater is considered to take place entirely within the treatment plant, whereas a sewer network serves the sole purpose of collecting and conveying wastewater from its sources to treatment. The concept of considering the sewer as a process reactor also serves the purpose of breaching this rather rigid understanding of a sewerage system. When considering the processes "starting at the sink," a number of basic aspects for improved engineering can be more directly and correctly taken into account. Furthermore, it is important that more holistic approaches expressed in terms of sustainability, public health, environmental protection, and enhancing the standard of living for the general population, can be considered. Figure 1.1 illustrates that sewers, treatment plants, and receiving water systems should not, from a process point of view, be viewed as stand-alone units.

It is the purpose of this book to provide a fundamental basis for understanding sewer processes and demonstrate how this knowledge can be applied for design, operation, and maintenance of collection systems. The overall criteria of a sewer network to observe efficient, safe, cost-effective, and sustainable collection and

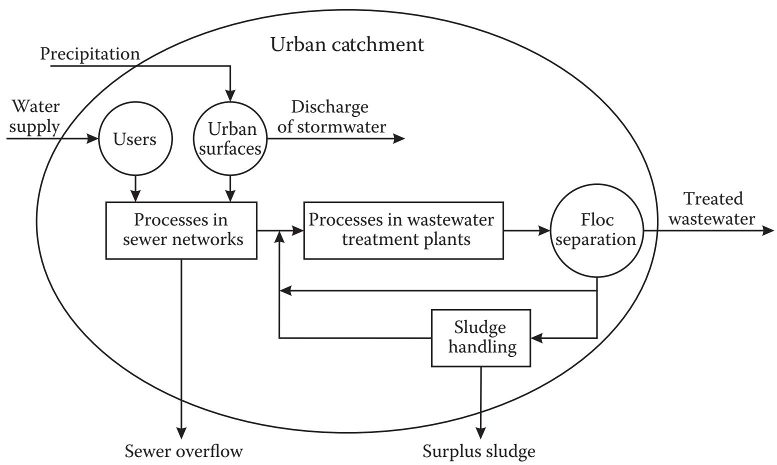

FIGURE 1.1 Integrated sewerage process system and its interactions with the surroundings.

conveyance of wastewater are still valid; however, they must be expanded with a process dimension.

Specific aspects of microbiology and chemistry will be dealt with in this book whenever considered relevant for the understanding of the in-sewer processes. Although a fundamental basis in applied microbiology, and chemistry is beneficial when reading this book, it is the authors' experience that the book in itself will provide sufficient basic knowledge to understand sewer processes and make use of this knowledge in practice.

In particular, the text will focus on the microbiological processes in the sewer, but also the chemical processes, especially the physicochemical processes. The environmental engineering relevance is the ultimate goal when deciding to which extent such details will be included. Hydraulics and solid-transport phenomena, sewer construction details, materials, and traditional sewer design and management will only shortly be dealt with and primarily when relevant for the microbial and chemical processes.

1.2 SEWER DEVELOPMENTS IN A HISTORICAL PERSPECTIVE

1.2.1 Early Days of Sewers

Sewer networks belong to the urban environment and may therefore, in principle, date back to the days of the urban revolution starting about 7000 BC when the first urban settlements were established. Several ancient civilizations, particularly those located in the Middle East, developed sewers and drainage systems to remove either wastewater from houses or surface runoff in populated areas (Burian et al. 1999; Bertrand-Krajewski 2005).

An example is Mohenjo-Daro, a city settlement of the Indus Valley Civilization (today located in West Pakistan). Buildings from the period 2500–2000 BC show bathing and latrine facilities and a sewer system equipped with a grit chamber (Figure 1.2). It is assumed that the grit chamber was important for a proper function of the sewer pipe located downstream.

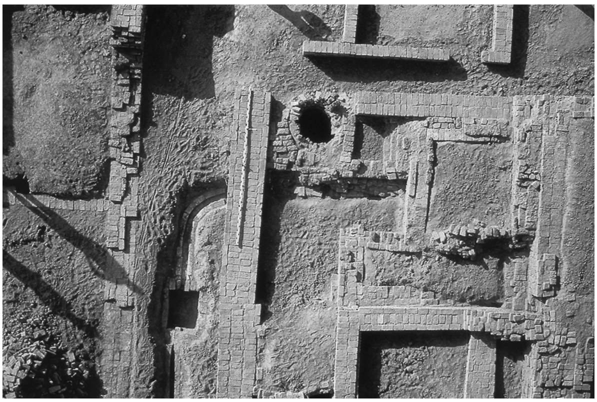

FIGURE 1.2 View of a sewer with a grit chamber, Mohenjo-Daro, now located in West Pakistan, 2500–2000 BC (Source: Picture courtesy of Dr. Michael Jansen.)

