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URBAN DRAINAGE SYSTEMS: EVOLUTION OF PROBLEMS

1.1 INTRODUCTION

The practice of urban drainage has been traced back to some of the earliest recorded histories of humankind. The expeditious conveyance of stormwater from urbanized areas was motivated primarily by reasons of convenience and the reduction of flood damage potential. The removal of domestic wastes from households using waterborne conveyances was also found to be convenient. Such practices to improve the quality of urban life, however, have resulted in other problems, such as artificially induced flooding, increased erosion, and environmental degradation stemming from the pollution of receiving waters. As a result, attention has focused on the comprehensive management of urban drainage systems, which includes, in addition to the ancient use of conveyances such as channels and pipes, the implementation of storage and treatment facilities as well as the real-time control of entire systems. The objective of this practice, is commonly referred to as stormwater management, is to intelligently utilize components of drainage systems in a manner that will improve the quality of urban life while protecting the environment in a cost-effective manner. To facilitate the effective management of these inherently complex combinations of natural elements and engineering works, mathematical modeling is often employed to better understand system behavior and performance which in turn leads to better engineering and management decisions. This book concentrates on the mathematical modeling of urban drainage systems, particularly for planning-level decision analyses.

In the present chapter we outline the problems, both past and present, related to drainage system design practices. It is fundamentally important for engineers and planners to understand the problems that must be addressed in modern drainage system design, to have an appreciation of the origins of these problems and to understand the long-term impacts that urban drainage systems are required to overcome. A case study is also presented to illustrate the severity of stormwater management problems from both an environmental and a legal perspective.

1.2 BRIEF HISTORY OF URBAN DRAINAGE SYSTEM PROBLEMS

> He who understands things in their first growth and origin will have the clearest view of them.
>
> —Aristotle, *The Politics*, Book I

Some of humanity's earliest cities were serviced by sewers. For example, archaeological excavations of settlements in the Indus and Tigris river basins have revealed the utilization of drainage conduits as far back as possibly 3500 B.C. The Romans were great builders of aqueducts, sewers, roads, and bridges. The great sewer (cloaca maxima) built in the sixth century B.C. to drain the Forum in Rome is still in use today. Across the millennia leading to our era, the practice of sewerage or drainage followed essentially the same philosophy. That is, sewers were built to drain only runoff from stormwater. So strictly was this practice followed that in Roman times, laws were enacted to specifically prohibit the entry of anything but rainwater into the sewer systems. Thus, sewers were put in place largely for reasons of convenience, to minimize the detention of water on roadways and other surfaces in wet weather.

Human and domestic wastes were managed by the *dry-carriage* system whereby heaps of night soil were accumulated outside dwellings to be carried away at night by the "honey wagon". This sewerage philosophy was practiced until well into the nineteenth century. The increased urban populations and resulting congestion following the era of industrialization in Europe caused the dry-carriage system to break down. Night soil removal could not keep pace. The accumulation of human and domestic wastes in cities increased the transmission of communicable diseases (particularly typhoid and cholera) through a variety of mechanisms: increased human contact with waste, increased opportunity for vector contact, and fecal pollution of local groundwaters, which acted as a common source of domestic water supply. The resulting epidemics in cities such as London and Paris in the 1840s and 1850s were of such a magnitude that action was demanded. An expedient solution to the accumulation of night soil in the city was to allow the discharge of human wastes into what had to that point been exclusively stormwater drains. This was the birth of the combined sewer or the *wet-carriage* waste disposal system. Existing storm sewers were converted to combined sewers and new sewers, were designed to act as combined sewers. This practice was also followed in North America.

Since the combined sewer arose as an ad hoc solution to a pressing problem, it is not surprising that it would have problems of its own. Storm sewers converted to combined sewers discharged their bounty directly to local watercourses. In the first instance as a storm sewer, this practice was seemingly reasonable because the sewer conveyed essentially rainwater to a hydrologic system that would have received it anyway. In the second instance, as a combined sewer, the wet-carriage system delivered human and domestic wastes directly to watercourses, a less reasonable proposition. Soon, gross water pollution left receiving waters anaerobic and foul; so foul was the stench from the River Thames that it is known to have closed a sitting of the Parliament in Westminster in the nineteenth century. So profound was the effect of this water pollution that fish began to reappear in the Thames at London only in recent decades. In addition to these ecological and aesthetic problems, the fecal contamination of surface waters further impaired the quality of surface water supplies. For example, the typhoid and cholera epidemics in Chicago from such contamination of the Lake Michigan water supply are well known and resulted in the engineered reversal of flow in the Chicago River to overcome this contamination.

It soon became apparent that treatment of combined sewage before discharge to watercourses was necessary. The implementation of sewage treatment was confounded by a large number of combined sewer outfalls (pipes entering watercourses). It was impractical to locate a sewage treatment plant at every combined sewer outfall, particularly considering that many outfalls are located in the city core. Thus began a need to centralize the sewage from many outfalls to downstream locations. This was effected by building interceptor pipes that "intercepted" the sewage at each outfall and conveyed it to a centralized location where treatment was practiced as illustrated graphically in Fig. 1.1.

