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Module 0: Introduction

Historical Review of Wet Weather Flow Management and Designs for the Future

Throughout history, many strategies have been implemented to control wet weather flows for reasons such as flood control, water quality improvement, aesthetic improvement, waste removal, and others. An urbanizing region must choose various management, control, and treatment alternatives specific to its circumstances in order to protect the receiving waters (both surface water and groundwater). A guidance manual for wet weather flow systems in newly urbanized areas is being developed as part of a cooperative agreement from the Urban Watershed Management Branch of the U.S. Environmental Protection Agency (Pitt, *et al.* 1997 and Heaney, *et al.* 1997. The following historical review is a summary from Pitt, *et al.* (1997) and was mostly prepared by Steven J. Burian, while he was a Ph.D. student at the University of Alabama (he is now a faculty member at the University of Utah), and Robert Pitt.

Introduction

Management of wet weather flows is an age-old problem. Ancient civilizations grappled with flood prevention and waste disposal in their cities of stone and brick long before engineering was a recognized profession. They devised successful strategies to mitigate flooding and remove sanitary waste, and constructed drainage appurtenances such as open channels and pipes that in some cases remain intact today. From the ancient Indus civilization to the Roman Empire, drainage systems were effective at removing stormwater and proved to be sources of civic pride. The methods used in the past to lessen the impacts of stormwater can provide insight into new methods applicable today and in the future. It is evident that lessons concerning wet weather flow (WWF) management can be learned from the past.

Wet Weather Flow Management: Ancient Times

Several ancient civilizations can be credited with implementing successful surface water drainage systems. In addition, some civilizations incorporated the removal of sanitary wastes into the surface runoff system to provide a comprehensive system of sewerage. The Indus civilization of circa 3000 B.C. presents one example of a sewerage system well ahead of its time. Evidence exists that the dwellers of the city of Mohenjo-Daro (now part of West Pakistan) used sanitary sewer systems and had drains to remove stormwater from the streets (Webster 1962). The ruins of this ancient system show the great care used to construct the sewers, which would make the engineer of today envious. One feature of note was the use of a cunette in the storm drain to accommodate sanitary sewage flows (Webster 1962). The masonry work and clever design of the storm drain system show that in some instances, much more care was taken with the sewers than with some of the buildings.

Other civilizations in the same region also exhibited WWF management planning. For example, the Mesopotamian Empires of Assyria and Babylonia marked great advances in civilization. The ruins of cities, Ur for example (Jones 1967), in these empires include their sanitary and storm drainage systems, and exemplify an advanced technical knowledge. As early as 2500 B.C., Mesopotamian engineers planned and built effective drainage and sanitary works, including vaulted sewers and drains for household waste, gutters and drains for surface runoff, and other appurtenances (Maner 1966). The typical materials of construction were baked brick and asphalt.

The Minoan Empire flourished from about 3000-1000 B.C. The ruins of the city of Cnossus on the Island of Crete show the highest development of the Minoans. These ruins reveal elaborate systems of well-built stone and terra-cotta drains, which carried sanitary sewage, roof runoff, and general surface drainage (Gray 1940). The drains emptied into a main sewer that disposed of the sewage a considerable distance from the origin of the wastes. The frequent and torrential rains in Crete, the island location of the Minoan civilization, resulted in excellent flushing of the system (Kirby, *et al.* 1990). The Minoans also devised ways to collect rainfall and keep it pure for later use.

The Greek civilization, especially during the era of Alexander the Great, marked a period in time that scientific and engineering advances were made (Kirby, *et al.* 1990). Many engineers, scientists, builders, and architects worked to improve water supplies, buildings, and drainage systems among other technologies. Their contribution to the development of WWF management is comparable to the above civilizations, but occurred at a later date.

Of all the societies of western Asia and Europe, from antiquity until the nineteenth century, only the Romans set out to build a carefully planned road system with properly drained surfaces (Hill 1984). Most of the streets were paved and well drained, with raised sidewalks and stepping-stones at street crossings to protect pedestrians against overflow from the aqueducts and stormwater flowing on the street surfaces. When the Romans came to power they rebuilt the Etruscan sewers and paved the streets and took over Greek architectural forms. Virtually all that the early Romans knew about engineering came to them out of the civilizations of the eastern Mediterranean (Kirby, *et al.* 1990). Essentially, the engineers of Rome were excellent developers of technology rather than originators. Regardless of the originator of the strategy, the intentions of the Roman road drainage systems were to mitigate the impact of stormwater runoff and aqueduct overflow on areas adjacent to roadways and on the roadways themselves.

Specific drainage structures utilized by the Romans included occasional curbs and gutters to direct surface runoff to open drainage channels alongside roadways (Hill 1984). Although some of the channels were lined, the most often-used drainage channel was simply the open ditch. To improve drainage, the roads would be graded in such a fashion to direct the surface runoff from the streets toward the drainage channels. The roads were not the only engineering structures that were designed for drainage control. Typically, rainwater was disposed of depending on where it fell. If it fell on a house, for instance, the roof was constructed such that it funneled the rainwater into a cistern somewhere in the interior for later use (Hodge 1992). Therefore, a great deal of the rain falling on a town was never drained away.

Although the drainage of excess water from the aqueducts and rainwater was the primary function of the drainage system, it was not the only function. More and more, sanitary wastes and garbage were being discharged to the surface water drainage system. This discharge of wastes into the open sewers prompted the development of underground sewers. Initially, open trenches or channels ran down city streets to convey the stormwater and excess public water. It was soon discovered that disposal of wastes in these trenches removed the waste from the area. However, the trenches relied on heavy rainfalls to adequately flush them of waste and debris, since overflow discharges from aqueducts were not sufficient to effectively convey the wastes. The wastes would therefore accumulate and cause unsanitary, not to mention repugnant, conditions. The solution to this was to cover the trenches. The covered channels eventually evolved into planned sewers.

The Romans planned and constructed the *cloacae*, or sewers, to drain their uplands to the nearby network of low-lying streams (Gest 1963). These sewers were originally open streams that drained most of the land prior to urbanization. Their philosophy was to use the existing natural drainage channels to remove wet weather flows. It was decided that the proper way to use the channels was to build the city over them and provide drains from the surface to the underground streams. As time progressed, the Romans became more elaborate with their construction of the sewers, which is evidenced by the increased care and detail given to their construction in later times (Gest 1963).

The sewers of Rome became a source of civic pride. The residents viewed the system as symbolic of their advanced civilization, and later some French and English engineers tried to instill similar pride amongst citizens during their push to improve WWF management systems in the 1800s (Hodge 1992). Although the Roman sewers were successful in their function and were well constructed, they didn't epitomize the perfect sewer design strategy. In fact, the design was simply trial-and-error based on drainage experience. Lewis Mumford (1961) observed that the sewer systems of ancient civilizations, including the Romans, were an 'uneconomic combination of refined technical devices and primitive social planning'. Therefore, although successful systems had been constructed, the pinnacle of WWF management had not yet been attained.

Wet Weather Flow Management: Middle Ages to the 1800s

From the time of the Roman Empire to the 1800s, WWF management strategies experienced very few noteworthy advancements, and even regressed considerably in terms of sanitation. However, as disease epidemics occurred in major metropolitan areas of Europe towards the start of the middle ages, some believed proper sanitation was partly dependent on adequate sewerage. As in ancient times, stormwater still provided an urban area with the needed flushing mechanism to remove wastes that accumulated in city streets and in the sewer system.

A consequence of developing wet weather and sanitary systems in response to maladies was an incoherent and varied overall system. Paris and London provide examples of European cities that developed piecemeal drainage systems in response to crisis situations and funding availability. The development from inadequate to adequate WWF management systems occurred mostly during a time period of 500 years, from approximately 1300 (when open ditches were again the main method used to convey drainage waters) to the 1800s (the advent of modern engineering drainage design).

The first sewers implemented in Europe following the fall of the Roman Empire were simply open ditches. Examples of this type of sewerage system in Europe are evident in Paris and London (Kirby and Laurson 1932; Reid 1991) during the 1300s and 1400s, as well as in a few other European cities. The open ditches used for drainage of stormwater were usually constructed in existing drainage pathways (Kirby and Laurson 1932) or down the centers of streets (Reid 1991). Besides being conveyances for stormwater, the open drainage channels became receptacles for trash, kitchen wastes, and sanitary wastes, the accumulation of which caused hazardous and nuisance conditions. To remedy this situation, Europeans simply covered the drainage channels, or sewers, which were emitting a terrible odor and producing unsightly conditions. Interestingly, this solution is similar to that used 1500 years earlier by the Romans during the construction of the *cloacae*. It seems that a strategy commonly utilized in the past to mitigate a sanitation problem was to remove it from sight; which unfortunately is still the case in many situations today.

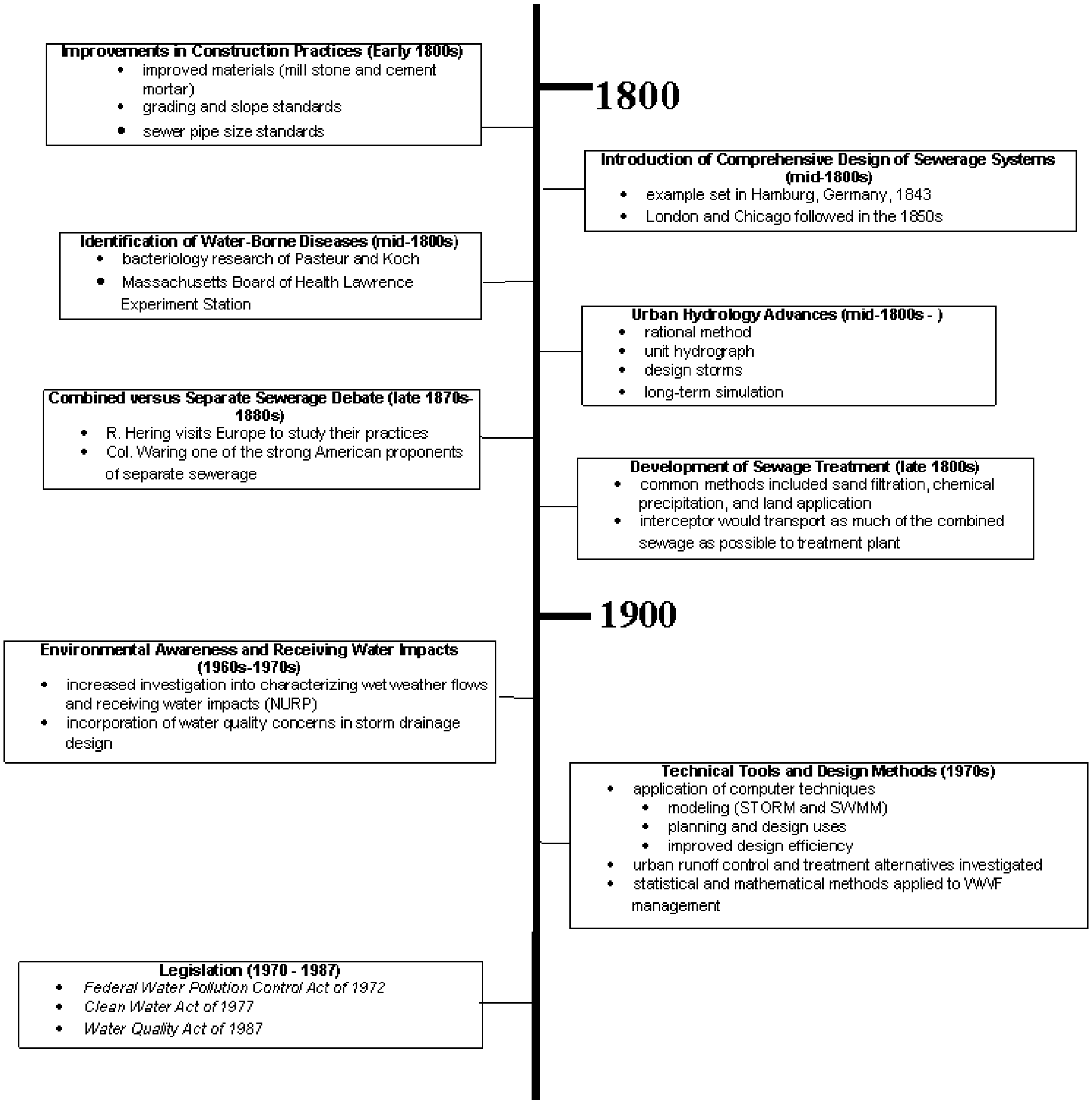
In Paris, the first covered sewer dates back to 1370 when Hugues Aubriot constructed the Fosse de St. Opportune (Reid 1991). This sewer, which became known as the beltway sewer (Reid 1991), discharged into the Seine River and acted as a collector for the sewers on the right bank of the Seine. The covered sewer concept was not instituted immediately throughout Europe. Other areas of Paris, for instance, continued to rely on the open drainage channels well into the 1700s, and London didn't construct a planned covered sewer until the 1600s (Kirby and Laurson 1932).