1.2.2 Sewers in Ancient Rome

From the golden age of ancient Rome, where water consumption per capita was in the same order of magnitude as present-day levels in the developed part of the world, sewers became both needed and common. During the reign of Emperor Augustus, it is known that his son-in-law, Agrippa—while sailing a boat—visited Rome's main sewer system, Cloaca Maxima, about 30 years B.C. (Figure 1.3). Apparently, he was not satisfied with its performance because he ordered it to be flushed, which was done by simultaneously diverting water from seven aqueducts. It is not known if the reason for this action was the sediment problems or malodors. However, what we know is that in ancient Rome, it was considered a punishment and a degrading work to clean sewers. Although this example indicates that the sewer network receives wastewater from households, these systems were typically constructed with the main purpose of conveying stormwater runoff from urban paved areas, protecting them against flooding. However, the contents of solid waste as a constituent of the runoff might also originate from wastes dumped at the streets. Sporadically, similar drainage systems were also in use in Europe during the 16th and 17th centuries. Typically, it was prohibited to discharge wastes from households into these storm drains.

1.2.3 Sewers in Middle Ages

In general, the knowledge on sewer construction and management gained in Ancient Rome got lost and the European cities of the Middle Ages had typically at best a rudimentarily developed drainage infrastructure. It was not until about the seventeenth century, that large European—and to some extent, American cities—started

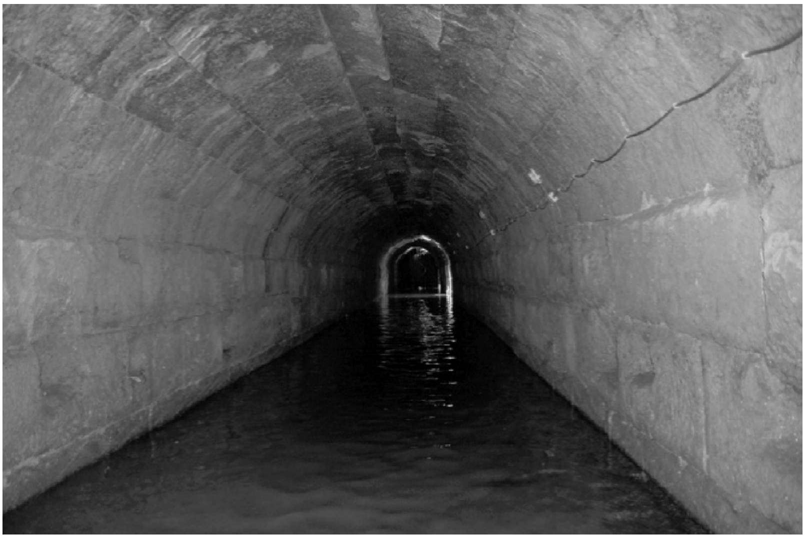

FIGURE 1.3 A tract of Cloaca Maxima from about 4 B.C. (Source: Picture courtesy of Dr. John Hopkins.)

developing underground sewer networks as we know them today. As late as the period of the French revolution—a little more than 200 years ago—the total length of the sewer network in Paris was only 26 km. In 1887, the total length was extended to 600 km.

1.2.4 Sewer Network of Today under Development

The sewer network we know today is a relatively newly invented infrastructure of cities. Not until the early days of the Second Industrial Revolution, starting around 1830 in Europe and America, did it become common to construct underground wastewater collection systems. Often, the sewers developed as "wild mixed systems" with a main purpose of fast removal of wastes and wastewater from the growing cities.

London and Paris were among the first to develop efficient sewer networks, but other European, Australian, and American cities followed rapidly. The first sewers developed from the storm drains, which were then allowed to receive waterborne wastes from flush toilets, in principle converting these drains into combined sewers. A major reason for collecting the wastewater in underground systems was the enormous problem of the unpleasant smell from the open sewers, cesspools, and privies, and the requirements for space in the streets of densely populated cities. Therefore, design procedures and construction details facilitating the efficient transport of the solid constituents of wastewater became central, an aspect that remains valid even today. As an example, in 1906 the 1177-km sewer system in Paris was equipped with 4369 small ancillary works with the sole purpose of flushing the pipe section located downstream. The so-called man-entry sewer is basically also a "construction detail" for the efficient removal of sediments that otherwise could cause blocking.

1.2.5 Sanitation: Hygienic Aspects of Sewers

The knowledge on the hygienic aspects of sewers and the corresponding human impacts in terms of water-borne diseases developed slowly from the late eighteenth century during the next 100 years. It was definitely in contrast to the rapidly developing urbanization that took place during the same period. The lack of an efficient infrastructure for wastes in growing cities and new settlements caused severe pandemics. There were numerous attempts to improve the understanding of how human wastes could affect health and the development of diseases. Several correct observations and solidly performed investigations on this relationship failed to find general acceptance. Based on studies of the environmental conditions in prisons, the famous French chemist Antoine Lavoisier concluded that the quality of water supply and sewerage affected the health of the inmates. Unfortunately, Lavoisier was beheaded in 1794 during the French revolution. The occurrence of pandemics of cholera and numerous local outbreaks from the beginning of the nineteenth century until about 1860 caused more than 5 million deaths, particularly in growing European cities with faulty sewerage infrastructure. An illustrative example is the cholera epidemic in Copenhagen, Denmark, during the months of June to August in 1853. A total of 4737 inhabitants died in less than 3 months, which at that time comprised almost 5% of the population in Copenhagen.