There are practical difficulties with sizing the interceptor pipe. Ideally, at any location along the interceptor, its capacity would equal the sum of the capacities of the combined sewers upstream of that location. However, such a procedure would result in enormous interceptor pipe size and, considering the typically long length of interceptors, would be prohibitively expensive. The reason for this large interceptor capacity requirement (if the interceptor capacity equals the sum of the combined sewer capacities upstream) lies in the fact that each combined sewer is designed not only for the domestic sewage flow [dry weather flow (DWF)] but also for the wet weather flow (WWF) from relatively large magnitude storms. The WWF may be as much as two orders of magnitude larger than the DWF. Thus the policy above would result in both enormous interceptors and enormous treatment plants. Therefore, decisions were made to size the interceptor for some multiple of the DWF in the combined sewers that it drained. Typically, the interceptor capacity is in the range 2 to 3 $\times$ DWF and sometimes higher. Whenever WWF in the combined sewer exceeds the diversion capacity to the interceptor, the excess flow is "overflowed" through the outfall to the watercourse. These combined sewer overflows (CSOs) are themselves a significant source of water pollution.

An additional problem of combined sewers arises from direct connection of interior building plumbing to the combined sewer. The lowest connection is usu-

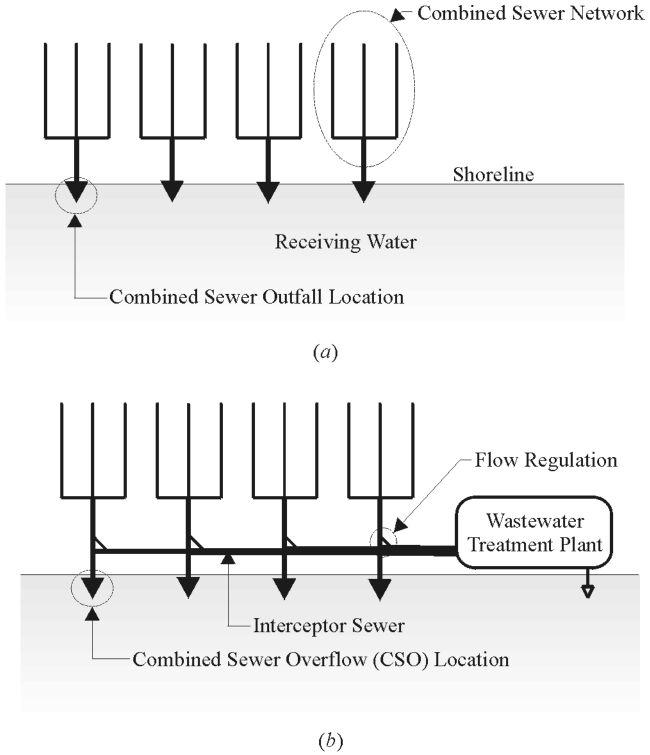


Figure 1.1 Combined sewer systems: (*a*) as originally constructed, discharging raw sewage directly to the receiving water; (*b*) with interceptor sewer conveying sewage to centralized treatment facility.

ally the basement floor drain. When storm conditions cause the hydraulic capacity of the combined sewer to be exceeded, the sewer becomes surcharged; that is, the pipe comes under hydraulic pressure. If the pressure is great enough, the flow may be reversed as shown in Fig. 1.2, from the sewer to the basement floor drain causing backups, flood damage, and potential health threats.

The initial forms of treatment employed for intercepted combined sewage were primitive. Prior to this century, holding ponds or tanks were used to provide quiescent settling conditions for the removal of settleable solids, which became known as primary sedimentation or primary treatment. In other cases, sewage farming or land irrigation with sewage was practiced. Around the turn of the century, experiments with aerobic biological treatment were in progress in the form of trickling filters or bacteria beds, oxidation ditches, and the activated sludge process. These forms of sewage treatment became known as secondary treatment. In the pre–World War I period, primary treatment dominated. The interwar period saw the transition from primary to secondary treatment. In the post– World War II period, secondary treatment in its various forms has dominated. The decades since the 1960s witnessed extensive research on tertiary or

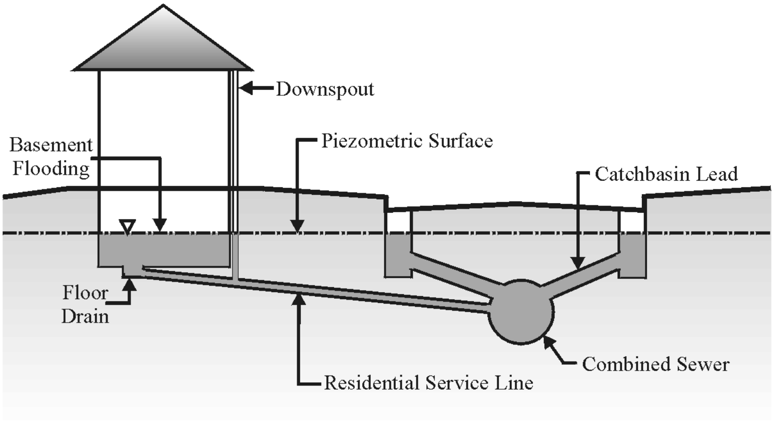


Figure 1.2 Surcharged combined sewer causing basement flooding.

advanced forms of wastewater treatment in the form of physical, chemical, and biological processes. Implementation of advanced wastewater treatment systems has been generally cautious and spotty except where specifically employed for wastewater reclamation.