The few covered sewers received insufficient maintenance throughout the middle ages. During periods of dry weather, the sanitary wastewater remained stagnant and allowed solids to settle in the sewer system, producing a terrible odor and repeated blockages. Maintenance problems notwithstanding, the municipal authorities continued to cover sewers in the major European cities. This simply compounded the problem. The solution in Paris during the 1700s was to build magnificent, large underground sewers for the drainage of stormwater. These sewers provided enough space for a work crew to clean the sewers comfortably, but they encouraged the accumulation of material due to the low flow rates.

Construction of sewer systems in the 1700s lacked proper engineering design and was conducted in piecemeal fashion in different parts of a city. In addition to the poor design and construction practices at the end of the middle ages, maintenance and operation of the systems were virtually neglected in most situations. In essence, the sewer systems of urban areas in Europe during the 1600s and 1700s were grossly under-planned, poorly constructed, and inadequately maintained.

Wet Weather Flow Management: 1800s

The 1700s ended with poorly planned, designed, constructed, and maintained sewer systems existing in many European cities. However, the outlook was not entirely bleak, since problems with the sewer systems were obvious and the enlightened, post-renaissance society began to realize that adequate sewerage was necessary to promote proper sanitation. The early part of the 1800s marked the beginning of a series of improvements, decisions, and technical advances related to WWF management that helped to direct the development of WWF management to the present day. The following discussion reviews many of these improvements, decisions, and technical advancements and Figure 1 displays them on a time line depicting the development of modern WWF management.



Improvements in Construction Practices (Early 1800s)
- improved materials (mill stone and cement mortar)
- grading and slope standards
- sewer pipe size standards

1800

Introduction of Comprehensive Design of Sewerage Systems (mid-1800s)
- example set in Hamburg, Germany, 1843
- London and Chicago followed in the 1850s

Identification of Water-Borne Diseases (mid-1800s)
- bacteriology research of Pasteur and Koch
- Massachusetts Board of Health Lawrence Experiment Station

Urban Hydrology Advances (mid-1800s -)
- rational method
- unit hydrograph
- design storms
- long-term simulation

Combined versus Separate Sewerage Debate (late 1870s-1880s)
- R. Hering visits Europe to study their practices
- Col. Waring one of the strong American proponents of separate sewerage

Development of Sewage Treatment (late 1800s)
- common methods included sand filtration, chemical precipitation, and land application
- interceptor would transport as much of the combined sewage as possible to treatment plant

1900

Environmental Awareness and Receiving Water Impacts (1960s-1970s)
- increased investigation into characterizing wet weather flows and receiving water impacts (NURP)
- incorporation of water quality concerns in storm drainage design

Technical Tools and Design Methods (1970s)
- application of computer techniques
  - modeling (STORM and SWMM)
  - planning and design uses
  - improved design efficiency
- urban runoff control and treatment alternatives investigated
- statistical and mathematical methods applied to WWF management

Legislation (1970 - 1987)
- *Federal Water Pollution Control Act of 1972*
- *Clean Water Act of 1977*
- *Water Quality Act of 1987*

Figure 1 The Development of Modern WWF Management since the Early 1800s

Improvements in Design and Construction Practices

Innovations in construction materials improved sewerage systems in the early 1800s. As an example, until the 1820s in Paris, sewers had been constructed of cut stone or brick with rectangular or roughly rounded bases, which led to solids deposition problems (Reid 1991). Engineers substituted mill stone and cement mortar for the hewn stone which allowed for the construction of curved and smooth sewer floors. This lessened the flushing effort required for sewer cleansing. The quality of brick and clay pipe also improved during this time and became the materials of choice. The next major improvement in sewer materials was the use of concrete, which did not occur until the end of the 1800s (Metcalf and Eddy 1928).

Another problem with sewers was the grade at which they were constructed. Often, caution was not exercised either during design nor construction, and the sewers did not have a sufficient slope to transport wastewater during dry weather periods. Addressing this situation, sewers began to be constructed on slopes sufficient to prevent ponding in the system. But, advocates of flat slopes with ample provision for flushing still existed.

In addition to improvements in construction, several advancements were made in the design of sewer pipes. The shapes of sewers had been constrained by construction and material capabilities, but with the introduction of new pipe materials in the early 1800s, they could be constructed in curved instead of simply rectangular shapes. These shapes included egg-shaped, oval, and v-notched patterns for combined sewer systems and provided improved hydraulic transport efficiencies over the rectangular sewer shape. Studies in England indicated that the lower part of a v-notch channel could carry sanitary waste well while the upper portion could provide sufficient capacity to transport storm water from the streets (Gayman 1997). Smooth pipe interiors resulting from the improved construction practices also contributed to the increased efficiency of the sewerage systems.

Minimum velocity and slope standards developed in the mid-1800s. For example, a 2 to 3 feet per second minimum velocity standard was established in London (Metcalf and Eddy 1928). The minimum velocity was not arbitrary, but based instead on actual tests of deposition of sand and other materials from running water. These tests indicated that a velocity of 2 feet per second would entrain solids in a sanitary sewer, but that a velocity of 3 feet per second was needed to prevent deposition of sand, gravel, and debris washed into the system during wet weather. Other standards and suggestions included restrictions on slope, materials, pipe size, and others.

Beginnings of Comprehensive Sewerage Design

The improvement in construction practices and pipe designs did not eliminate the problems with sewer systems in Europe. System design strategy became the focus of the next wave of innovations in sewerage practice. Hamburg, in 1843, is considered to have implemented the first comprehensively planned sewerage system (Metcalf and Eddy 1928). The circumstances were advantageous for this as a large part of the city had been destroyed by a conflagration in 1842. William Lindley, an Englishman residing in Hamburg, was commissioned to plan and design the system. The system was not planned for the sanitary benefits as is often assumed, but was rather the result of shrewd business decisions in taking advantage of exceptional local conditions to plan streets and sewers to meet the recognized needs of the community (Metcalf and Eddy 1928). Therefore, then, as today, economics ultimately influenced civil infrastructure design.

London followed suit with a detailed study by many engineers of note, resulting in the decision to devise a comprehensive plan of sewerage. Joseph William Bazalgette was commissioned in 1852 to plan and design the system (Kirby and Laurson 1932). Actual work on the Main Drainage of London began in 1859, and was practically completed in 1865. Features of this ambitious enterprise were the early experiments with rainfall calculations and a version of portland cement. Meanwhile, the sewers of Paris were still being constructed without any coordinated plan until 1823. At this time, construction practices began to improve, which allowed engineers such as Duleau to plan an adequate system of drainage for portions of the city. The interceptor sewer concept dates to this period in Paris and London (Kirby and Laurson 1932).

The 1800s saw rapid urbanization in the United States. In 1840 about 89% of all Americans lived on farms, but by 1860 over 20% of the population lived in urban areas and by 1880, the urban percentage had risen to 28% (Tarr and McMichael 1977). In response to this urbanization, the comprehensive design of WWF management systems began to be practiced in the U.S. Chicago had the first comprehensive design implemented by a major American city. The system was designed by E.S. Chesbrough in a report completed in 1858 (Metcalf and Eddy 1928). He and other contemporary engineers soon consulted on similar comprehensive plans for additional U.S. cities (J.W. Adams for Brooklyn, New York for example). Prior to these comprehensive designs, very little is noteworthy concerning the history of American sewerage. In many towns, early drains were built, maintained, and even owned by private individuals or groups of individuals who charged for their use by others. This was the situation in Boston, for example, where sewers were originally constructed in 1700, but the city did not acquire control of them until 1823 (Kirby and Laurson 1932).

The planning of early American sewerage was influenced by two general factors, the topography of the city and the place of disposal (Metcalf and Eddy 1928). The grade of the ground surface affected decisions concerning the mode of sewer transport (open channels or below ground conduits), the size of the sewers, and the arrangement of small and large sized sewers. With gravity being the desired vehicle for transportation, it can be understood why the topography would play such an important role. In most situations, the use of natural drainage patterns in conveying stormwater was preferred, especially when streets were planned according to the lay of the land. The second factor mainly concerned the direction and distance that the sewage would be conveyed. Specific considerations included the dilution capability of the receiving stream and determination of the proper disposal location.

The comprehensive designs implemented in the U.S. made use of empirical data obtained from European practice for capacity and probable quantities of rainwater to be carried by the sewers (Webster 1921). The use of this empirical data caused deficiencies in the drainage systems because of the climatologic and topographic differences between parts of the U.S. and Europe. It is noteworthy that among the branches of engineering, American sewerage is observed to have developed many of its features through experience, rather than experiment (Metcalf and Eddy 1928). In America, Julius W. Adams was probably the most influential engineer of his day. His treatise on 'Sewers and Drains for Populous Districts', published in the *Transactions of the American Society of Civil Engineers* in 1880, was widely used by engineers for sewerage design for at least 25 years (Metcalf and Eddy 1928).

Combined Versus Separate Systems of Sewerage

Although sanitary waste was a constant input to the sewer systems of Europe, designs did not anticipate this addition until 1843 in Hamburg. This does not imply that illegal connections were not present as this was often the case. The first types of wastewater legally allowed into the sewer system were dishwater and other liquid kitchen wastes. When the flushing toilet (water closet) came into general use in the early 1800s existing cesspools became overwhelmed. Eventually, this led to the permitted discharge of water carried sanitary wastes into the sewers previously restricted to surface runoff, creating combined sewage. London did not allow legal sanitary connections to its sewer system until 1847 (Kirby and Laurson 1932) and Paris did not allow sanitary connections until 1880 (Reid 1991).

The combined sewage scheme became widely implemented, in spite of the opponents who thought it sensible to keep the sanitary wastes and stormwater separate. Edwin Chadwick and John Phillips, both from England, were two of the earliest proponents of the separate system of sewage. Phillips proposed the separate system of sewerage for London in 1849, but eventually Bazalgette's combined system with interceptors was implemented (Metcalf and Eddy 1928). Although supporters for separate systems existed, combined systems were mostly constructed because they were usually cheaper to design and build.

Bourne (1866) made one of the first American arguments for separate sewerage. He advocated the separate system for reasons of sanitation. Benezette Williams designed one of the earliest comprehensive separate systems in the U.S. in 1880 for Pullman, Illinois. Another adamant supporter of separate sewer systems in the U.S. was Col. George E. Waring, Jr. (Waring 1879). He argued that the separate system was better because it could transport sanitary wastes faster, a characteristic he deemed important for proper sanitation. Waring designed several of the early separate systems, including one for the city of Memphis, Tennessee in 1880, at almost the same time as the system was implemented in Pullman (Odell 1881). Of the other cities that did implement separate sewer systems, most constructed only sanitary sewer lines, with no pipes for stormwater (gutters and ditches carried this water) (Tarr and McMichael 1977). Some of the systems performed adequately, but others failed miserably with repeated blockages and backups in the sanitary sewer lines. Part of the problem attributed to Waring's designs was his insistence that the size of the house connection to the lateral sewer be small (typically four inches) (Metcalf and Eddy 1928). This small size in comparison to other designs of six inches or more is what many believed to be the basic cause of failures in Waring's systems.

To learn more about separate and combined sewer systems, an American named Rudolph Hering visited Europe in 1881 at the behest of the U.S. National Board of Health. His findings from the trip became a report to the National Board of Health on the benefits and drawbacks of each type of system (Hering 1881). Hering's recommendations included using combined systems in extensive and closely built-up districts (generally large or rapidly growing cities), while using separate systems for areas where rainwater did not need to be removed underground. Despite Hering's report and the support of his conclusions by many, the debate continued between the advocates of the two types of sewerage.

Identification of Water-Borne Diseases

Several individuals through time have conjectured that sanitary and other types of wastes and unsanitary living conditions could be linked to diseases (Tarr and McMichael 1977). However, it was always difficult to express their thoughts in a scientific manner. During the early 1800s, evidence pointed to the link between sewage discharges, polluted receiving waters, and disease outbreaks. The key factor was the new knowledge which had come from the researches of L. Pasteur, R. Koch, T. Schlösing and A. Muntz, R. Warington, and others into the nature and activities of bacteria.

A publication by Dr. Jack Snow in 1849 discussed the communication of cholera by contaminated water and later he had a hand in identifying the source of the Broad Street cholera epidemic in London during 1854. But it was Pasteur in 1857 who established the formative theory that infectious disease is caused by germs or bacteria (Kirby, *et al.* 1990). By the 1880s the theory was firmly established by Koch and others. This research led to the attempt to filter drinking water during the late 1800s to remove water-borne diseases.

During the middle 1800s, many assumed that cities could safely dispose of their wastes into adjacent waterways. The process of dilution was the typical method of waste treatment and disposal. However, by 1890, bacteriologic research was challenging the effectiveness of dilution strategies. Studies made at the Massachusetts Board of Health's Lawrence Experiment Station identified the relationship between typhoid fever and sewage-polluted waterways (Tarr and McMichael 1977). This identification and others raised serious questions about the safety of discharging untreated combined sewage directly into receiving waters, especially those that were used as a drinking water source. These findings and others led to the next major issue in WWF management: early control and treatment of wastewater and combined sewage.