A major step toward understanding the impact of wastewater contamination of drinking water sources took place in 1848 when an English physician, John Snow, observed that outbreaks of cholera in London occurred within geographically concentrated areas where people received their water supply from the very same water well. Then, he correctly concluded that a substance "materia morbus" was excreted by cholera-infected humans and transported into the drinking water systems, typically local underground wells. At that time, however, his considerations were totally rejected by physicians who continued to insist that diseases such as cholera and "black death" were caused by foul air. During a cholera epidemic in the Soho area of London in 1854, John Snow continued his studies and identified the outbreak as the public water pump on Broad Street (now Broadwick Street). However, the water pump was not finally closed until 1866—proving that the adoption of new knowledge takes time. The significance of John Snow's accomplishment is that he, based on solid statistical facts, identified the link between cholera infection and water polluted with human excreta, i.e., he identified polluted water as the vector for the cholera disease. However, it was not until 1883 when the German doctor, Robert Koch, isolated *Vibrio cholerae*, that the microbial cause of the disease was finally identified. For his work as the founder of bacteriology, Robert Koch received the Nobel Prize in physiology and medicine in 1905.

The concept of a deliberate separation of wastewater and drinking water was, however, not generally accepted and might, in most cases—compared with the need for space in the narrow streets—not have been a principal initiating factor in the establishment of underground sewers. Later, during the twentieth century, it became quite clear that a sewer is a "technical hygienic and sanitary installation" that efficiently reduces epidemic diseases. This characteristic is still valid and is a major reason why underground sewer networks are still expanding, even in developing countries under conditions of limited financial resources. The need for sanitation is clearly shown by the fact that the World Health Organization (WHO) reported that around 2005, more than 1.1 billion people lack access to drinking water from an improved source and that 2.6 billion people do not have basic sanitation.

It is generally recognized that the sewer network is a sanitary installation that effectively hinders wastewater in being a vehicle for dissemination of infectious diseases. It is in this respect interesting that the *British Medical Journal* (*BMJ*), during the period between January 5 and January 14, 2007, invited its readers (mainly medical doctors from countries all over the world) to submit on its web site a nomination for the top medical breakthrough since 1840, the year the journal was launched. *BMJ* posted 15 areas of medical advances as potentials for nomination, of which sanitation garnered the top vote—ahead of, for example, antibiotics, anesthesia, vaccines, and discovery of the DNA structure (Hitti 2007).

1.2.6 Sewer and Its Adjacent Environment

The polluting impact onto the environment of the waste stream from sewers is historically a relatively recent concern. In 1889, the following excerpt was included in an article on the advantages of a separate sewer system (Manufacturer and Builder 1889): "A theoretically perfect sewer would be one in which all the sewage would be carried rapidly to its outfall outside the city, so that no time would be given for decomposition." Although the environment outside the city is not considered a problem, it is apparently problematic if "decomposition" occurs within the city area. In the same article, it is referred to as a problem that the combined sewers result in "obstructions form a series of small dams in the sewer, and in dry weather the sewage stands in a succession of pools along the sewers, decomposing and sending volumes of sewer gas out of every crevice through which it can escape." It is, however, not further discussed what "sewer gas" is. In 1889, details relating to the chemical and microbial processes in sewers were unknown among constructors and operators of sewers.

Until the middle of the twentieth century, the sewage collected in cities was typically discharged into the adjacent environment without any type of treatment, resulting in problems such as bacterial contamination, malodors, dissolved oxygen depletion, and fish kills in downstream receiving waters. Even today, such problems are well known, and other problems such as eutrophication and toxicity of heavy metals and organic micropollutants including, for example, chemical substances originating from pharmaceutical drugs have been added. The "end-of-pipe" solution to these problems in terms of wastewater treatment was not introduced in several countries until after World War II. Although wastewater treatment plants—with different levels of treatment—are now common worldwide, the process of further development of treatment and reuse of resources from the waste streams is still in progress. We still suffer from the aftereffects of a missing integrated development of the urban wastewater system by a narrow distinction between the sewer as a collecting and conveying system for wastewater and the treatment plant as a pollutant reduction system.

The older parts of the cities in Europe and the United States are typically served by combined sewer networks with outfalls from where the excess wet weather flows are more or less untreated and routed into an adjacent receiving water system. Although separate sanitary and storm sewers have dominated construction for the past 50 to 100 years, numerous old combined systems are still in operation, often being upgraded and equipped with basins to detain wet-weather discharges of untreated water.

1.2.7 Hydrogen Sulfide in Sewers

Today's sewerage in terms of a combined wastewater conveyance in sewers followed by its treatment is, as described in Sections 1.2.5 and 1.2.6, the solution for problems associated with both sanitation and environmental effects. However, the way we construct sewer networks may lead to in-sewer anaerobic process-related problems, primarily in terms of the formation of hydrogen sulfide and volatile organic compounds. The corresponding problems appear as concrete and metal corrosion degrading the sewer network, health-related impacts on the sewer personnel, and malodors observed in the adjacent environment.

It is likely that anaerobic processes in terms of production of hydrogen sulfide and other malodors have always been associated with conveyance of human wastes. "Sewer processes" are in this respect not a new "invention." However, it was not until the beginning of the twentieth century that hydrogen sulfide formation and concrete corrosion were finally identified in terms of a cause–effect relationship (Olmsted and Hamlin 1900).