Although the widespread practice of combined sewerage was continued in North America until as recently as the mid-twentieth century (and the construction of combined sewerage systems continues, particularly in western Europe, albeit with relatively sophisticated management controls: e.g., tanks, pumpbacks, tank flushing, screening, disinfection, and diversions) the problems of combined sewer overflows and sewer backups have generally led to the practice of sewer separation. This system employs two pipes rather than one as in combined sewer systems. One pipe transports only domestic, commercial and industrial, wastes (the sanitary sewer), while the other pipe transmits only drainage originating from stormwater (the storm sewer). This type of system was advocated in England a century earlier by Edwin Chadwick, who coined the phrase "the rain to the rivers, the sewage to the soil." On the surface, the separated sewer system appears eminently reasonable. The highly polluted sanitary sewage is contained in one pipe system and undergoes treatment while the relatively clean stormwater is contained in another pipe system and is discharged untreated to a local watercourse. Additionally, sewer backups are theoretically eliminated because the building floor drains are connected to the sanitary sewer, which should not be surcharged.

Unfortunately, this idealized performance of separated sewer systems has not been realized. One problem encountered by sanitary sewer systems is that stormwater often finds its way into the system from illegal connections (extraneous flows) and from cracks in the sewer pipe, leaks in maintenance hole covers, and so on [infiltration/inflow (I/I)]. Extraneous flows and I/I may cause surcharging of the sanitary sewers, leading to sanitary sewer backups and sanitary sewer overflows. Another problem encountered in storm sewer systems is that urban stormwater runoff has been proven to be relatively contaminated by suspended materials, dissolved constituents, and coliform organisms. Among the constituents of stormwater runoff are heavy metals and toxic organic compounds. Water pollution from storm sewer discharges has been estimated to be of the same order of magnitude (more or less, depending on the water quality constituent) as the effluents from secondary treatment plants. Thus further treatment of sanitary sewage beyond the secondary stage appeared unwarranted if the water quality problem associated with storm sewer discharges were not addressed. Additionally, treatment of stormwater runoff encounters problems similar to those of treating CSOs: the need to treat enormous quantities of wastewater of varying quality over short periods of time on an intermittent basis due to the stochastic behavior of rainfall.

1.3 CURRENT DRAINAGE SYSTEM PROBLEMS

History has given cities a mixture of infrastructure for urban drainage and water pollution control. The various systems were conceived at different times, planned with different philosophies, designed according to different criteria, and built to operate differently. It is therefore not surprising that as a metasystem, this collection of infrastructure has many residual problems, problems that require not one solution but a set of solutions. It is characteristic of particularly larger North American cities that both combined and separated sewer systems service a city. Typically, combined systems are found in the older and more densely built urban core, while separated systems are found in the more recently developed suburban areas. Wastewater or sewage treatment plants (STPs) are found to treat either combined or separated sewage or various mixtures of both, typically to the secondary treatment level. Urban stormwater runoff has customarily been discharged untreated until relatively recently.

1.3.1 Combined Sewer System Problems

The two problems residual to the operation of combined sewer systems are the occurrence of combined sewer overflows and the occurrence of combined sewer surcharge conditions resulting in sewer backup and flooding. Although the sewer backup problem is not directly related to receiving water quality problems, it is indirectly related inasmuch as the remediation of sewer backup problems may compete with the remediation of water quality problems for funding. The issue of combined sewer overflows occupies the current discussion.

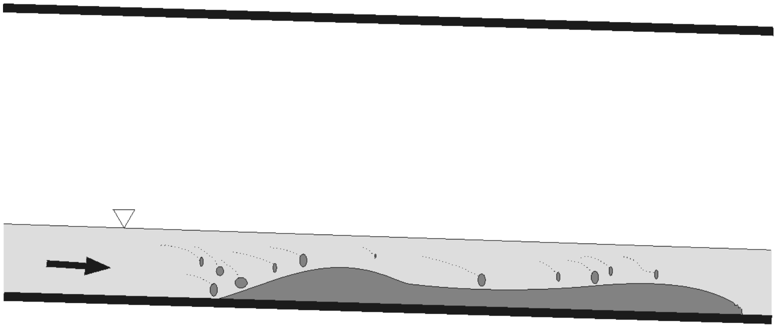
Combined sewer overflows occur when the volumetric flow rate at the trunk sewer outfall exceeds the interceptor diversion capacity during times of wet weather or when the interceptor diversion is not functioning properly. The interceptor diversion rate is typically in the range 2 to 3 $\times$ DWF; thus, even moderate rainfalls may cause CSOs. The magnitude of the overflow event volume is governed by the volume and duration of the runoff event. The magnitude of the overflow event pollutant mass is more obscure. Using Toronto as an example, the customary interceptor diversion rate was 2.5 × DWF which resulted in an average overflow frequency of 12 events per month (Hogarth, 1977). Since then, Toronto has embarked on aggressive overflow control measures to reduce this frequency. In Cincinnati, Roesner et al. (1990) report an average of 50 to 60 CSOs per year. Such statistics are typical for North American cities without modern control facilities. An individual overflow event may be small or large; therefore, the average annual volume of DWF overflowed to the receiver is often thought to be more meaningful. For conventional systems, approximately 3 to 6% of the DWF volume is lost to overflows (Camp, 1963).