Treatment of Separate Sanitary and Combined Wastewater

Regardless of the type of sewerage (combined or separate), the primary method of disposal was still discharging to local receiving waters in the late 1800s. The control and treatment of sewer discharges was very limited during the 1800s. Typically, combined sewage, sanitary wastewater, and stormwater were simply discharged into a stream or river of adequate capacity to dilute the waste. The sewerage systems would be designed such that the maximum amount the receiving water system could dilute would be discharged. The placements of outfalls would occasionally be planned or adjusted to accommodate this requirement.

In the late 1800s, sewage was treated primarily by three methods: irrigation of farmlands (sewage farming), intermittent filtration (typically sand filters), or chemical precipitation (Whipple, *et al.* 1906; Tarr and McMichael 1977). These systems of treatment were more conducive to the smaller and easier controlled sanitary sewage flows from a separate system. Centralized municipal wastewater treatment facilities were just beginning to be constructed in the late 1800s. For combined sewer systems, the intercepting sewer would be used to transport as much of the flow to the dry weather treatment facility. The wet weather flows that could not be transported via the interceptor were discharged directly into the adjacent receiving water, creating a combined sewer overflow (CSO).

Whipple, *et al.* (1906) discussed the combined sewage treatment operations being utilized in the U.S. at the beginning of the 1900s. The usual method instituted for combined sewer systems entailed sending as much of the storm flow/sanitary sewage mixture to a dry weather wastewater treatment plant by way of an intercepting sewer. The plant capacity and interceptor size were the limiting design factors for this action. In most cases, the interceptor sewer conveyed a certain amount of the waste stream to the plant, with the remainder being overflowed directly to the receiving water system. Treatment plants and collection systems were typically designed to treat twice the flow rate, or more, of the typical dry weather flow (Whipple, *et al.* 1906). During wet weather, flows were observed to increase in sewer systems by a factor of one hundred over dry weather flows on occasion. Occurrences such as this could not be economically considered in conveyance or treatment system design, and thus, the excess sewage flows greater than the design capacity of the conveyance system would result in frequent overflows.

Although research had displayed the connection between sewage-polluted waters and disease, sewage treatment was not widely practiced. It was debated whether it was more economical to treat the sewage prior to discharge or treat the water source before distributing as potable water. Basically, the debate argued that the sewage could be assimilated or treated in the receiving water and would be much less polluted by the time it was withdrawn for drinking water supplies. This argument had validity, except it neglected the fact that the sewage discharges were harming other uses for the receiving water in addition to drinking water supply.

Urban Hydrology

In the mid-1800s, the estimation of surface runoff was based on empirical results. For example, much of the European engineering community used Roe's Table to size sewer pipes draining a specified size catchment (Metcalf and Eddy 1928). The table was supposedly empirically derived from Roe's observations of London sewers in the Holborn and Finsbury divisions over a span of 20 years. It gave the catchment areas which could be drained by sewers of various sizes and on various slopes, as indicated by his experience. Numerous equations and tables similar to Roe's existed in both basis and function.

In the second half of the 1800s the hydrologic and hydraulic design methods used to size sewers were enhanced. Most notably, the present day rational method was developed in this time period by Mulvaney (1851) and Kuichling (1889). The rational method, in general, was based on the assumption that a realistic flow of the chosen frequency can be obtained if the rain intensity of duration similar to the travel time of water in the sewer system was applied to the drainage catchment. The flow was subsequently used to design the size of the sewer pipes.

Prior to the rational method, runoff determinations took the form of empirical formulae. Most of these formulae calculated the runoff reaching a sewer system based on drainage basin size, sewer slope, and other parameters, while others calculated the sizes of the pipes directly. Some of the equations used can be attributed to Adams, McMath, Hering, Parmley, Gregory, Burkli-Zeigler, and Hawksley (McMath 1887; Buerger 1915). These equations were all derived based on site-specific data; consequently, they yielded poor results when applied to other drainage basins (Buerger 1915).

Intensive efforts in rainfall data collection and analysis occurred in the U.S. during the second half of the nineteenth century (Berwick, *et al.* 1980). The primary motivation was to study the relationship between the intensity of the rain and its duration for the needs of storm drain design. Talbot, in 1899, performed some of the initial work, using U.S. Weather Bureau records at 499 stations to plot storm intensities versus durations on a cross-section paper. Two envelope curves were drawn, one depicting the very rare rainfalls, and the other the ordinary rainfalls. These curves became the forerunner of the present day intensity-duration-frequency curves for drainage design. Since Talbot constructed his curves, many cities, public agencies, and engineering firms have developed similar equations for specific locations (Berwick, *et al.* 1980), while some still use Talbot's results directly.

Wet Weather Flow Management: 1900s

Urban Hydrology Continued

As stated in the previous section, the design of sewer systems in the nineteenth century usually involved the use of an empirical equation to determine the sizes of the pipes required. Some of the more popular equations used to design sewer systems in the U.S. during the early 1900s included the Hawksley (or Bazalgette), Adams, McMath, and Burkli-Ziegler equations (Buerger 1915). The Hawksley equation is distinct from the other three in that it calculates the size of the sewer directly. The other three formulae, which were developed to replace Roe's Table and other formulae such as Hawksley's, calculated the discharge from the drainage basin for a storm event of a particular intensity. This flow was then used to design the pipes.

The rational method was not accepted by the engineering community immediately. Well into the 1900s, the older empirical formulae mentioned above were still being utilized (Buerger 1915). Only after a slow transition in the early part of the 1900s did the rational method become the dominant technique for drainage design in the U.S. and worldwide.

The early 1900s also witnessed attempts to describe the rainfall-runoff process more accurately (Rafter 1903; Gregory 1907; Justin 1914; Buerger 1915; Grunsky 1922). Prior to this time, drainage design formulae had not considered the rainfall-runoff process carefully; instead empirical relationships were used which related pipe size to watershed characteristics such as size, slope, etc. (Roe's Table or Hawksley's formula, for instance). By the 1920s the use of rain gage records enabled more typical 'design storms' to be used, in which rainfall intensity rose to a peak and then died away. The unit hydrograph (UH) concept is an example of these enhanced procedures based on design storms. Sherman (1932) developed the concept of the UH for gaged watersheds and, subsequently others modified it and applied it in different manners (Pettis 1938; Brater 1939). Since reliable rainfall-runoff data were rare, it was difficult to develop unit hydrographs for many drainage basins. To solve this problem, others developed methods to utilize the UH principles on ungaged watersheds. The derivation of these synthetic unit hydrographs were typically based on the characteristics of the watershed (Snyder 1938; Clark 1945). The direct application of UH theory to urban watersheds was made later by Eagleson and March (1965), Viessman (1968), and Roa, *et al.* (1972).

Economical and adequate design of wet weather sewer systems is possible only with a knowledge of the magnitude and timing of the expected peak flow in the absence of contributing laterals. The proper sizing of more complex systems and the testing of the capacity of existing systems requires a knowledge of the time-history of flow in the sewers in addition to the time-history of rainfall (Eagleson 1962). Until the introduction of unit hydrographs, few design techniques had considered using the storm hyetograph and runoff hydrograph; only the peak rate of runoff was utilized. Horner and Flynt (1936) first applied hydrograph techniques to storm sewer design (Horner and Flynt 1936; Eagleson 1962). They considered the variability of rainfall both spatially and temporally in their design methodology.

Following the UH applications, a renewed interest in the rainfall-runoff process was observed in the 1940s. Previous methods for determining runoff from rainfall had been mostly based on coefficients to account for losses of rainfall. In the late 1930s and early 1940s, rainfall abstractions became a concentrated topic of research. Horner and Jens (1942) developed a methodology to mathematically describe the process of infiltration, among other abstractions, and applied hydrograph techniques to a small basin. Linsley and Ackerman (1942), among others, also presented rainfall losses as being an important part of the rainfall-runoff process.

Environmental Awareness and Receiving Water Impacts

During the 1960s, wet weather flows were recognized by many to cause receiving water quality problems in most cases. To mitigate the problems, methods of control and treatment for urban runoff and CSOs were devised. Although it was known that controlling wet weather flows would not eliminate the problem, it was considered to be helpful in reducing the problems and in certain situations to be more cost effective than improving the capacity for dry weather wastewater treatment.

With the interest in reducing receiving water impacts through control and treatment of wet weather flows developing, numerous research projects were initiated in the 1960s and 1970s. The main focus of these projects was to evaluate the effectiveness of control and treatment alternatives for combined sewer overflows. The control and treatment alternatives included physical/chemical methods such as detention, swirl technology, filtration, screening, and disinfection; biological methods such as rotating biological contactors, contact stabilization, trickling filters, treatment lagoons, and activated sludge; and storage/treatment methods.

The next step in the 1970s was the attempt to evaluate problems on a larger scale. This was manifested in the Section 208 (from the *Federal Water Pollution Control Act of 1972*) planning studies and the watershed-wide planning philosophy that gained attention in the late 1970s and early 1980s. The planning studies focused on mitigating the impacts of urban runoff on receiving waters on a watershed scale instead of looking at a single outfall or a single stream reach. The Section 208 area-wide planning studies and implementation projects during the late 1970s resulted in very few documented successes.

In the early 1980s, problems remained with attempting to predict relationships between wet weather discharges and receiving water impacts. To remedy this problem, data was sought that would characterize the pollutants of concern and the impacts they would have on receiving waters. One of the major research efforts was the Nationwide Urban Runoff Program (NURP), conducted in the United States predominantly by EPA and USGS (EPA 1983). The overall goal of the NURP was to collect data and develop information for use by local decision makers, states, EPA, and other interested parties.

Other research projects attempted to evaluate the impacts of wet weather flows on the receiving water systems. Some of these investigators include Porcella and Sorenson (1980), Field and Turkeltaub (1981), Pitt and Bozeman (1982), and Heaney and Huber (1984). Many of the findings of these projects indicated a significant impact on receiving waters downstream from urban areas. Pollution tolerant species of aquatic life were observed to reside near CSOs and stormwater discharges (Pitt and Bozeman 1982) and a significant portion of the nation's waterways had impacts associated with discharges of wet weather flows (Heaney and Huber 1984).

Technical Tools and Design Methods

In the late 1960s and early 1970s the development of the computer and its applications to the field of WWF management had a significant impact on the direction of development of WWF management. Specifically, the analysis and design of WWF systems became dependent on computer applications. Early applications of computers were seen in modeling of environmental systems and processes, such as STORM (HEC 1973) and SWMM (Metcalf & Eddy Engineers, *et al.* 1971); two models developed in the late 1960s and early 1970s that significantly affected WWF management. The collection of data from demonstration projects for control and treatment measures increased the capacity to accurately model these processes. This led to updates and improvements to the early models (HEC 1975; Huber, *et al.* 1975; Huber, *et al.* 1984; Huber and Dickinson 1988) as well as the development of new models.

In addition to computers, the mathematical and statistical methods being applied to WWF management were also improving. Mathematical optimization methods were applied extensively to the wet weather field in the 1970s in an effort to find cost minimized solutions to the problem of controlling wet weather flows. The least cost sewer network design was determined using linear programming (Deininger 1969; Dendrou , *et al.* 1978), dynamic programming (Tang, *et al.* 1975; Mays and Yen 1975), and several other optimization algorithms. The use of statistics was seen in the analysis of long-term simulation results, the analysis of collected rainfall, runoff, and water quality data, and the evaluation of the optimum urban runoff control system configuration, among other uses (Howard 1976; DiToro and Small 1979; Hydroscience, Inc. 1979).

By the late 1980s, much of the technology necessary for WWF management had already been developed: ways existed to plan, design, construct, maintain, and rehabilitate WWF management systems. But all facets of the technology had room for improvement. The 1980s involved improving much of the technology and ideas initially introduced in the 1960s, 1970s and early 1980s. Personal computer advancements during the late 1980s and early 1990s were such that most WWF management technology currently revolves around the use of personal computers. The proliferation of computer modeling has also occurred as a result of the increased use of the personal computer. One consideration that accompanies modeling is the need for accurate data to develop and calibrate the models. Future sampling and monitoring efforts will have to be conducted in a manner that produces reliable, useful data in order for advancements to be made in WWF modeling applications.

Computational aids such as GIS, databases, and model pre- and post-processors have seen many advances during the 1990s. These aids have improved the planning, design, and operation stages of WWF management significantly in terms of time, effort and money. The use of these aids has also made the technology developed in the 1970s and 1980s more user friendly such that the excuse that WWF management techniques are too esoteric to utilize is typically no longer valid.

Current Storm Drainage Design Practices

In 1967, researchers at the University of Wisconsin distributed a survey to engineers in the state of Wisconsin to determine the level of stormwater drainage service considered adequate (Ardis, *et al*. 1969). Questions on this survey explored design procedures and policies and were divided into two parts. The initial part of the survey collected background information on procedures, site information, and system requirements. The second portion of the survey asked the respondent to design a simple stormwater system for a specified area based on the procedures and practices they regularly applied.