The scientific and technical aspects of chemical and biological sewer processes focusing on hydrogen sulfide formation and its impacts and control were not deliberately dealt with until about 1930 (Bowlus and Banta 1932; Pomeroy 1936; Parker 1945a, 1945b). Knowledge on the sulfide problem was the result of the work of prescient scientists and practitioners and particularly developed in the Los Angeles area in California, the United Kingdom, and Australia. Although this knowledge was published internationally, it was not generally known among constructors and operators of sewer networks worldwide. Even in the late twentieth century, several structures were constructed that reflected their builders' lack of knowledge on the nature of chemical and biological processes in sewers, and corresponding wrong network constructions led to fatal disruptions caused by hydrogen sulfide formation. Even today it is frequently seen that inappropriate sewer constructions and operational mistakes are due to an incomplete understanding of the process.

It is, however, important to notice that since about the 1960s, problems related to hydrogen sulfide in terms of deterioration of sewer networks and concerns for the toxicity and odor nuisance have became clear to several municipalities and network stakeholders. Investigations were performed in several countries to gain knowledge on the formation and control of hydrogen sulfide. A number of models for prediction of sulfide formation and guidelines for solving the sulfide problems in gravity sewers and pressure mains were developed. These models and guidelines have been widely used for sewer design and for implementation of appropriate control methods to prevent the generation of sulfide or its effects (cf. Chapters 6 and 7).

1.2.8 Final Comments

The development of sewers that has taken place is the result of 100 to 150 years of enormous investments. All over the world, it has left us with a sewer and treatment plant infrastructure that will be in use for an unknown length of time. We will still see developments in terms of technical improvements and sustainable solutions. However, as a general trend, we will not see the present wastewater collection and treatment concept replaced by, for example, centralized collection of "solid" human excreta or on-site solutions. It might have been a realistic option for implementation and further development 150 years ago. Not now!

1.3 TYPES AND PERFORMANCE OF SEWER NETWORKS

Sewer network characteristics in terms of design, use of materials, and operation affect sewer processes, and, what is important, knowledge on sewer processes can be actively applied in the design and operation of a sewer system. As an example, the type of sewer determines, to a great extent, if aerobic or anaerobic processes dominate. Furthermore, the flow regime in the water phase and ventilation of the sewer atmosphere may affect the gas phase buildup of odorous, corroding, and toxic volatile substances produced by microbiological processes in the water phase.

Sewers can be classified into different categories. The three major ways of classification refer to (1) which type of sewage is collected, (2) which type of transport mode is applied, and (3) the size and function of the sewer. These three different categories of sewers divide sewers into groups with different characteristics in terms of wastewater collection and transport. In addition, it is also extremely relevant to consider these aspects when addressing sewer processes.

1.3.1 Type of Sewage Collected

There are three main types of sewer networks that refer to the sources of the sewage: sanitary sewers, storm sewers, and combined sewers. Wastewater of domestic, commercial, and industrial origin is conveyed in both sanitary sewers and combined sewers, whereas the storm sewers in principle only transport runoff water from urban surfaces and roads. Each of the three types of sewers has, in terms of different flow and pollutant characteristics, specific properties related to sewer processes. This book does not cover the specific characteristics related to stormwater runoff. These aspects are, in terms of processes and pollution, addressed in a "parallel" book by the same authors (Hvitved-Jacobsen et al. 2010).

1.3.2 Transport Mode of Sewage Collected

There are two main types of sewer networks that refer to the transport mode: gravity sewers and pressure sewers (Figure 1.4). A gravity sewer is designed with a sloping bottom and the flow occurs by gravitation. In contrast, the driving force for flow in a pressure sewer is pumping. A pressure sewer is therefore also named a pumping sewer or a force main. In terms of processes, it is important that the water surface in a gravity sewer is most of the time exposed to a gas phase (sewer atmosphere), whereas this is clearly not the case in a pressure sewer. The exchange of volatile compounds between the water phase and the gas phase in a gravity sewer, e.g., molecular oxygen resulting in reaeration of the water phase, is crucial. In contrast, anaerobic conditions in wastewater of pressure sewers are typically occurring.

1.3.3 Size and Function of Sewer

A sewer system is a network and the sewage flows typically from small collecting sewers in the upstream part of a catchment through larger and larger sewers until it reaches the wastewater treatment plant. Different terms are used to characterize a sewer in this respect. The small-diameter sewers in the upper part of a catchment are often called lateral sewers. A number of lateral sewers typically discharge into

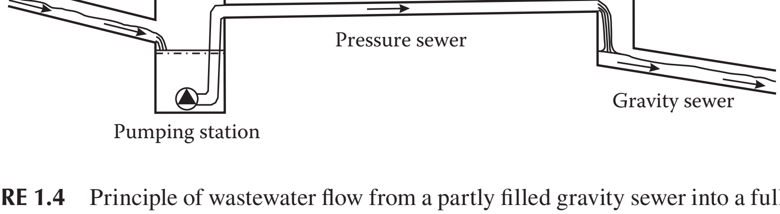

FIGURE 1.4 Principle of wastewater flow from a partly filled gravity sewer into a full flowing pressure sewer followed by a gravity sewer.

a trunk sewer that thereby serves a larger catchment area. The main structure of the sewer network is the intercepting sewer that may receive sewage from several trunk sewers and diverts the sewage to treatment and disposal. The size and function of a sewer affect sewer processes in different ways. As an example, the water phase processes are more dominating compared with surface related processes—the biofilm processes—in large-diameter sewers.