On the surface, this appears to be a reasonably high level of DWF volume control; however, two factors complicate this conclusion. The first factor concerns solids deposition during dry weather. Because combined trunk sewers were designed to accommodate peak runoff rates from relatively large magnitude storms, they are usually very large diameter pipes. During times of dry weather, the flow rates are a small fraction of the pipe capacity, hence the flow depths are small. Accompanying the small flow depths are correspondingly small flow velocities. Flow velocities may be too small to keep solids constantly in suspension. In such cases, deposition of solids on the pipe invert can occur as illustrated in Fig. 1.3. The mass of deposition is related to the duration of sustained low flows. During times of wet weather, the combined sewer flow rates may increase rapidly. The resulting increase in flow velocity may then resuspend the previously deposited solids, causing a sharp increase in suspended solids concentration. This phenomenon is commonly termed the *first flush*. If the first flush is passed as an overflow, the mass of solids lost in the system may be substantially higher than the corresponding volume of DWF that is lost. Studies have indicated that although only 3 to 6% of the DWF volume may be lost in overflows, as much as 30% of the dry weather solids may be lost in overflows (Camp, 1963). Table 1.1 gives a comparison of combined sewer overflow constituent concentrations under first-flush conditions as well as under extended overflow conditions. It should be noted that first-flush effects are not always observed in monitoring programs and the first-flush phenomenon is not universally accepted. This issue is discussed further in Chapter 5.

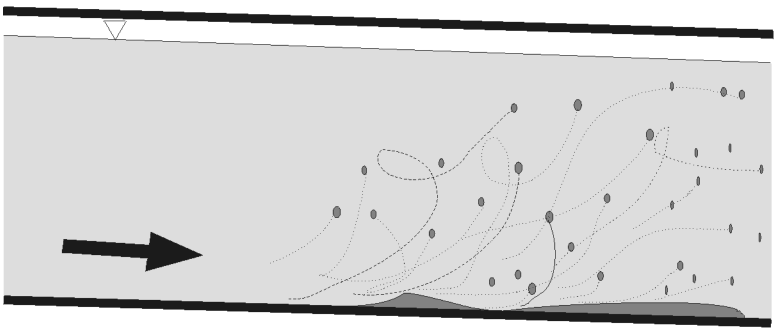
The second factor complicating conclusions regarding the level of water quality control offered by combined sewer systems is the quality of urban stormwater runoff itself. Numerous studies have indicated that surface runoff, particularly from densely occupied urban areas, may be highly polluted by many of the same water quality constituents found in domestic sewage. In addition to the DWF component lost in overflows, the pollutant mass of most of the surface runoff is also lost in overflows.

1.3.2 Sanitary Sewer System Problems

Although the reporting of serious sanitary sewer system operation problems is not as widespread, problems have been known to occur in these systems. These



(*a*)



(*b*)

Figure 1.3 Combined sewer. (*a*) during periods of low flow, velocities may be too small to keep solids in suspension. (*b*) during wet weather flow conditions, the flow velocities increase significantly and may resuspend the settled matter contributing more pollutants to combined sewer overflows.

Table 1.1 Comparison of quality characteristics from first flushes and extended overflows of a combined sewer[a]

Characteristic	First Flushes (mg/L)	Extended Overflows (mg/L)
Chemical oxygen demand	500–765	113–166
5-Day biochemical oxygen demand	170–182	26–53
Suspended solids	330–848	113–174
Volatile suspended solids	221–495	58–87
Total Nitrogen	17–24	3–6
Coliforms $1.5 \times 10^5/100\,\text{mL} - 310 \times 10^5/100\,\text{mL}$		

[a]Range at 95% confidence level.

Source: Lager and Smith in Corbitt (1990).

problems are associated largely with sewer capacity exceedence by extraneous flows and infiltration/inflow. Extraneous flows result from illegal stormwater connections to sanitary sewers, while I/I results from groundwater seeping into sanitary sewer pipes through cracks, fissures and holes in the pipe barrel and through dislocated or unsealed pipe joints and from surface water seeping through maintenance hole covers and other pipe appurtenances. Sanitary sewer overflow points are built into the system for such eventualities (see Fig. 1.4). These overflow points may be directed to stormwater drains or directly to receiving waters. The effects are similar to those encountered with combined sewer overflows.