A 1997 storm drainage design survey (Lilburn 1997) was mailed to over 350 individuals in engineering firms and municipal water authorities across the nation, plus it was posted on several Internet list servers associated with environmental engineering, and handed out at several regional conferences and workshops in the southeast and upper Midwest. Slightly more than 100 responses were received from 24 states (mostly from Minnesota, Ohio, New York, Florida, California, and Kentucky). The following is a summary from Lilburn's (1997) survey. Regulations were found to govern acceptable design methods and levels of service for most projects (about 75%), with most being established by local or county authorities, indicating a regional focus.

Design Storm Use

Most survey participants (42%) used a 10-year storm for drainage design in almost all cases. Several of the engineers who indicated the use of 10-year storms stated that most structures were also checked for flooding with respect to the 100-year storm. About 10% of the participants indicated the use of a 5-year design storm, 9% indicated the use of a 100-year storm, and 7% indicated the use of a 25-year storm for all land uses. Most other answers indicated combinations of design storms, for example the use of 2- and 10-year, or 5- and 10-year design storms were common. Those who used different storms for different land uses used design storms ranging from 2 to 100 years. These were divided with the smaller storms being used in the less dense areas, and larger storms used in the more urbanized areas. One survey participant mentioned that one storm type was used for drainage design while another, more frequently occurring storm, was used for water quality concerns.

In the 1967 survey, 70% of the reporting cities supported the use of 5- to 10-year design storms. Those cities with significantly different responses used smaller, rather than larger, storms. In the 1997 survey, the majority of participants used storms in approximately the same range, with most stating a 10-year design storm. Currently, more communities examine the effects of larger storms, but essentially, the design storm frequency has apparently not appreciably changed during the past thirty years.

Design Methods

The respondents were also asked to describe the overall design method they used most often in drainage design. The most popular methods were the rational method (41%) and the NRCS (SCS) procedures (12%), or a combination of the two (27%). Regional methods were also used by some (12%). Computer programs and models have become an important tool used in storm drainage design. Some form of computer-assisted storm drainage design program was used by 86% of the respondents. The most common models used included SWMM (25%) and HEC-1 (17%). Other common packages included those based on TR-55 and TR-20 NRCS procedures (13%). Custom programs, designed in-house or for a specific region, were used by 8%.

Respondents were also asked to identify how time of concentration was determined because of its great significance in storm drainage design. Time of concentration formulas (such as the Kirpich, Izzard, or TR-55 equations) were used to determine the times of concentration by 65% of those responding to the survey. Local engineering practice ("rules of thumb") were used by 29% of the participants. About 7% noted the use of field testing and local measurements to determine times of concentration.

The survey distributed earlier by UW demonstrated that "practically all" cities responding to the survey used the rational method for design. (Ardis, *et al*. 1969). There were problems reported in its use, however. Most cities using this procedure were not using it correctly: either the runoff coefficient, or the rainfall intensity were determined incorrectly. The most significant problem was the use of the 24-hr average rain intensity instead of the rain intensity associated with the drainage area time of concentration. This error can cause gross under-designs of drainage systems. In the 1997 survey, it was established that a majority of engineers still employ the rational method for design. Newer methods, such as those promoted by NRCS, are beginning to be used more in design practices. These methods found significant use in larger watersheds, which is a positive indication of the realization of the major limitations of the rational method (lack of adequate routing of flow hydrographs).

The most common indication of recognized system failures was manhole covers popping off. Water entering basements and water rising above curbs were also widespread indicators. Usually, these occurring more often than once every 10 years were indicative of system failure. System failure indicators were another factor examined in both surveys. In the UW survey, it was determined that the most common indicator of system failure was water ponding at inlets. Although this also noted as a current concern, it was not as prevalent. The second leading sign of system failure in the 1967 survey was water ponding in back yards. Again, this was not a priority for design engineers today.

Stormwater Quality Concerns

The 1997 survey respondents were also asked to identify water quality concerns they associate with stormwater runoff. The most widespread stormwater quality concerns were sediment (63%), nutrients (35%) and metals (34%). Other frequent answers were oils and grease, bacteria, toxicants, CSOs, floatables, and salts. A few survey participants answered the question from a different angle and stated their main water quality concerns dealt with permit and discharge limits. Their focus was simply to remain within these regulated limits. Answers obtained in the two surveys give a similar list of stormwater constituents of concern. Reoccurring answers included sediment, oil and grease, salts, and fertilizers.

Wet Weather Flow Management: Lessons Learned from the Past

Much can be learned from observing past WWF management practices. Indeed, the review of the literature has provided helpful insights that should prove useful in developing future WWF management strategies. The following characteristics were often observed in successful strategies or were conspicuously missing from unsuccessful strategies. The list provided below indicates considerations that should be incorporated into future WWF management strategies:

- technology transfer
- user friendly design methods and tools
- political, social, and economic ramifications
- sustainability of design
- goal of wet weather system should be to mitigate impacts on the environment
- designs should be optimized in terms of pollutant control, receiving water impacts, and cost

McPherson (1975; 1978) voiced concerns 20 years ago and offered suggestions to reduce the technology transfer (development to implementation) lag time. Professional societies have published monographs with the purpose of bridging the gap between research and practice (Kibler 1982). History has displayed examples of the technology transfer time lag. Take the prediction of runoff from a watershed as an example. The formula methods, such as McMath, Roe, and Burkli-Ziegler, dominated sewer design in the late 1800s. The rational method of determining stormwater runoff was introduced to the United States by Emil Kuichling in 1889, but it did not become a widely utilized method until much later. A paper by Charles Buerger (1915) states:

> *It [the rational method] is not widely used, however, and the formula methods, of which the Burkli-Ziegler and the McMath are the most popular, are generally used, in spite of the common realization of the fact that the results given by them lack consistency, and are very erratic and unreliable.*

This statement can be applied today, except now the rational method might be considered the method that engineers are continuing to embrace while the new technology that has been introduced recently is not being implemented. The reasoning Buerger offered in 1915 for the lack of implementation is even more interesting. He stated that the rational method had not received the widest use because it was relatively laborious, and required a material exercise in judgment. This again is a popular reason expressed today for the lack of application of other techniques.

An advantage of developing user friendly design methods and tools is the reduction in the time lag between development and implementation. Practitioners generally embrace technology that is simple to understand while still providing the means to perform the job in the most cost effective manner possible. The methods and tools that have gained application through history have been simple to implement and easy to understand, although not necessarily the most accurate or appropriate.

Another consideration noticed during the review of the literature is that past design engineers and planners were forced to consider the socioeconomic, political, and legal ramifications associated with their plans and designs. These topics can be the primary inhibitors to the implementation of innovative technology and in the future must be addressed for progress to be made (Berwick, *et al.* 1980). Berwick, *et al.* (1980) and others have reviewed the reasons for lack of implementation and attribute it to a variety of problems. Some of the problems have been identified as the regulatory framework surrounding development, risks associated with development, public attitudes, and others. A future design methodology for WWF management will have an advantage if it considers the socioeconomic, political, and legal implications of system implementation.

Considering the other points listed above, a sustainable development will have the benefit of significantly reducing the environmental impacts over time associated with a project; while promoting economic stability as well. The literature is replete with examples of entire systems (Paris in the middle ages) or parts of systems that were designed without considering the long-term sustainability of the project. The systems performed poorly and resulted in additional money being contributed to rehabilitate and maintain the design.

Insuring that a design is optimal in terms of pollutant control, receiving water impacts, and cost will eliminate many characteristics of a design that may lead to unsustainable development. Mathematical optimization is a relatively recent addition to WWF management, but variations have existed in the past. Essentially, the selection of a “best” method has always occurred, but it did not involve mathematical algorithms considering a range of possible alternatives. For example, the design of Hamburg’s sewerage in 1842 was based on providing a comprehensive system that took advantage of the situation to provide a low-cost, effective design. This and other comprehensive designs of that era involved the designers deciding between several possible alternatives. The implementation of mathematical optimization would have made that decision more objective and efficient.

Use of Combined Sewers in Newly Developing Areas

Even though domestic sewage collection systems is not a major topic for this book, the topic cannot be ignored when addressing wet weather flow. The continued use of combined sewer systems is common in many parts of the world, and the U.S. has many existing combined systems still in use. In addition, separate sewer overflows (SSOs) are also common in many urban areas that only have separate systems. Overflows of raw sewage during wet weather is therefore unfortunately common in many areas of the U.S. Overlooking these wet weather problems can badly distort efforts in stormwater management. In addition, there is renewed interest in the use of combined sewer systems in the U.S. under specific conditions, where their use (in conjunction with improved treatment facilities) may result in reduced, and more cost-effective, WWF discharges. Heaney, *et al.* (1997) for example, found that combined systems may discharge a smaller pollutant load to a receiving water than separate systems in cases where the stormwater is discharged untreated and where the sanitary wastewater is well treated. They present an example in southern Germany where combined sewer systems are being designed with extensive infiltration components to reduce the inflow of stormwater to the drainage system, reducing the frequency and magnitude of CSO events. Similar systems are also used in Switzerland and in Japan with comparable results.

Some of the important issues facing the use of combined sewers in the future include:

- the use of separate versus combined sewers and under what watershed/demographic conditions and characteristics warrant separate versus combined systems;
- the concept of larger size combined sewers providing for inline storage and flushing cells with or without steeper slopes and bottom shapes to alleviate antecedent dry-weather flow solids deposition; and
- taking advantage of new construction for larger capacity of dry-weather flow treatment and sludge handling facilities to accommodate additional flow during wet weather conditions.
- solids deposition in sewerage and prevention of solids from entering sewerage

These issues are discussed in the following parts of this module.

Conditions for the use of Combined Sewers

The debate on the use of combined sewers has been long. As noted above, Hering (1881) visited Europe and made recommendations to the U.S. National Board of Health concerning the use of combined sewers. He recommended that combined sewers be used in extensive and closely built-up districts (generally large or rapidly growing cities), while using separate systems for areas where rainwater did not need to be removed in underground drainage conveyance systems. His recommendations were largely ignored. Combined sewers were extensively used in many of the older U.S. cities because of perceived cost savings. Of course, the existing combined sewer systems in the U.S. are now mostly located in the most dense portions of central cities, along with some of the older residential areas. Many newer separate sanitary sewer systems also connect to downstream combined systems. In addition, current separate sewer systems actually may operate as combined systems due to excessive infiltration of sewage into stormwater systems, or by direct connections of sewage into stormwater systems.

Current Separate Systems that are actually Combined Systems. Unfortunately, many separate sanitary sewage collection systems in the U.S. are in poor repair, resulting in inappropriate discharges of sewage into receiving waters. Pitt, *et al.* (1994) and Pitt and Lalor (1997) developed a method for cities to identify and correct inappropriate discharges. The following discussion is from these reports.

Current interest in illicit or inappropriate connections to storm drainage systems is an outgrowth of investigations into the larger problem of determining the role urban stormwater runoff plays as a contributor to receiving water quality problems. Urban stormwater runoff is traditionally defined as that portion of precipitation which drains from city surfaces exposed to precipitation and flows via natural or man-made drainage systems into receiving waters. Urban stormwater runoff also includes waters from many other sources which find their way into storm drainage systems. For example, Montoya (1987) found that slightly less than half the water discharged from Sacramento's stormwater drainage system was not directly attributable to precipitation. Sources of some of this water can be identified and accounted for by examining current NPDES (National Pollutant Discharge Elimination System) permit records, for permitted industrial wastewaters that can be discharged to the storm drainage system. However, most of the water comes from other sources, including illicit and/or inappropriate entries to the storm drainage system. These entries can account for a significant amount of the pollutants discharged from storm sewerage systems (Pitt and McLean 1986).

Three categories of non-stormwater outfall discharges were identified by Pitt, *et al.* (1994): pathogenic/toxicant, nuisance and aquatic life threatening, and clean water. The most important category is for stormwater outfalls contributing pathogens or toxicants. The most likely sources for this category are sanitary or industrial wastewaters. Section 402 (p)(3)(B)(ii) of the 1987 reenactment of the federal Clean Water Act (CWA) requires that National Pollutant Discharge Elimination System (NPDES) permits for municipal separate storm sewers shall include a requirement to effectively prohibit problematic non-stormwater discharges into storm sewers. Pitt, *et al.* (1994) developed a scheme to identify and correct problem outfalls to allow compliance with these CWA requirements. Outfall analysis surveys should have a high probability of identifying all of the outfalls in this most critical category. High probabilities of detection of other contaminated outfalls are also likely when using these procedures. After identification of the contaminated outfalls, their associated drainage areas are then subjected to a detailed source identification investigation. The identified pollutant sources are then corrected.

Sanitary sewage finds its way into separate storm sewers in a number of ways. Direct cross-connections may tie sanitary lines directly to storm drains (relatively rare), or seepage from leaking joints and cracked pipes in the sanitary collection system can infiltrate storm sewers (much more common). Surface malfunctions and insufficiently treated wastewater from septic tanks may contribute pollutants to separate storm sewers directly or by way of contaminated groundwater infiltration. Seepage of sewage or septic tank effluent (septage) into underground portions of buildings may be pumped into separate storm sewers by sump pumps (EPA 1989).