The classification of sewers in terms of which type of sewage is collected will in the following be further explained and focused on.

Sanitary sewer networks. Sanitary sewers—often identified as separate sewers—are designed to collect and transport the daily wastewater flow from residential areas, commercial areas, and industries to a wastewater treatment plant. Typically, the wastewater transported in these sewers has a relatively high concentration of more or less biodegradable organic matter and microorganisms and is therefore biologically active. Wastewater in these sewers is, from a process point of view, a mixture of biomass (especially heterotrophic bacteria) and substrates for this biomass.

The flow in sanitary sewers is controlled by either gravity (gravity sewers) or pressure (pressure sewers) exerted by pumps installed in pumping stations (Figure 1.4). In a partially filled gravity sewer, transfer of oxygen across the air–water interface (reaeration) is possible, and aerobic heterotrophic processes in the wastewater may proceed. On the contrary, pressurized systems are full flowing and do not allow for reaeration of the water phase. In these sewer types, anaerobic processes in the wastewater will, therefore, generally dominate.

Among other parameters, the residence time in a sewer network affects the degree of transformation of the wastewater. The residence time depends on the size of the catchment, the distance to the wastewater treatment plant located downstream, and specific sewer characteristics, such as pipe diameter and slope of a gravity sewer pipe. The residence time is often relatively high in a pressure sewer, principally during nighttime hours when a reduced flow of wastewater is typical.

Storm sewer networks. Storm sewers or stormwater sewers are constructed for collection and transport of stormwater (runoff water) originating from impervious or semipervious urban surfaces such as streets, parking lots, and roofs and from roads and highways. Surface waters typically enter these networks through inlets located in street gutters. The storm sewers are in operation during and after periods with rainfall—and in cold climate areas, also during snowmelt periods. Typically, a storm sewer diverts the runoff water into adjacent watercourses with no or limited chemical and biological treatment although treatment of the runoff in, e.g., detention and retention ponds or other types of facilities, is becoming more common.

In the context of this book, focusing on the dry weather performance of sewers, the storm sewer network will only be given limited attention. The quality aspects of storm sewer networks in terms of design, performance, and impacts are central subjects of Hvitved-Jacobsen et al. (2010).

Combined sewer networks. The combined sewers collect, mix, and transport the flows of municipal wastewater and urban runoff water. In terms of the processes that proceed in the combined sewers, these systems generally perform like sanitary sewers during dry weather periods. However, because of their ability to serve runoff purposes, combined sewer networks are designed differently compared with separate sewers and include constructions such as overflow structures and detention basins to manage large quantities of wet weather flows. These ancillaries may influence a number of process details. Furthermore, the combined systems are subject to a higher degree of variability in the processes compared with the sanitary sewers because of the frequent shift in the flow conditions. Combined sewer networks are constructed as either gravity sewer lines or pressure pipes—or as a combination of both of these types.

The main characteristic features of the three different types of sewer networks are depicted in Figure 1.5.

The three types of sewer networks represent the main types. In practice, sanitary sewers often exist in catchments partially operated by separate sewers, i.e., the sanitary sewers may to some extent receive runoff water. Furthermore, sanitary sewage may also be discharged into storm sewers. Such illicit connections are frequently seen. Other alternative sewer systems include, for example, the vacuum sewers that are typically small systems and are operated locally.

1.4 SEWER AS A REACTOR FOR CHEMICAL AND MICROBIAL PROCESSES

Sewer processes proceed in complex systems, i.e., in one or more of the five phases: the suspended water phase, the biofilm, the sewer sediments, the sewer atmosphere, and at the sewer walls. Furthermore, exchange of substances across the interfaces takes place. Processes that proceed in the sewer system also affect other parts of the urban system, e.g., the urban atmosphere with malodorous substances. Furthermore, wastewater treatment plants and local receiving waters receive not just those substances discharged into the sewer but also products that are the result of the sewer processes (Figures 1.1 and 1.6).

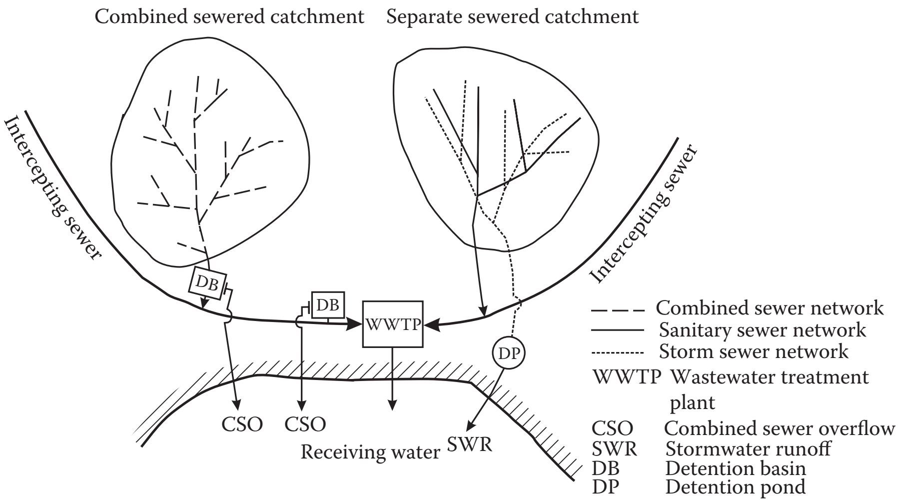

FIGURE 1.5 Outline of sewer networks in separate sewer catchments and combined sewer catchments.