The following quotation serves to illustrate the potential problems associated with the physical conditions of sewers: ‘‘With the advent of advanced photography, Etobicoke [Ontario] was one of the first [cities] to add a still camera for taking photographs of the interior of the sewers. What these pictures disclosed was astounding to us. Often the condition of the sewer, with deteriorating pipes, offset joints, massive roots and atrocious practices in connecting laterals to the main sewer, was enough to make any designer or operator of a sewerage system shudder’’ (Swann, 1978).

1.3.3 Storm Sewer System Problems

As a result of urbanization, stormwater runoff flow rates and volumes are significantly increased due to increased impervious land cover and the decreased availability of depression storage. These increased flows are conveyed to natural watercourses, which are not adapted to the larger runoff events and their increased frequency of occurrence. The resulting effects are the increased frequency of flooding occurring downstream of urban drainage systems as well as

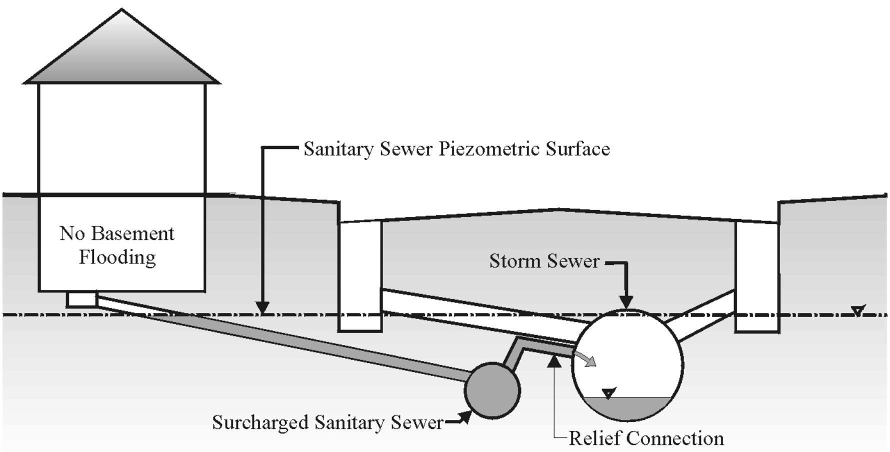


Figure 1.4 Sanitary sewer overflow through relief connection to storm sewer.

the increased potential for streambank erosion due to high flow velocities, which can degrade water quality in general and contribute to drastic changes in streambed morphology. Moreover, increased flow rates and changes in streambed morphology threaten the ecosystem of the receiving waters; this effect is amplified if the stormwater runoff is itself polluted. It is also noted that the large percentage of impervious surfaces (roads, parking lots, roofs, etc.) in an urban landscape contributes to another form of pollution: thermal enrichment of stormwater runoff. Many North American watercourses classified as cold water fisheries are especially sensitive to variations in stream temperature and thus are adversely affected by such thermal enrichment.

Storm sewer systems have been designed to convey surface stormwater runoff directly to watercourses. This practice was based on the premise that since stormwater runoff is generated by pure rainwater, it too is relatively pure. Numerous studies have indicated that this is not the case (see, e.g., Table 1.2). Rainfall scrubs pollutants from the atmosphere before it reaches the ground. Once on the surface, stormwater runoff erodes previous areas and washes impervious surfaces. The result is contaminated runoff, which may have the potential to seriously impair receiving water quality. That such observations are not of

Table 1.2 Urban stormwater pollutant constituent concentrations

Parameter	U.S. EPA	East York, Ontario	St. Catharines, Ontario	Kingston, Ontario	Ontario Water Quality Standards Ontario
Total suspended solids (mg/L)	125	281	250	72	—
5-Day biochemical oxygen demand (mg/L)	12	14	8.2	8.5	—
Chemical oxygen demand (mg/L)	80	138	—	—	—
Total phosphorus (mg/L)	0.41	0.48	0.33	—	0.03
Soluble phosphorus (mg/L)	0.15	0.06	0.084	0.118	—
Kjeldahl nitrogen (mg/L)	2.00	2.20	0.89	—	—
Nitrate and nitrite (mg/L)	0.90	0.46	0.65	0.25	—
Copper (mg/L)	0.040	0.050	0.021	0.009	0.005
Lead (mg/L)	0.165	0.570	0.084	0.013	0.025
Zinc (mg/L)	0.210	0.330	0.1	0.064	0.030
Fecal coliforms (count/100 mL)	21,000	11,000	68,000	21,000	100

Source: MOE/MNR (1991).

recent origin is testified by the following verse of Jonathan Swift describing a London shower of October 1710:

Now from all parts the swelling kennels flow,
and bear their trophies with them as they go:
Filth of all hues and odour
seem to tell what street they sail'd from,
by their sight and smell.

Early water pollution control efforts focused on the control of *point sources*, such as industrial waste discharges and wastewater treatment plant discharges. To a large extent, current water pollution problems have been attributed to non-point-source pollution resulting from stormwater drainage practices. Table 1.3 presents a comparison of pollutant sources and their relative contributions of several constituents. It is clear that measures to control the adverse impact of stormwater discharges deserve attention.