Due to indifference, ignorance, poor enforcement of ordinances, or other reasons, a stormwater drainage system may have sanitary wastewater sewerage direct connections. Obviously, the sanitary wastewater entering the storm drain will not receive any treatment and will pollute a large flow of stormwater, in addition to the receiving water. If the storm drain has a low dry-weather flow rate, the presence of sanitary wastewater may be obvious due to toilet paper, feces, and odors. In cases of high dry-weather flows, it may be more difficult to obviously detect raw sanitary wastewaters due to the low percentage of sanitary wastewater in the mixture. Even though the sanitary wastewater fraction may be low, the pathogenic microorganism counts may be exceedingly high.

Corrective measures involve undertaking a program of disconnecting the sanitary sewer connections to the storm drainage system and reconnecting them to a proper sanitary wastewater sewerage system. The storm drainage system then has to be repaired so that the holes left by the disconnected sanitary sewer entrances do not become a location for dirt and groundwater to enter. However, there are situations in which the sanitary system is so connected to the stormwater system that good intentions, vigilance, and reasonable remedial actions will not be sufficient to solve the problems. In an extreme case, it may be that while it was thought that a community had a separate sanitary sewer system and a separate storm drainage system, in reality the storm drainage system is acting as a combined sewer system. When recognized for what it really is, the alternatives for the future become clearer: undertake the considerable investment and commitment to rebuild the system as a truly separate system, or recognize the system as a combined sewer system, and operate it as such, without the disillusionment that it is a problem-plagued storm drainage system which can be rehabilitated.

It would be best to correct the sanitary sewer if only one drainage system can be corrected. This would have the dual advantage of preventing infiltration of high or percolating groundwaters and preventing pollution of stormwater with exfiltrating sanitary wastewater. Rehabilitation of the drainage systems by use of inserted liners, or otherwise patching leaking areas, are possible corrective measures. It is important that all drains with infiltration problems be corrected for this corrective action to be effective. This would also include repairing house lateral sanitary wastewater lines, as well as the main drainage runs. However, these corrective measures are more likely to be cost effective when only a relatively small part of the complete drainage systems require rehabilitation.

Normally, widespread failure of septic tank systems might necessitate the construction of a sanitary sewer to replace the septic tanks. Also, identifying and disconnecting sanitary sewers from the storm drainage system is usually undertaken. Connections (whether directly by piping or indirectly by exfiltration or infiltration) of sanitary sewers to the storm drainage system may be so widespread that the storm drainage system has to be recognized as a combined sewer system. This could also be the case when the prevalence of septic tank failures leads to widespread sanitary wastewater runoff to the storm drainage system. One usually thinks of a combined sewer system as having all of the sanitary sewer connections to the same sewers that carry stormwater, but, there are degrees of a storm drainage system becoming a combined sewer system. Prior to these actions taking place, the storm drainage system operates to some degree as a combined sewer system. It may be that the sanitary sewerage system is not capable of handling the load that would be imposed on it if a complete sewer separation program were undertaken. Or, in an extreme case, no sanitary sewer system may exist.

By recognizing that a combined sewer system does in fact exist may help to focus attention on appropriate remedial measures. The resources may not be available to undertake construction of a separate sanitary wastewater drainage system. One should then focus on how to manage the combined sewer system that is in place. Conventional CSO end-of-pipe storage/treatment needs to be investigated, in addition to methods to reduce the entry of stormwater into the drainage system (through upland infiltration, for example). Also, the combined sewer system may be tied into other combined sewers so that more centralized treatment and storage can be applied. While operation of a combined sewer system is not a desirable option, it may be preferable to having the stormwater and the large number of sanitary entries receive no treatment.

An early identification and decision to designate a storm drainage system a combined sewer system, will prevent abortive time and costs being spent on further investigations. These resources can then be more effectively used to treat the newly designated combined sewer system. In essence, recognition of a system as being a combined sewer system provides a focus in the regulatory community so that it may be possible to operate the system so as to minimize the damage to the environment. Plans can then be developed to provide the resources to separate the system.

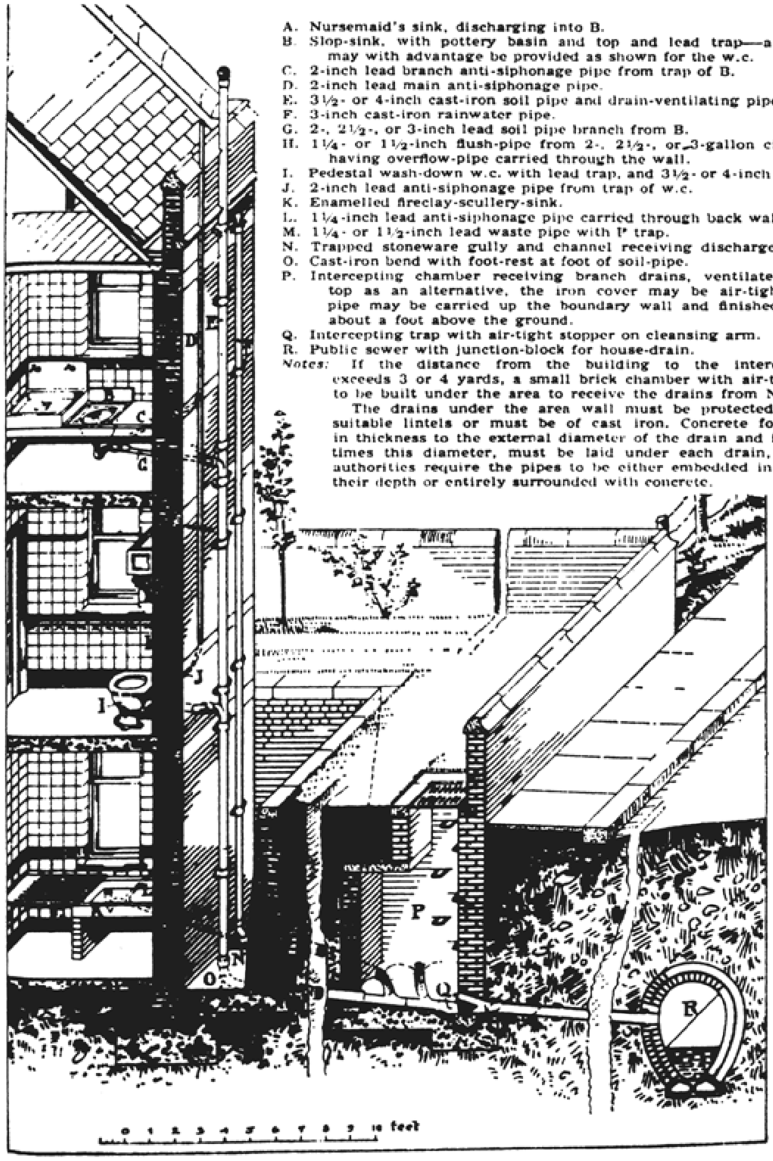
Conditions where New Combined Systems may be Appropriate. As noted above, it may be more cost-effective and result in the least pollutant discharges to operate separate drainage systems that are badly in need of repair as actual combined sewer systems, compared to costly and ineffective repairs to the separate systems. However, proposed construction of new combined sewer systems would be very controversial in the U.S. and it would be very difficult to overcome resistance to their construction. The main areas of resistance relate to the massive efforts expended in the last several decades in reducing the number and severity of combined sewer overflows (CSOs), usually under court order. In addition, current interest and massive correction efforts to control separate sewer overflows (SSOs) in many cities would also result in a great deal of resistance from engineers, municipalities, regulatory agencies and environmental groups to the construction of new combined sewer systems. The political resistance to the construction of new combined sewer systems in the U.S. is therefore considered almost insurmountable. However, it may be interesting to note where they may be appropriate, from a technical viewpoint.

As pointed out by Hering in 1881, combined sewer systems may be suitable in dense urban areas, where the sanitary sewage flow is relatively high per area. Of course, any use of a combined sewer must be accompanied with provisions to reduce any untreated overflows to almost zero. In reality, the current level of untreated sanitary sewage discharges in urban areas from badly functioning separate systems is likely much higher than anyone acknowledges or considers when conducting wet weather flow management projects. The major concern with combined sewer systems is the overflow discharges of dangerous levels of pathogenic microorganisms, and nuisance conditions associated with floatable debris and noxious sediment accumulations. Discharges of potentially dangerous medical wastes and drug paraphernalia is also of great concern. However, it may be possible to construct a new combined sewer system that would operate with fewer annual untreated discharges of sewage than many currently separate systems, plus provide treatment of stormwater. The following attributes would be helpful for any new sewerage system, especially a combined system:

- The major goal of any new WWF collection system should be the minimization of stormwater runoff and sanitary wastewater entering the system. As noted previously, there are many beneficial uses of stormwater that could account for substantial fractions of the annual runoff. Similarly, household water conservation (especially low-flow toilets and reduced flow showerheads, etc.) can also substantially reduce wastewater flows to the sewerage.

- The conveyance system could be either a conventional combined system, or one of two possible new scenarios that would reduce the flows in the sewerage that could cause CSOs or SSOs. These new options include: 1) utilize a flow storage tank at each household to retain sanitary wastewater during wet weather, or 2) prohibit the entry of stormwater into the sewerage at a level that would cause overflows. The effective use of an existing conventional combined sewer system would require extensive modifications to provide adequate storage and increased treatment capacity to reduce overflows. These new options are briefly described below:

The first option may be termed a shared sewer system as the two flows (stormwater and sanitary wastewater) are not co-mingled at the same time in the single drainage system, but are kept separate as much as possible. This option, commonly used in England in the later part of the last century, and recently re-introduced by Pruel (1996) would require an adequately sized storage tank that could hold household wastewater for specific periods of time (depending on rain durations, conveyance capabilities, and treatment rate available). Figure 2 (Reyburn 1989) shows a old drawing of sanitary fittings and drains from a catalogue from Thos. Crapper & Co., Ltd., Sanitary Engineers, Chelsea, England. The house connections are all directed to an intercepting chamber which receives the branch drains from the house. This chamber is vented and is fitted with a trap. The large intercepting chamber is connected to the public sewer. In this drawing, the roof runoff is also directly connected to the intercepting chamber, possible as an aid in flushing the chamber.



A. Nursemaid's sink, discharging into B.
B. Slop-sink, with pottery basin and top and lead trap—a flushing cistern may with advantage be provided as shown for the w.c.
C. 2-inch lead branch anti-siphonage pipe from trap of B.
D. 2-inch lead main anti-siphonage pipe.
E. 3½- or 4-inch cast-iron soil pipe and drain-ventilating pipe.
F. 3-inch cast-iron rainwater pipe.
G. 2-, 2½-, or 3-inch lead soil pipe branch from B.
H. 1¼- or 1½-inch flush-pipe from 2-, 2½-, or 3-gallon cistern; the latter having overflow-pipe carried through the wall.
I. Pedestal wash-down w.c. with lead trap, and 3½- or 4-inch branch soil-pipe.
J. 2-inch lead anti-siphonage pipe from trap of w.c.
K. Enamelled fireclay-scullery-sink.
L. 1¼-inch lead anti-siphonage pipe carried through back wall.
M. 1¼- or 1½-inch lead waste pipe with P trap.
N. Trapped stoneware gully and channel receiving discharge from M and F.
O. Cast-iron bend with foot-rest at foot of soil-pipe.
P. Intercepting chamber receiving branch drains, ventilated by grating at top as an alternative, the iron cover may be air-tight, and a 4-inch pipe may be carried up the boundary wall and finished with a grating about a foot above the ground.
Q. Intercepting trap with air-tight stopper on cleansing arm.
R. Public sewer with junction-block for house-drain.

Notes: If the distance from the building to the intercepting chamber exceeds 3 or 4 yards, a small brick chamber with air-tight cover ought to be built under the area to receive the drains from N and O.

The drains under the area wall must be protected from injury by suitable lintels or must be of cast iron. Concrete foundations, equal in thickness to the external diameter of the drain and in width to three times this diameter, must be laid under each drain, and some local authorities require the pipes to be either embedded in concrete to half their depth or entirely surrounded with concrete.

Figure 2. Nineteenth century English household holding tank located before sanitary sewerage (Reyburn 1989).

The intercepting chamber would normally be empty, with the wastewater flowing across the bottom of the tank in a small-flow channel (for an in-line installation), or the tank could be off-line. During wet weather, a flapper valve or other fitting at the connection to the full-flowing sewer would prevent additional water from entering the drainage, causing wastewater to back up into the intercepting chamber. When the wet weather flow subsided, the tank would empty into the sewerage. In a modern application, tank flushing could be accomplished (possibly using captured stormwater) with a tipping bucket or sprays to remove any settled solids in the tank. The flushing mechanisms would not need to be very complex. The initial higher flows (less than the capacity of the treatment facility) in the sewerage would therefore be mostly stormwater and would be used to flush solids, that accumulated during the low-flow sanitary wastewater flow conditions, to the treatment facility. This "first flush" would therefore be captured, along with a sizeable amount of stormwater, for treatment. As the WWF exceeded the capacity of the treatment facility, overflows of stormwater would occur. There are many options available that can be used to temporarily increase the capacity of the treatment facility, or to provide temporary storage before treatment.