The conditions for reduction and oxidation of substances—the redox conditions—are in general central for understanding which chemical and biological processes can proceed. For the sewer as a chemical and biological reactor, the redox conditions therefore play a central role. In principle, a redox reaction proceeds by transferring electrons at the atomic or molecular scale from one compound to another compound. By this transfer of electrons, oxidation and reduction, respectively, of the involved compounds will proceed.

The microbial system in wastewater of sewers is dominated by heterotrophic microorganisms, which degrade and transform wastewater components. The redox conditions are determined by the availability of the electron acceptor, i.e., the substance that receives electrons in a redox reaction. Examples of important electron acceptors in a sewer are dissolved oxygen (O_2), nitrate $\left(NO_3^-\right)$, and sulfate $\left(SO_4^{2-}\right)$, determining whether aerobic, anoxic, or anaerobic processes, respectively, may occur. By the transfer of electrons, reduction of the central element of these three compounds to water (H_2O), molecular nitrogen (N_2), and hydrogen sulfide (H_2S), respectively, takes place. The importance of the processes for the sewer and the surroundings is not just caused by the removal and transformation of organic substrates—the electron donor—but is also a result of transformation of the electron acceptors exemplified by the formation of hydrogen sulfide from sulfate.

The design characteristics and operation mode of a sewer network determine, to a great extent, which redox conditions prevail. Table 1.1 gives an overview of sewer system characteristics important for the process conditions. Primarily, aerobic and anaerobic conditions arise, whereas anoxic conditions in principle only

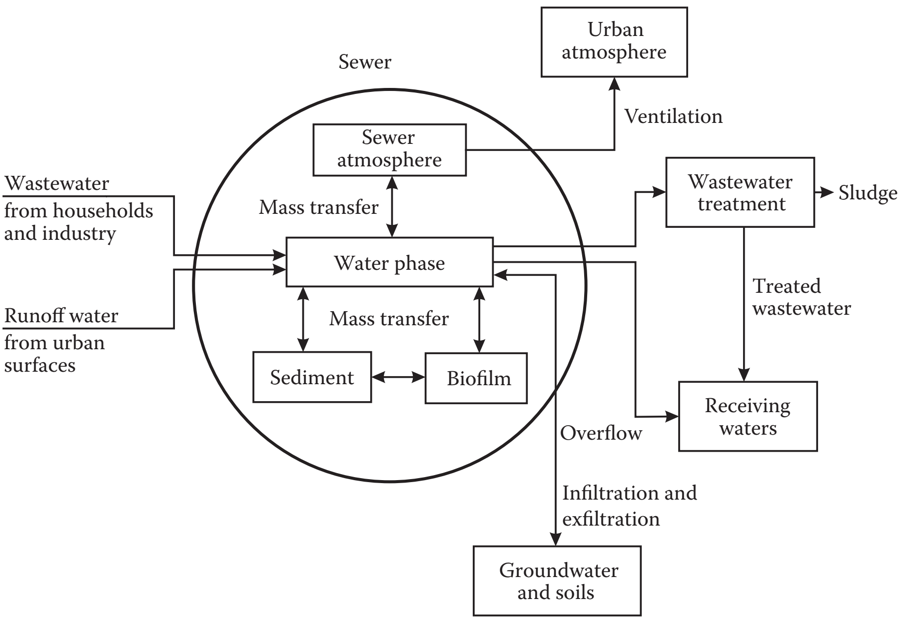

FIGURE 1.6 Outline of wastewater flows related to a sewer system showing locations for potential occurrence of sewer processes and the receiving environment.

exist if nitrate—or oxidized inorganic nitrogen substances—is artificially added to the wastewater. The extent of reaeration, which is closely related to the design and operation of the sewer, is a fundamental process that determines if aerobic or anaerobic conditions exist. Under aerobic conditions, degradation of easily biodegradable organic matter is a dominating process. If dissolved oxygen or nitrates are not available, strictly anaerobic conditions occur, and sulfate is typically the external electron acceptor, resulting in the formation of hydrogen sulfide, a phenomenon well known among practitioners dealing with collection systems. Furthermore, fermentation occurring under anaerobic conditions plays a major role for formation of malodors.

It should briefly be noted that the redox processes shown in Table 1.1 are the so-called respiration processes, i.e., they require the participation of an external electron acceptor. In contrast, organic matter can, in fermentation processes, undergo a balanced series of oxidative and reductive reactions, i.e., organic matter reduced in one step of the process is oxidized in another.