An additional problem of storm sewer systems is the illegal connection of untreated sanitary sewage or industrial waste flows which are undetected. Such illegal connections, although not known to be widespread, can pose serious local water quality problems, as illustrated by the following statement: ''Etobicoke has had several cases where storm water from industrial areas has carried chemicals which completely corroded away the concrete sewer pipes. In one case the invert of the pipe was completely corroded away from the liquid wastes and the obvert completely corroded away by the gaseous fumes...'' (Swann, 1978).

Table 1.3 Point- and nonpoint-source contributions of pollutants (%)

Pollutant	Point-Source Contribution	Nonpoint-Source Contribution
Chemical oxygen demand	30	70
Phosphorus	34	66
Kjeldahl nitrogen	10	90
Oil	30	70
Fecal coliforms	10	90
Lead	43	57
Copper	59	41
Cadmium	84	16
Chromium	50	50
Zinc	30	70
Arsenic	95	5
Iron	5	95
Mercury	98	2

Source: U.S. EPA (1983).

1.4 CHARACTERIZATION OF URBAN STORMWATER RUNOFF QUALITY

The control of urban runoff can be classified in two categories: runoff quantity control and runoff quality control. Quantity control techniques are well established and are based on the physical laws of conservation and momentum. Such measures seek to attenuate peak runoff flow rates and to reduce hydrograph volumes to mitigate flooding and the potential for erosion downstream. A much more difficult task is the water quality control of urban runoff. This problem is confounded by the intermittent nature of rainfall, the variability of rainfall characteristics, such as volume and intensity, and the variability of constituent concentrations.

To address water quality concerns adequately as they relate to stormwater discharges and combined sewer overflows, it is important to understand the types of pollutants that are present, or are expected to exist, as well as their potential impacts on receiving water bodies. It is equally important that the origins of the various pollutants be identified such that source controls may be applied. In this section are describe briefly common pollutants found in stormwater runoff. This list is by no means exhaustive and the concentrations of the various pollutants will vary from site to site depending on local land-use practices, vehicular traffic, population density, and other factors. A more detailed treatment of this topic is presented in Chapter 5.

1.4.1 Suspended Solids

The most prevalent form of stormwater pollution is the presence of suspended matter that is either eroded by stormwater or washed off paved surfaces by stormwater. Suspended solids increase the turbidity of the receiving water, thereby reducing the penetration of light, resulting in decreased activity and growth of photosynthetic organisms. The increased turbidity also detracts from the aesthetics of natural waters. In addition, the clogging of fish gills has been attributed to the presence of suspended solids. Combined sewer overflows typically contain high suspended solids concentrations. The solids that settle in the receiving water pose long-term threats resulting from their oxygen demand and gradual accumulation of toxic substances (Moffa, 1990). Sedimentation and other forms of physical separation are often an effective means of removing suspended solids from stormwater.

1.4.2 Oxygen Demanding Matter and Bacteria

Sufficient levels of dissolved oxygen (DO) in the water column are necessary to maintain aquatic life, growth, and reproductive activity as well as to maintain aerobic conditions. The introduction of stormwater containing oxygen-demanding organic matter can impair the receiving water quality by reducing the DO levels such that it is unable to sustain certain forms of aquatic life and can further cause the water to become foul. Bacteria enter the stormwater drainage system typically from the washoff of animal feces and organic matter from the catchment surface. Occasionally, bacteria may enter the drainage system through residential sanitary lateral connections and industrial or commercial drains, although such practices are typically illegal. Organic matter, usually in the form of vegetation and detritus, is carried through the conveyance system by the stormwater. Pathogenic bacteria and viruses in stormwater discharges and CSOs pose human health threats and result in numerous beach closures annually; thus the bacterial control of stormwater discharges and CSOs to body contact recreation areas is of particular importance. The removal of pathogenic bacteria is achieved primarily through the process of biological decay and physical–chemical disinfection where practiced.

1.4.3 Nutrients

Nitrogen and phosphorus are plant nutrients (biostimulants) that promote the growth of plants and protista, such as algae. Such nutrients contribute to the eutrophication of water bodies. Nutrients are typically derived from agricultural runoff as well as municipal wastewaters (of more concern for combined sewer overflows). Nutrients can be removed from stormwater prior to discharge through biological uptake such as by plantings in stormwater quality control ponds. In combined sewer systems, the sewage that is conveyed by the interceptor sewer to the centralized treatment facility may receive some nutrient removal; however, combined sewer overflows are typically left untreated.

1.4.4 Heavy Metals and Other Toxic Constituents

Studies in the United States and Canada indicate that heavy metals were the most prevalent toxic contaminant found in urban runoff (US EPA, 1983; Marsalek et al., 1997). In urban runoff, commonly found heavy metals are lead, zinc, and copper. Other toxic pollutants found in stormwater include phthalate esters (plasticizer compounds), phenols and creosols (wood preservatives), pesticides and herbicides; oils and greases (Wanielista and Yousef, 1993), and polycyclic aromatic hydrocarbons (PAHs; Marsalek et al., 1997) among others.