Preul (1996) calculated the needed on-site storage volumes for this "shared sewer" concept. His "combined sewer prevention system" (CSPS) was investigated for locations in Cincinnati, Ohio, and in Toronto, Ontario. He found that storage tanks capable of detaining household sanitary wastewater on-site for 6 hours in Cincinnati would prevent about 90% of the CSO occurrences. The Toronto location would only require on-site detention capabilities of 3 hours for similar benefits. He has predicted an expected domestic wastewater production of about 60 to 80 liters per person per day in the future, with the required use of low water use plumbing fixtures. For a typical 2.8 person household, the daily sanitary wastewater flow in Cincinnati would be about 170 to 220 L per day per household. Therefore, a household storage volume of 55 L would provide 6 hours of storage and 90% control of CSO occurrences. A 220 L storage capacity per household would virtually eliminate all CSOs in Cincinnati. Required household storage capacities in Toronto would be even less, with 30L storage tanks providing almost complete control. These are all relatively small volumes and would cost only a very modest amount, if designed and constructed at the time the housing units are built.

Another option is basically a separate sanitary sewerage system that is constructed to be very tight. This would be a less complex option than above, in some ways, but does require very good construction and maintenance practices. The sanitary sewerage system may be best a vacuum or small diameter pressurized system, both having been used for many years at numerous locations throughout the U.S. The stormwater would be conveyed separately, emphasizing on-site reuse and infiltration, through either open channels if compatible with the land use, or through a separate drainage system. Critical source area controls would be utilized, along with end-of-pipe treatment, as appropriate. With a tight conveyance system, no extra stormwater could enter the sanitary sewerage, greatly lessening the threat of overflows during wet weather.

Use of Larger, Steeper, and More Efficient Cross-Sections for Combined Sewers
According to Field, *et al*. (1994), new urban areas or upstream additions to older combined sewer systems should use advanced combined sewer designs requiring larger diameter sewers having steeper slopes and more effective bottom cross-sections to add storage capacity to the system and eliminate antecedent dry weather flow pollutant deposition and resulting pollutant concentrated storm flushes (Field 1975, 1980, and 1990b; Kaufman and Lai 1978; Sonnen 1977). The additional capital cost of an advanced combined sewer system would be incrementally small, considering the overall cost of installing a conventional combined sewer system or a two-pipe separate (storm and sanitary) sewer system, and the cost effectiveness for storm-flow pollution control.

Larger combined sewers would provide in-system storage for short periods of excessive flows, and would allow larger flows to be conveyed to the treatment facility. Inflatable dams in the sewerage could be used to selectively back up water in the sewerage, reducing excessive flows. Upland detention can also be used to significantly reduce stormwater flows. Stormwater flows can be captured and detained at many locations before entering the drainage system. Temporary rooftop storage, parking lot storage, and even limited road flooding have been used to reduce stormwater flows into combined sewers. Conventional stormwater detention facilities are also available for storage of large volumes of stormwater. However, the use of extensive stormwater infiltration, as demonstrated in Germany, Switzerland, Canada, and in Tokyo in areas having combined sewerage appears to be very effective in reducing CSO volumes and frequency. The previously described household detention of sanitary wastewater should also be considered in conjunction with increased in-line storage and conveyance capacity. Of course, in order to be effective, treatment capacity would need to be increased to allow for a greater portion of the WWF to be treated. The following discussion presents several methods for increasing the treatment facility capacity for combined sewerage systems.

Solids in Sewers
Heaney, *et al.* (1997) stated that historically, sanitary sewers were designed primarily based on peak sewage flow rates, assuming that solids would be carried with the sewage if simple guidelines were followed. Generally, these guidelines require sewage flow rates of between 0.6 and 3.5 m/sec. Much more can be done to more effectively accommodate solids in sewers, however. Knowledge about solids in sewers and their associated pollutants is extensive after more than a decade of detailed research in Europe and Scandinavia, and elsewhere (USA and Japan in particular) prior to that, but little of this work has been incorporated in modern sewerage design. However, there are still significant outstanding uncertainties and research is continuing worldwide. The sewer sediments working group (SSWG) of the Joint Committee on Urban Storm Drainage of IAWQ/IAHR is producing a Scientific and Technical Report entitled *Solids in Sewers: state of the art*, and subtitled *Characteristics, effects and control of sewer solids and associated pollutants* which will summarize the available knowledge, and recommend future research directions (Ashley, *et al.* 1996). The following briefly summarizes these solids in sewers issues covered in this special report that have dramatic effects on combined sewer and separate sanitary sewer design and maintenance.

Origins, occurrence, nature and transport of solids in sewers. The emerging importance of sewers as a part of the treatment process and interaction with treatment plants has recently led to the concept of the “sewer as a reactor” (Hvitved-Jacobsen, *et al*. 1995). In-sewer processes are perhaps the least understood aspect of sewer solids. The transport and movement processes and mechanisms, together with aggregation and disaggregation effects, sediment deposition, change in nature and subsequent erosion and transport are all important processes. There are particular problems which differentiate sewers from fluvial sediment transport systems, such as source limitation, rigid non-erodible boundaries and organic effects.

Effects sewer solids have on the performance of wastewater systems. Problems caused by sewer solids relate to physical effects, such as blockages, conveyance constraints, and overall effects on the hydraulics. These all affect the relative roughness of the boundary between the flowing wastewater and the pipe material. The quality and potential pollution problems of erosion and sediment flushes and associated shock loads on treatment plants are significant and control rules are as yet poorly developed. Sewer corrosion and other gas related problems are also important, especially for H_2S, VOCs and odors.

Sediment management options. It is important to integrate watershed source management opportunities with in-sewer control and treatment plant and CSO operation. Source controls can be applies prior to and at entry to sewerage systems. These include best management practices (BMPs), problems of sanitary wastes and cultural habits which may be difficult to change. For example, reductions in water usage for the promoted of conservation and/or alternative options for sanitary waste disposal may lead to inadequate flows within sewers for traditional assumptions about self-cleansing performance.

There are new ideas for the structural design of sewers and ancillary components for the minimization of sediment problems. The use of recent research results in developing controlled sedimenting sewer designs (May 1995) is considered to be a major new design option. New research is needed in this area if design guidelines are to be developed (Bertrand-Krajewski, *et al.* 1995). Settling basins, varieties of tanks and overflow structures and innovatory screening systems are also available to minimize the introduction of solids into sewers. Operational measures such as flushing systems, balls, vane wagons and other cleaning methods are also available for flushing solids through the sewerage.

Future requirements and research needs. Ashley, *et al.* (1996) identified notable new developments in sewerage design, in addition to major research needs. These include:

- the concept of sewers as reactors,
- the interaction of solids with treatment plants,
- disposal of sewer solids,
- the interaction between gross solids and other sediments and options for their control,
- physical factors such as bed-forms in sewers and their effects,
- the ideal sewer shape, and

- proper determinations of particle settling velocity and particle size.

Increasing Capacity of Treatment and Sludge Handling Facilities
The design of new POTW should include treatment of CSO and not just treatment for peak dry weather flow conditions. Larger interceptors, higher treatment flowrates, and alternative highrate treatment methods should be used in new POTW designs (Field, *et al*. 1994). During construction of new facilities, many new opportunities are available, compared to retrofitting modifications to existing and outdated facilities. Some of these include specialized treatment unit operations that are capable of handling a wide range of flows, utilizing parallel processes to optimize treatment for widely varying flows, and using specialized high-rate processes for polishing effluent during high flow periods. There are many possible options for enhanced wet weather flow treatment at POTWs. Some of these are listed below (from Field, *et al.* 1994):

- POTW operational changes. Directing increased flows through primary settling tanks is usually the cheapest option for operating a treatment facility during increased wet weather flows. Generally, increased flows would decrease the performance of the settling tanks. However, when the normally untreated CSO is considered, significant improvements in pollutant discharges can usually be achieved, especially when considering the settling characteristics of wet weather flows that enable more effective settling compared to dry weather sanitary flows.

- Numerous modifications to settling tanks are also available to enhance wet weather performance. These include the use of dissolved air floatation, the use of lamella plates, with the possible use of chemical coagulants and polyelectrolytes.

- High-rate physical/chemical processes can also be used at POTWs during wet weather flows for enhanced treatment. These could be used as polishing units that would not normally be used during dry weather. Microscreens, polymer additions, coagulants with microsand and plate separators, plus deep-bed filters have all been shown to be highly effective when treating CSOs.

- Swirl degritters and deflection separators are also useful unit processes for combined sewage treatment that have not been used in separate sanitary sewage treatment.

- The production of solids in the treatment of combined sewage would be greater than typical for separate sanitary sewage. Much of the increased solids would be relatively gritty from the stormwater component, plus substantial litter may reach the POTW. These solids may have to be handled differently than conventional sanitary sewage solids.

Stormwater Drainage Design Objectives

An idealized WWF management system would include several attributes affecting the conveyance of the stormwater. Basic to these is an understanding of the different objectives of stormwater drainage systems, and the associated rainfall and runoff conditions. There are four major aspects of the drainage system, each reflecting distinct portions of the long-term rainfall record. Figure 3 is an example of observed rainfall and runoff observed at Milwaukee, WI, (Bannerman, *et al.* 1983) as monitored during the Nationwide Urban Runoff Program (EPA 1983). This observed distribution is interesting because of the unusually large rains that occurred twice during the monitoring program. This figure shows the accumulative rain count and the associated accumulative runoff volume for a medium density residential area. This figure shows that the median rain, by count, was about 0.3 inches, while the rain associated with the median runoff quantity is about 0.75 inches. Therefore, more than half of the runoff from this common medium density residential area was associated with rain events that were smaller that 0.75 inches. These rains included two very large storms which are also shown on this figure. These large storms (about 3 and 5 inches in depth) distort this figure because, on average, the Milwaukee area only can expect one 3.5 inch storm every five years. If these large rains did not occur, such as for most years, then the significance of the small rains would be even greater. Figure 4 shows the accumulative loadings of different pollutants (suspended solids, COD, phosphates, and lead) also monitored during the Milwaukee NURP monitoring activities. When these figures are compared, it is seen that the runoff and discharge distributions are very similar and that runoff volume is the most import factor affecting pollutant discharges.

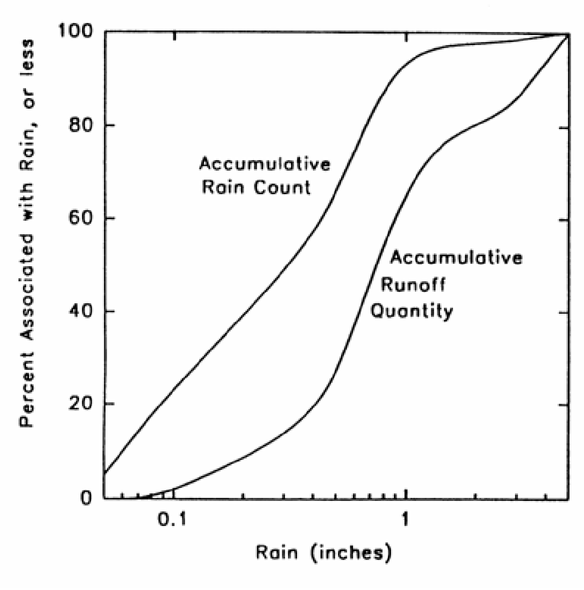


Figure 3. Milwaukee rainfall and runoff probability distributions.

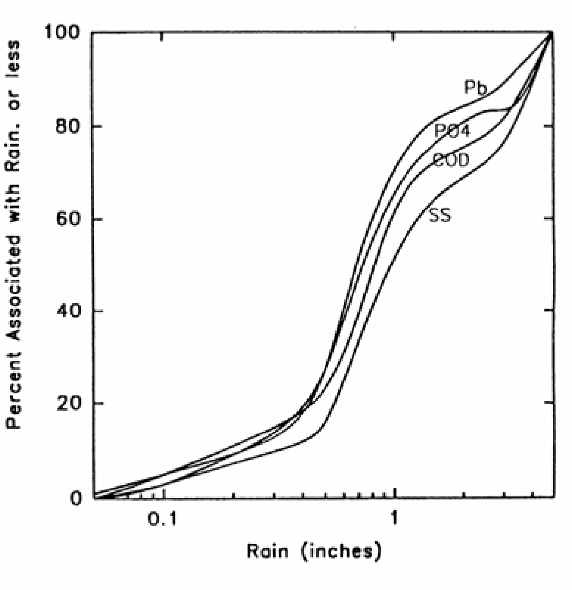


Figure 4. Milwaukee pollutant probability distributions.