In addition to the redox conditions affected by the design characteristics of the sewer network as outlined in Table 1.1, several other sewer characteristics influence the process conditions. The following examples illustrate the close relations between design and operation characteristics and the resulting conditions for the sewer processes:

Turbulence and flow of wastewater affect reaeration and release of odorous and corrosive substances into the sewer atmosphere.

Ventilation of the sewer system releases odorous and toxic substances into the urban atmosphere, and if—as an example—hydrogen sulfide is released to the surroundings, the corroding effect of this substance is reduced in the network itself.

The hydraulic mean depth of the water phase, i.e., the cross-sectional area of the water volume divided by the width of the water surface, affects the process conditions for reaeration and thereby the potential occurrence of aerobic transformation of organic matter.

The wastewater velocity and shear stress at the sewer walls affect the buildup of sewer biofilms and deposits.

TABLE 1.1
Electron Acceptors and Corresponding Conditions for Microbial Redox Processes (Respiration Processes) in Sewer Networks

Process Conditions	External Electron Acceptor	Typical Sewer System Characteristics
Aerobic	+ Oxygen	Partly filled gravity sewer Aerated pressure sewer
Anoxic	– Oxygen + Nitrate or nitrite	Pressure sewer with addition of nitrate
Anaerobic	– Oxygen – Nitrate and nitrite + Sulfate (+CO_2)	Pressure sewer Full-flowing gravity sewer Gravity sewer with low slope and deposits

The relation between design and operation characteristics and process conditions is emphasized to draw attention to the fact that knowledge on sewer processes can actively be used to design sewers to observe specific process requirements. What is important in this respect is, of course, a quantification of relevant knowledge on sewer processes addressing relevant aspects of engineering sewer networks in terms of planning, design, and management. Knowledge that can be expressed for prediction and simulation in terms of models is of specific importance. In this way, it should, as an example, not be unrealistic to "design" wastewater for intended purposes. Applying sewer design characteristics that enhance the formation of low molecular organics and thereby improve nutrient removal in wastewater treatment is an example.

Wastewater characteristics play an important role for the nature and the course of the sewer processes. A number of parameters such as temperature and pH and quality characteristics, for example, biodegradability of the organic matter and the amount of active biomass, are crucial for the outcome of the transformations. Microbial transformations—and thereby biochemical transformations—characterize the sewer environment in terms of wastewater quality. On the other hand, the physicochemical characteristics, e.g., diffusion in the biofilm and transfer of substances across the water–air interface, play an important role and are therefore an integral aspect of microbial transformations. The hydraulics and the sewer solids transport processes have also a pronounced impact on the sewer performance. These physical processes, however, are dealt with in books on hydraulics and are, therefore, only included in this book when directly related to the chemical and biological processes. The following section is, however, included to give a brief introduction to the physical processes.

1.5 WATER AND MASS TRANSPORT IN SEWERS

The need for collection and conveyance of wastewater from its many sources to treatment and discharge are the fundamental cause why the sewer infrastructure is established. The hydraulics of the water phase with its contents of constituents is therefore traditionally the basis for design and management of sewer networks. In addition, it must be addressed that the sewer processes need to be included to observe safe, efficient, environmentally acceptable, and sustainable transport of the sewage.

Details of sewer hydraulics and corresponding procedures for design of sewers are, as previously mentioned, not a central subject of this book. Knowledge on basic flow characteristics of the water phase and its constituents is, however, needed to fully understand the nature of sewer processes. Such fundamental aspects will therefore briefly be dealt with in this section. It is in this respect important that traditional sewer hydraulics does not include transport processes such as mass transport across the air–water interface and the water–biofilm surface. Neither is the movement of the sewer atmosphere and ventilation considered in traditional hydraulic design of sewers. Such mass transport processes play a central role when dealing with sewer processes and are therefore definitely an objective of this work to deal with.

Several textbooks on different hydraulic subjects are available and relevant for sewer design. The books published by Hauser (1995) and Chanson (2004) are two examples of work that deal with basic and general hydraulics. Comprehensive details on water and mass transport in sewers are found in the work of, for example, Ashley et al. (2004) and ASCE (2007).

The physical transport processes are, in terms of chemical and microbial processes in sewers, generally important as a basis to determine where the pollutants occur. Transport-related aspects concern both soluble and particulate forms of the constituents. An important aspect relate to sediment deposition in sewers that may cause both physical blocking and hydrogen sulfide problems. Scouring of sediments in combined sewers caused by increased flow during extreme rainfall runoff may induce the release of pollutants into the water phase and discharge of these substances into adjacent receiving waters.

1.5.1 Advection, Diffusion, and Dispersion

A fundamental characteristic of flowing waters is related to the mode of movement defined as either being laminar or turbulent—and a transition state between these two types of flow regimes. Laminar flow generally exists at low flow velocities, whereas at increased flow, the movement of the water changes from a calm to a whirling motion. When laminar flow exists, it is possible to determine the velocity field in time and place as a transport of the water and its associated constituents in just one direction and with a constant flow velocity over time. In turbulent flow, however, the velocity profile of the fluid varies, caused by a mutual exchange of the water elements. Contrary to laminar flow, the turbulent flow velocity is therefore determined by two terms: a mean value and a component that varies stochastically. At turbulent flow, the velocity vector therefore changes both magnitude and direction.