1.5 CASE STUDY: SCARBOROUGH GOLF AND COUNTRY CLUB

This section illustrates a problem associated with stormwater drainage practices and has been abstracted from court reports (D.L.R., 1986) and a paper reporting the modeling of the subject lands (James, 1995). The Scarborough (Ontario) Golf and Country Club (SGCC) has been in operation since 1912. Running through the subject lands is Highland Creek, which drains 4300 ha of land upstream of the golf course. Until 1946, the surrounding area was primarily agricultural, and occasional flooding occurred on the course, resulting in minimal damage. After 1946, rapid urbanization occurred and the stormwater drainage originating upstream of the golf course was conveyed in storm sewers and discharged into the creek. The upstream development and resulting increase in intensity and volume of flow through the creek caused it to become up to twice as wide and twice as deep through erosion and flooded large areas during heavy rainfalls. In fact, the quantity of runoff had increased by 2.5 times and the stream velocity by 23% since 1954 (Belcher in James, 1995).

The continuous simulation modeling study undertaken by William James (1995) produced some interesting results comparing the frequency and durations of flows for predevelopment (assumed to be represented by the 1947 land use) and the postdevelopment (1976) conditions. Figs. 1.5, 1.6 illustrate the results of that study. As can be seen in the figures, the postdevelopment flow conditions are dramatically more severe in magnitude, and hence in erosion potential, than the predevelopment conditions. Using $5\,m^3/s$ as the critical erosive flow, the total duration of erosive flows is increased under urbanized conditions by 125 hours per year. If bankful flow occurs approximately once every 1.5 years (estimated by Leopold as noted by James, 1995), the bankful flow rate in this case was determined to be increased by a factor of about 11 by postdevelopment conditions. This bankful flow typically determines the degree of erosion of the channel; that is, the channel will widen and deepen itself with time to accommodate this flow.

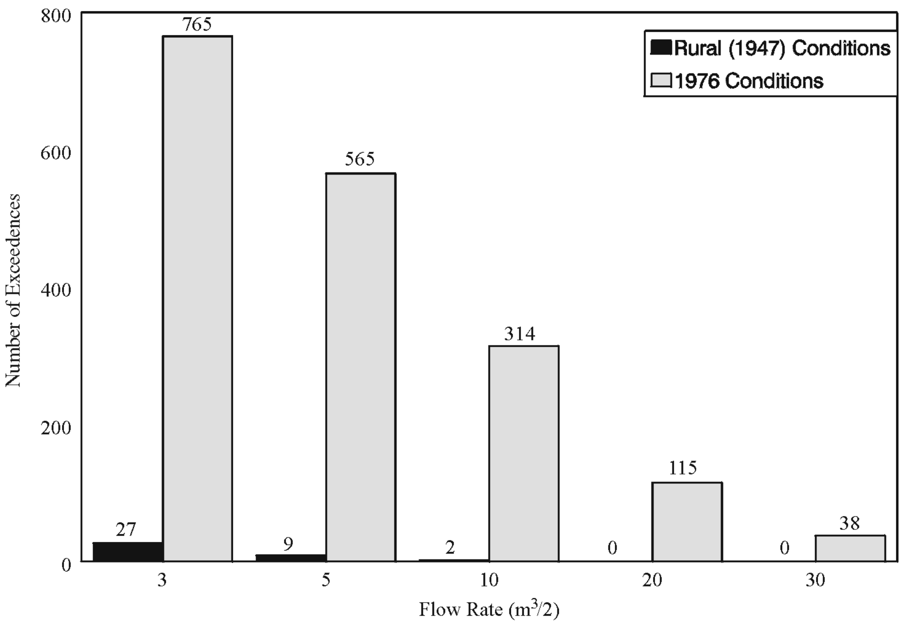


Figure 1.5 Number of flow exceedences over study period of 43 years [data from James (1995)].

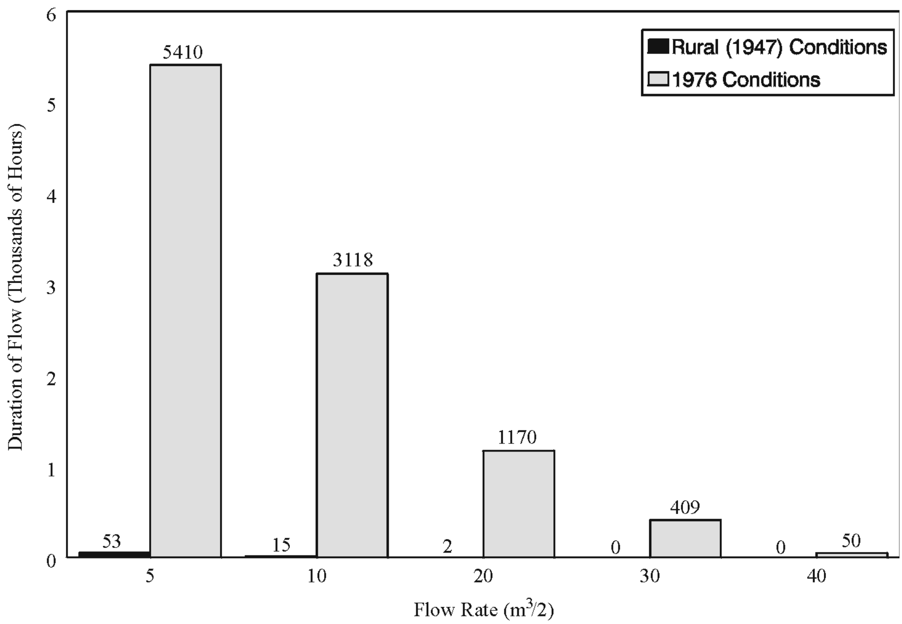


Figure 1.6 Duration of flows over study period of 43 years [data from James (1995)].