As noted, these example rainfall and runoff distributions for Milwaukee can be divided into four regions:

- <0.5 inch. These rains account for most of the events, but little of the runoff volume, and are therefore easiest to control. They produce much less pollutant mass discharges and probably have less receiving water effects than other rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants, especially bacteria and some total recoverable metals. They also cause large numbers of overflow events in uncontrolled combined sewers. These rains are very common, occurring once or twice a week (accounting for about 60% of the total rainfall events and about 45% of the total runoff events that occurred), but they only account for about 20% of the annual runoff and pollutant discharges. Rains less than about 0.05 inches did not produce noticeable runoff. In most areas, runoff from these rains should be totally captured and either re-used for on-site beneficial uses or infiltrated in upland areas. These rains should be removed from the surface drainage system.

- 0.5 to 1.5 inches. These rains account for the majority of the runoff volume (about 50% of the annual volume for this Milwaukee example) and produce moderate to high flows. They account for about 35% of the annual rain events, and about 20% of the annual runoff events. These rains occur on the average about every two weeks during the spring to fall seasons and subject the receiving waters to frequent high pollutant loads and moderate to high flows. The small rains in this category should also be removed from the drainage system and the runoff re-used on site for beneficial uses or infiltrated to replenish the lost groundwater infiltration associated with urbanization. The runoff from the larger rains should be treated to prevent pollutant discharges from entering the receiving waters.

- 1.5 to 3 inches. These rains produce the most damaging flows, from a habitat destruction standpoint, and occur every several months (at least once or twice a year). These recurring high flows, which were historically associated with much less frequent rains, establish the energy gradient of the stream and cause unstable streambanks. Only about 2 percent of the rains are in this category and they are responsible for about 10 percent of the annual runoff and pollutant discharges. Typical storm drainage design events fall in the upper portion of this category. Extensive pollution control designed for these events would be very costly, especially considering the relatively small portion of the annual runoff associated with the events. However, discharge rate reductions are important to reduce habitat problems in the receiving waters. The infiltration and other treatment controls used to handle the smaller storms in the above categories would have some benefit in reducing pollutant discharges during these larger, rare storms.

- >3 inches. The smallest rains in this category are included in design storms used for drainage systems in Milwaukee. These rains occur only rarely (once every several years to once every several decades, or less frequently) and produce extremely large flows. The monitoring period during the Milwaukee NURP program was unusual in that two of these events occurred. Less than 2 percent of the rains were in this category (typically <<1% would be), and they produced about 15% of the annual runoff quantity and pollutant discharges. During a “normal” period, these rains would only produce a very small fraction of the annual average discharges. However, when they do occur, great property and receiving water damage results. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of organisms great distances downstream and out of the system) can conceivably naturally recover to before-storm conditions within a few years. These storms, while very destructive, are sufficiently rare that the resulting environmental problems do not justify the massive controls that would be necessary for their reduction. The problem during these events is massive property damage and possible loss of life. These rains typically greatly exceed the capacities of the storm drainage systems, causing extensive flooding. It is critical that these excessive flows be conveyed in "secondary" drainage systems. These secondary systems would normally be graded large depressions between buildings that would direct the water away from the buildings and critical transportation routes and to possible infrequent/temporary detention areas (such as large playing fields or parking lots). Because these events are so rare, institutional memory often fails and development is allowed in areas that are not indicated on conventional flood maps, but would suffer critical flood damage.

The above specific values are given for Milwaukee, WI, selected because of the occurrence of two very rare rains during an actual monitoring period. Obviously, the critical values defining the design storm regions would be highly dependent on local rain and development conditions. Computer modeling analyses from about 20 urban locations from throughout the U.S. are presented later. These modeled plots indicate how these rainfall and runoff probability distributions can be used for more effective storm drainage design in the future. In all cases, better integration of stormwater quality and drainage design objectives will require the use of long-term continuous simulations of alternative drainage designs in conjunction with upland and end-of-pipe stormwater quality controls. The complexity of most receiving water quality problems prevents a simple analysis. The use of simple design storms, which was a major breakthrough in effective drainage design more than 100 years ago, is not adequate when receiving water quality issues must also be addressed.

Design of Wet Weather Flow Systems in the Future

There are many questions that remain concerning the "best" wet weather flow drainage and treatment systems that should be used in newly developing areas. Of course, there is no one "best" answer for all areas and conditions. A wide variety of options exist and an engineer must select from these depending on numerous site specific situations. One of the purposes of this book is to illustrate these options, stressing stormwater, by showing how they can be used to their best advantage for different conditions. In most cases, conventional separate sanitary wastewater and stormwater drainage systems would seem most appropriate. However, these systems have shown to be of reduced value in many cases. The most significant problems relate to the large amount of inflow and infiltration (I/I) occurring in separate sanitary wastewater systems and the lack of stormwater pollution controls in separate stormwater systems. Pertroff (1996) estimated that more than half of the annual flows treated by municipal wastewater treatment plants are from I/I. In addition, I/I is likely the major cause of SSOs in separate sanitary wastewater collection systems. Therefore, in order for separate sanitary wastewater collection systems to be effective in the future, they must be constructed to eliminate almost all I/I contributions. This is possible, as demonstrated by current vacuum and pressurized sanitary wastewater collection systems.

Several discussion groups were held concerning future drainage design as part of the Engineering Foundation/ASCE conference *Sustaining Urban Water Resources in the 21st Century* held in Malmo, Sweden, on Sept. 7 – 12, 1997. Conference participants (mostly from western Europe, plus some from North America, Asia and eastern Europe) were separated into municipal, regulator, planner, and researcher/consultants groups to highlight their specific areas of concern. These concerns and suggestions for future drainage systems are summarized below.

Municipal Representatives (owners and operators of systems)

The municipal representatives are the real experts of the current systems and present conservative viewpoints because they will most likely be responsible for operations of drainage systems in the future. The following are some of their concerns and predictions for the future concerning urban drainage issues:

- We must start with existing systems and make slow and gradual changes.
- Future citizens will be better educated and will be willing to make life style changes that will reduce wastewater discharges.
- Will still have centralized wastewater treatment systems in the future because of better hygienic, health, energy, and environmental benefits, compared to de-centralized systems.
- Stormwater will be eliminated from sewerage in the future, increasing capacity for sanitary wastewater.
- I/I will be reduced considerably due to new methods of detection and prevention.
- There will be more rigid restrictions on the use of materials to prevent corrosion problems.
- Multi-disciplinary/integrated planning in urban areas will be more widespread, with clear strategies for operations. Relationships between precipitation, sewerage, treatment facilities, and receiving waters will be better considered.
- Urban drainage will become better integrated with other technical aspects of the infrastructure.
- Reuse of stormwater and treated wastewaters should be promoted where necessary (dual water systems, with degraded water available for less critical uses for example). Don't rely on highly purified domestic water for all uses.
- There is no consensus for the uniform use of either combined or separate systems.

Representatives of Regulatory Agencies

Regulators stressed the need to live within the carrying capacity of the planet (water, food, housing, and industry). The central focus here was on water quantity and quality and the need to enhance water resources in the broadest context, such as at planet, country, catchment, community, and citizen levels. The principles of ideal regulations for urban drainage include the following:

- Self regulation is preferred. Too much regulation stifles innovation.
- Regulations must be balanced against risk.
- Only regulate that which is not managed in other ways.
- Good legislation is the least amount. Financial support and positive enforcement is needed most. However, effective punishment is also needed.
- Related resources (air, land, and water) should be regulated in one agency.
- Regulatory consistency, not uniformity, is needed most.
- Must have appropriate time scales for action considering needed planning.
- Education is the key component of what regulators should do. Designers are a key group for education. They should be linked with citizens for political and financial support. Politicians are short-term and typically have few long-term goals. Polluters need to know the objectives and problems.
- Prevention (polluter pays) is better than cure (where all pay).

Planners

The planners felt there must be a better agreement between all parties on the definition of sustainability. Planners encouraged the need to move away from urban stormwater management by drains and towards urban waterways. They also felt there are better ways to manage stormwater pollutants besides transport of the pollutants by water. Other issues that the planners brought up included:

- Much more effort should be spent on source control (prevention) than on treatment (cure).
- Emphasis should be placed on keeping stormwater on site instead of transporting it downstream.
- Soil characteristics need just as much consideration as transportation elements when selecting sites for new development.
- The planning for urban development should be holistic by integrating water supply and drainage, for example. Currently, the developer does the planning.
- Only a small portion of the total domestic water needs require the highest quality water. Reuse of gray water on site, plus storage of stormwater for use on site needs to be considered.
- Greater emphasis should be placed on increasing density of urban development and making high density areas more comfortable, in order to preserve more open space.
- A multi-disciplinary approach in planning is critically needed. Developers and citizens should be brought together to examine new development scenarios.
- Better communication is needed between planners, developers, citizens, and politicians.
- Improved building techniques and materials are needed.
- Must convince politicians of the importance of long-term goals.
- Catchment planning is needed to increase building density in order to decrease impervious density.
- Water can give more identity in urban areas and should receive more attention in planning efforts.

Researchers and Consultants

The lack of a universal definition for sustainability was recognized by the researchers and consultants. Many local considerations make a universal definition impractical. However, there are many acceptable criteria for sustainability; the most basic being that sustainable actions would be acceptable over long periods of time. The urban area needs to consider both the built-up area plus the surrounding natural area. Similarly, the urban water cycle needs to consider water supply, stormwater, and sanitary wastewater together. Guiding principles of sustainable urban water resources include the following:

- Water is renewable on a large scale. We can have sustainable use of water if careful.
- We must accept multiple objectives and use a multi-disciplinary approach.
- Source control (especially pollution prevention) should be a top priority.
- We must not transport our problems downstream.

Technological aspects of the sustainability of urban stormwater resources include:

- “Best management practices” (BMPs) are not yet proven to be sustainable (functionally or economically).
- BMPs are more sustainable in new growth areas.
- It is barely possible to counterbalance new problems related to new growth if we impose high levels of effective controls in areas of new development, and simultaneously use high levels of retro-fitted controls in existing areas. It will be difficult to improve or fix existing problems with existing resources.
- Retro-fitting is possible, but much less effective and much more expensive than using controls in new development.
- Combined sewers will eventually function adequately.
- Future urban drainage approaches are not likely to change radically or quickly.
- Urbanization will continue in a manner similar to recent trends.
- There will be a gradual acceptance of source control of stormwater pollution.
- The urban water cycle may eventually include: bottled water for all consumptive uses, piped water for cooking and water contact, and recycled graywater and stormwater for other uses (such as irrigation and toilet flushing).
- There will be eventual optimization of combined and separate sewer systems.

Candidate Scenarios for Urban Drainage for the Future

The following list indicates some likely effective wastewater collection scenarios for several different conditions for the future:

- low and very low density residential developments (<2 acre lot sizes). Sanitary wastewater should be treated on site using septic tanks and advanced on-site treatment options. Domestic water conservation to reduce sanitary wastewater flows should be an important component of these systems. Most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bio-retention areas. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Roads should have grass swale drainage to accommodate moderate to large storms.

- medium density developments (¼ to 2 acre lot sizes). Separate sanitary wastewater and stormwater drainage systems should be used. Sanitary wastewater collection systems must be constructed and maintained to eliminate I/I, or use vacuum or pressurized conveyance systems. Again, most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bio-retention areas. Paved areas should be minimized and the use of porous pavements and paver blocks should be used for walkways, driveways, overflow parking areas, etc. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Grass swale drainages should be encouraged to accommodate moderate to large storms for the excess runoff in residential areas, depending on slope, soil types, and other features affecting swale stability. Commercial and industrial areas should also use grass swales, depending on groundwater contamination potential and available space. Wet detention ponds should be used for controlling runoff from commercial and industrial areas. Special controls should be used at critical source areas that have excessive pollution generating potential.

- high density developments. Combined sewer systems could be effectively used in these areas. On-site infiltration of the least contaminated stormwater (such as from roofs and landscaped areas) is needed to minimize wet weather flows. On-site storage of sanitary wastewaters during wet weather (using Preul's CSPS), plus extensive use of in-line and off-line storage, and the use of effective high-rate treatment systems would minimize the damage associated with any CSOs. The treatment of the wet weather flows at the wastewater treatment facility would likely result in less pollutant discharges in these areas than if conventional separate wastewater collection systems were used.

Module 0 References

Ashley, R., M.Verbanck, J-L Bertrand-Krajewski, T. Hvitved-Jacobsen, C. Nalluri,. G. Perrusquia, R. Pitt, E. Ristenpart, and A. Saul. "Solids In Sewers - The State of the Art." *7th International Conference on Urban Storm Drainage.* Hannover, Germany, 1996.

Bertrand-Krajewski J-L., H. Madiec, and O. Moine. "Study of two experimental sediment traps: operation and solids characteristics." *Proc. Int. Conf. Sewer Solids*. Dundee, Scotland. Sept. 1995. *Wat.Sci.Tech.* 1996.