In the following sections, a number of fundamental hydraulic phenomena that are important for the movement of soluble as well as particulate pollutants are briefly defined and described:

- Advection
- Molecular diffusion (Fick's first law)
- Dispersion (eddy diffusion)

1.5.1.1 Advection

Advection—also named convective transport—describes a mode of transport where a constituent is transported by the net flow of the water phase. Advection thereby describes a situation where no spreading of a constituent takes place. Advection is quantified in terms of a flux. The flux, J, of a constituent is defined as a transport, i.e., as an amount of a constituent transported per unit of time and per unit of cross sectional area. It is basically a vector, i.e., it includes both the magnitude of the phenomenon and a direction. The magnitude of the flux—also named the flux rate is:

$$J = Cu \tag{1.1}$$

where:

J = flux (rate) of a constituent (g m^{-2} s^{-1})
C = constituent concentration (g m^{-3})
u = net flow velocity of water (m s^{-1})

Advection describes a mode of flow where all soluble and particulate constituents are exposed to a uniform velocity, i.e., the flux vector is equal for all constituents in the water phase, soluble species, as well as suspended particles.

1.5.1.2 Molecular Diffusion

Diffusion is a disordered movement of the constituents that takes place at the molecular scale. The molecular scale movement of a constituent is caused by a temperature-induced mutual impact of the molecules. This temperature-induced movement is also known as Brownian movement. The net movement of the constituents always (on average) takes place from a high concentration to an area of lower concentration.

At the macroscopic level, molecular diffusion is expressed by Fick's first law of diffusion. The temperature-dependent driving force for the flux of a constituent is the concentration difference per unit of distance, i.e., the concentration gradient:

$$J = -D\frac{\mathrm{d}C}{\mathrm{d}x} \tag{1.2}$$

where:

D = molecular diffusion coefficient (m^2 s^{-1})
x = distance (m)

The magnitude of the diffusion coefficient depends on both the properties of the constituent that is transported and the fluid (water). The temperature has an influence on the magnitude of D, but it is, by definition, independent of the mode of transport because it fundamentally describes a phenomenon that takes place at the molecular scale.

Molecular diffusion is a phenomenon that causes a slow movement of a constituent, and the molecular diffusion coefficient for small molecules is typically in the order of 10^{-9} m^2 s^{-1}. The characteristic distance of travel versus time is:

$$x = (2Dt)^{0.5} \tag{1.3}$$

where t denotes time (s).

Molecular diffusion is important when dealing with, e.g., transport in biofilms and transport across interfaces (e.g., the air–water interface). However, within the water phase it is generally exceeded by several orders of magnitude by dispersion, which is described in the following section.

1.5.1.3 Dispersion

Dispersion of a constituent describes a phenomenon related to its spreading in a fluid (water). In contrast to molecular diffusion, dispersion is a movement at the macroscopic scale and is caused by flow velocity variations in time and place. Dispersion is therefore related to turbulent conditions and typically exceeds molecular diffusion by several orders of magnitude. In practice, it is always occurring in sewer flows. Dispersion is also known as eddy diffusion.

Dispersion is a random process that by nature is quite different compared with molecular diffusion. However, dispersion on average also concerns transport of constituents from areas of high concentration to areas of low concentration. The empirical description of dispersion therefore follows a similar form as shown by Fick's first law (Equation 1.2):

$$J = -\varepsilon \frac{\mathrm{d}C}{\mathrm{d}x} \tag{1.4}$$

where ε is the dispersion coefficient ($m^2\ s^{-1}$).

Contrary to values for D, it is basically not possible to produce tables that give values of ε for specific compounds. The reason is that the actual flow pattern—more than the type of compound—determines the magnitude of the dispersion coefficient. Determination of ε therefore basically requires flow measurements followed by a model calibration procedure.

1.5.2 Hydraulics of Sewers

The following is a rather brief introduction to the hydraulics of sewers. Further details are found in the work Yen (2001) and WEF (2007).

As described in Section 1.3 and illustrated in Figure 1.4, the flow regime in gravity sewers and pressure sewers are fundamentally different. For both types of sewers, it is crucial that they are designed and constructed to manage varying flow rates of the sewage over time. The pressure sewer must therefore be designed with sufficient pipe and pump capacity to observe this variability. In the gravity sewer, the capacity is determined by the gravity force as the driving force for the water flow and the resistance in terms of friction. The one-dimensional unsteady state flow in a gravity sewer pipe is expressed by the two so-called Saint-Venant equations (Equations 1.5 and 1.6) that are formulated here for open-channel flow (cf. Figure 1.7).

The continuity equation:

$$\frac{\mathrm{d}Q}{\mathrm{d}x} + b\frac{\mathrm{d}y}{\mathrm{d}t} = q \tag{1.5}$$

The momentum equation:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{Q^2}{A}\right) + gA\frac{\mathrm{d}y}{\mathrm{d}x} = -gAS_{\mathrm{f}} \tag{1.6}$$