The Supreme Court of Canada found the City of Scarborough et al. liable for damages to the Scarborough Golf and Country Club as a result of upstream drainage practices. Furthermore, the Court preferred the use of continuous hydrologic analysis over the commonly practiced design event or design storm approach. As a result of this ruling, engineers must be aware of their potentially increased liability when designing urban drainage systems using conventional modeling practices and implementing conventional structural stormwater management facilities such as stormwater detention ponds.

Current engineering practice often seeks to control postdevelopment flow rates for design storms ranging in return frequency from 2 to 100-year rainfall events. Although this practice attempts to mitigate erosion impacts by controlling flow rates to predevelopment levels, it neglects the duration over which these flows occur, which, in turn, plays a major role in determining the erosion potential of a stormwater management system. It would be useful to have a methodology in which a long-term erosion index may be developed such that instead of (or in addition to) controlling postdevelopment flow rates not to exceed predevelopment flow rates, the postdevelopment erosion potential can be controlled not to exceed the predevelopment potential.

1.6 CONCLUSIONS

Urban runoff problems are of two distinct but related types: quantity and quality. The control of runoff quantities, in the form of peak flow rates and runoff volumes, is required to reduce the potential for streambank erosion and downstream flooding. These problems are typically exclusive to stormwater systems, and control techniques are reasonably well established. The protection of receiving water quality is of greater recent concern in the engineering community and is not easily addressed, due to the complexity and variability of stormwater and CSO constituents, their interactions, and their removal mechanisms. In this book we focus on the control of urban runoff in combined sewerage systems and stormwater drainage systems. There exists a need for the comprehensive planning, design, and management of such systems, which can only be accomplished in an efficient manner by the implementation of models for urban runoff and its control. Moreover, to address water quality concerns adequately, long-term analyses of urban drainage systems are required.

In following chapter we introduce strategies to reduce the volume of stormwater and combined sewer overflows and to reduce both the peak flows and pollution loads emanating from stormwater drainage systems. In Chapter 3 we present an overview of stormwater management modeling and the models that are the fundamental components of decision support systems for engineers and planners. The remainder of the book is devoted to the development and implementation of analytical probabilistic models for urban runoff control.

PROBLEMS

1.1. From an environmental engineer's viewpoint, discuss the causes of typhoid and cholera epidemics such as those experienced in London, Paris, Chicago, and Toronto in the nineteenth and early twentieth centuries.

1.2. Once the need for the treatment of sewage from combined sewer systems was recognized, explain why interceptor sewers were designed to carry only a relatively small multiple of dry weather flow.

1.3. A residential community in Toronto with a gross area of 500 ha has a housing density of 6 residences per hectare and an average occupancy of 5.4 per house. The average (horizontally projected) roof area of houses is 90 m^2, the average dry weather flow is 350 L/capita per day and the peak factor is 2.5. (a) Compare the peak dry weather flow rate from this community with the roof drainage flow rate from a rainstorm with an intensity of 50 mm/hr. (b) Size a sewer (with a circular cross-section on a grade of 0.5%) to accommodate (i) the peak dry weather flow alone, (ii) the roof drainage alone, and (iii) the combined flow.

Manning's equation for the minimum required diameter of a circular conduit flowing full is:

$$D = 4^{5/8}\left(\frac{nQ}{\pi\sqrt{S}}\right)^{3/8}$$

where D is the diameter (m), Q the volumetric flow rate (m^3/s), S the slope expressed as a fraction and n is the roughness coefficient ($n = 0.013$).

1.4. Wastewater (sanitary sewage) design flow rates are typically estimated with reasonable accuracy and are generally not subject to large fluctuations as storm flows are. Therefore, sanitary sewers are designed for these flows and, theoretically, should not surcharge. Often, however, sanitary sewers become surcharged and overflows occur. Briefly explain the causes of such occurrences and describe how these problems can be controlled.

1.5. What is the most influential practical constraint that prevents engineers from providing complete treatment of stormwater runoff and CSOs?

1.6. Explain the first-flush effect in combined sewer flows. Illustrate using the data provided in Problem 1.3. [*Hint*: Use a *hydraulics element graph* for partially filled circular sewers to compute flow velocities; [see Fig. 7.2 in (Viessman and Hammer, (1993).]

1.7. Discuss briefly the problems associated with stormwater runoff in terms of both its quantity and its quality.

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