Berwick, R., Shapiro, M., Kuhner, J., Luecke, D., and Wineman, J. J. "Select topics in stormwater management planning for new residential development." *EPA-600/2-80-013*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1980.

Bourne, J. *Engineering*, 2, 267. 1866.

Brater, E. F. "The unit hydrograph principle applied to small water-sheds." *Transactions of the American Society of Civil Engineers*, 105, 1154-1178. 1939.

Buerger, C. "A method of determining storm-water run-off." *Transactions of the American Society of Civil Engineers*, 78, 1139-1205. 1915.

Clark, C. O. "Storage and the unit hydrograph." *Transactions of the American Society of Civil Engineers*, 110, 1419-1488. 1945.

Dendrou, S. A., Delleur, J. W., and Talavage, J. J. "Optimal planning for urban storm drainage systems." *Journal of the Water Resources Planning and Management Division*, ASCE, 104(1), 17-33. 1978.

Deininger, R. A. "Systems analysis for water supply and pollution control." *National Resource System Models in Decision Making*, G. H. Toebes, ed., Water Resources Center, Purdue University, Lafayette, IN. 1969.

Di Toro, D. M. and Small, M. J. "Stormwater interception and storage." *Journal of the Environmental Engineering Division*, ASCE, 105(1) 43-54. 1979.

Eagleson, P. S. "Unit hydrograph characteristics for sewered areas." *Journal of the Hydraulics Division*, ASCE, 88(2), 1-25. 1962.

Eagleson, P. S. and March, F. "Approaches to the linear synthesis of urban runoff systems." *Report 85*, Hydrodynamics Lab., Massachusetts Institute of Technology, Cambridge, MA. 1965.

EPA (U.S. Environmental Protection Agency). *Results of the nationwide urban runoff program, volume I - Final report*. Water Planning Division, Washington, D.C. 1983.

Field, R. "Urban runoff pollution control-state of-the-art." *J. Environ. Eng. Div.,* 101, (EE1), 107. 1975.

Field, R. "EPA research in urban stormwater pollution control." *J. Hyd. Div.* 106 (HY5), 819. 1980.

Field, R. and Turkeltaub, R. "Urban runoff receiving water impacts: program overview." *Journal of the Environmental Engineering Division*, ASCE, 107(1), 83-100. 1981.

Field, R. *Storm and combined sewer overflow: an overview of EPA's research program*. Rep. No. EPA-600/8-89/054 (NTIS PB90-187006), U.S. Environmental Protection Agency, Cincinnati, Ohio. 1990b.

Field, R. T. O'Connor, and R. Pitt. "Optimization of CSO storage and treatment systems." Proceedings: *A Global Perspective for Reducing CSOs: Balancing Technologies, Costs, and Water Quality*. July 10 to 13, 1994, Louisville, Kentucky. Water Environment Federation. Fairfax, VA. 1994.

Gayman, M. "A glimpse into London's early sewers, parts 1-3." Reprinted from *Cleaner Magazine*, URL http://klingon.util.utexas.edu, downloaded January 13, 1997.

Gest, A. P. "Engineering." *Our Debt to Greece and Rome*, G. D. Hadzsits and D. M. Robinson, eds., Cooper Square Publishers, Inc., New York, NY. 1963.

Gray, H. F. "Sewerage in ancient and mediaeval times." *Sewage Works Journal*, 12, 939-946. 1940.

Gregory, C. E. "Rainfall, and run-off in storm sewers." *Transactions of the American Society of Civil Engineers*, 58, 458-510. 1907.

Grunsky, C. E. "Rainfall and runoff studies." *Transactions of the American Society of Civil Engineers*, 85, 66-136. 1922.

Heaney, J. P. and Huber, W. C. "Nationwide assessment of urban runoff impact on receiving water quality." *Water Resources Bulletin*, 20(1), 35-42. 1984.

Heaney, J.P., L. Wright, D. Sample, R. Pitt, R. Field, and C-Y Fan. "Innovative wet-weather flow collection/control/treatment systems for newly urbanizing areas in the 21st century." Proceedings of: *Sustaining Urban Water Resources in the 21st Century*. Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. Malmo, Sweden. Sept. 7 – 12, 1997. An Engineering Foundation/ASCE Conference. To be published by ASCE in 1998.

HEC (Hydrologic Engineering Center). "Urban runoff, storage, treatment, and overflow model: STORM." *Program No. 723-58-22520*, U.S. Army Corps of Engineers, Davis, CA. 1973.

HEC (Hydrologic Engineering Center). "Urban storm water runoff: STORM." *Generalized Computer Program 723-58-L2520*, U.S. Army Corps of Engineers, Davis, CA. 1975.

Hering, R. "Sewerage systems." *Transactions of the American Society of Civil Engineers*, 10, 361-386. 1881.

Hill, D. *A history of engineering in classical and medieval times*. Croom Helm Ltd., London. 1984.

Hodge, A. T. *Roman aqueducts & water supply*. Gerald Duckworth & Co. Ltd., London. 1992.

Horner, W. W. and Flynt, F. L. "Relations between rainfall and runoff from small urban areas." *Transactions of the American Society of Civil Engineers*, 101, 140. 1936.

Horner, W. W. and Jens, S. W. "Surface runoff determination from rainfall without using coefficients." *Transactions of the American Society of Civil Engineers*, 107, 1039-1117. 1942.

Howard, C. D. D. "Theory of storage and treatment-plant overflows." *Journal of the Environmental Engineering Division*, ASCE, 105(1), 709-722. 1976.

Huber, W. C., Heaney, J. P., Medina, M. A., Jr., Peltz, W. A., Sheikh, H., and Smith, G. F. "Storm water management model user's manual - Version II." *EPA-670/2-75-017*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1975.

Huber, W. C., Heaney, J. P., Nix, S. J., Dickinson, R. E., and Polman, D. J. "Storm water management model user's manual - Version III." *EPA-600/S2-84-109a*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1984.

Huber, W. C. and Dickinson, R. E. "Storm water management model - Version 4, user's manual." *EPA-600/3-88-001a*, U.S. Environmental Protection Agency (EPA), Athens, GA. 1988.

Hvitved-Jacobsen T., P. H.Nielsen, T.Larsen, N. A.Jensen (Eds.) "The sewer as a physical, chemical and biological reactor." *Wat.Sci.Tech*. Vol. 31 No. 7. 1996.

Hydroscience, Inc. "A statistical method for the assessment of urban storm water." *EPA-440/3-79-023*, U.S. Environmental Protection Agency (EPA), Washington, D.C. 1979.

Jones, D. E., Jr. "Urban hydrology - a redirection." *Civil Engineering*, 37(8), 58-62. 1967.

Justin, J. D. "Derivation of run-off from rainfall data." *Transactions of the American Society of Civil Engineers*, 77, 346-384. 1914.

Kaufman, H. L. and Lai, F. H. *Conventional and Advanced Sewer Design Concepts for Dual Purpose Flood and Pollution Control - A Preliminary Case Study, Elizabeth, NJ*. Rep. No. EPA-600/2-78-90 (NTIS PB 285 663), U.S. Environmental Protection Agency, Cincinnati, Ohio. 1978.

Kibler, D. F., ed. *Urban stormwater hydrology*. Water Resources Monograph 7, American Geophysical Union, Washington, DC. 1982.

Kirby, R. S. and Laurson, P. G. *The early years of modern civil engineering*. Yale University Press, New Haven, CT, 227-239. 1932.

Kirby, R. S., Withington, S., Darling, A. B., and Kilgour, F. G. *Engineering in history*. Originally published in 1956, Dover Publications, Inc., New York, NY. 1990.

Kuichling, E. "The relation between the rainfall and the discharge of sewers in populous districts." *Transactions of the American Society of Civil Engineers*, 20, 1-60. 1889.

Linsley, R. K. and Ackerman, W. C. "Method of predicting the runoff from rainfall." *Transactions of the American Society of Civil Engineers*, 107, 825-846. 1942.

Maner, A. W. "Public works in ancient Mesopotamia." *Civil Engineering*, 36(7), 50-51. 1966.

May R.W. P. (1995): Development of design methodology for self-cleansing sewers. *Proc. Int. Conf. Sewer Solids*. Dundee, Scotland. Sept. 1995. *Wat.Sci.Tech.* 1996.

Mays, L. W. and Yen, B. C. "Optimal cost design of branched sewer systems." *Water Resources Research*, 11(1), 37. 1975.

McMath, R. E. "Determination of the size of sewers." *Transactions of the American Society of Civil Engineers*, 16, 179-190. 1887.

Metcalf & Eddy Engineers, University of Florida, and Water Resources Engineers, Inc. "Storm water management model, volume I - Final report." *Report No. 11024EQG03/71*, U.S. Environmental Protection Agency (EPA), Washington, D.C. 1971.

Metcalf, L. and Eddy, H. P. *American sewerage practice, volume I: Design of sewers*. McGraw-Hill Book Company, Inc., New York, NY, 1-33. 1928.

Mulvaney, T. J. "On the use of self-registering rain and flood gages, in making observations of the relation of rainfall and flood discharges in a given catchment." *Proceedings of the Institute of Civil Engineers of Ireland*, 4, 18-31. 1851.

Mumford, L. *The city in history: Its origins, its transformations, and its prospects*. Harcourt, Brace & World, New York, NY. 1961.

McPherson, M. B. "Translation of research results to users." *Urban Runoff Quantity and Quality, Conference Proceedings*, August 11-16, 1974, New Hampshire, ASCE, New York, NY, 4-8. 1975.

McPherson, M. B. "Urban runoff planning and control." *EPA-600/9-78-035*, U.S. Environmental Protection Agency (EPA), Washington, D.C. 1978.

Odell, F. S. "The sewerage of Memphis." *Transactions of the American Society of Civil Engineers*, 10, 23-52. 1881.

Personal Bibliographic Software, Inc. *ProCite for Windows, Version 3.0*, Ann Arbor, MI. 1995.

Petroff, R.G. "An analysis of the root causes of SSOs." In: *National Conference on Sanitary Sewer Overflows (SSOs).* EPA/625/R-96/007. U.S. Environmental Protection Agency. Office of Water. Washington, D.C. 1996.

Pettis, C. R. "Appraisal of unit-graph method of flood estimation." *Civil Engineering*, 8(2), 114-115. 1938.

Pitt, R.E. and Bozeman, M. "Sources of urban runoff pollution and its effects on an urban creek." *EPA-600/S2-82-090*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1982.

Pitt, R., M. Lilburn, S. Nix, S.R. Durrans, S. Burian, J. Voorhees, and J. Martinson *Guidance Manual for Integrated Wet Weather Flow (WWF) Collection and Treatment Systems for Newly Urbanized Areas (New WWF Systems).* U.S. Environmental Protection Agency. 612 pgs. 1997.

Porcella, D. B. and Sorenson, D. L. "Characteristics of nonpoint source urban runoff and its effects on stream ecosystems." *EPA-600/3-80-032*, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency (EPA), Corvallis, OR. 1980.

Preul, H.C. "Combined sewage prevention system (CSCP) for domestic wastewater control." Presented at the *7th International Conference on Urban Storm Drainage*, Hannover, Germany, 1996. pp. 193 – 198. 1996.

Rafter, G. W. "The relation between rainfall and run-off." *Water Supply Paper No. 80*, U.S. Geological Survey. 1903.

Rao, R. A., Delleur, J. W., and Sarma, P. B. S. "Conceptual hydrologic models for urbanizing areas." *Journal of the Hydraulics Division*, ASCE, 98(7), 1205-1220. 1972.

Reid, D. *Paris sewers and sewermen*. Harvard University Press, Cambridge, MA. 1991.

Reyburn, W. *Flushed with Pride, the Story of Thomas Crapper*. Pavilion Books, Ltd. London. 1989.

Sherman, L. K. "Streamflow from rainfall by unit-graph method." *Engineering News - Record*, 108, 501-505. 1932.

Snyder, F. F. "Synthetic unit-graphs." *Transactions, American Geophysical Union*, 725-738. 1938.

Sonnen, M. *Abatement of Deposition and Scours in Sewers*. Rep. No. EPA/6002-77-212 (NTIS PB 276 585), U.S. Environmental Protection Agency, Cincinnati, Ohio. 1977.

Tang, W. H., Mays, L. W., and Yen, B. C. "Optimal risk-based design of storm sewer networks." *Journal of the Environmental Engineering Division*, ASCE, 101(3), 381-398. 1975.

Tarr, J. A. and McMichael, F. C. "Historic turning points in municipal water supply and wastewater disposal, 1850-1932." *Civil Engineering*, ASCE, October, 82-86. 1977.

Viessman, W., Jr. "Runoff estimation for very small drainage areas." *Water Resources Research*, 4(1), 87-93. 1968.

Waring, G. E. "Separate systems of sewerage." *Atlantic Monthly*, 61, July 1879.

Webster, C. "The sewers of Mohenjo-Daro." *Journal Water Pollution Control Federation*, 34(2), 116-123. 1962.

Webster, G. S. "Municipal engineering." *Transactions of the American Society of Civil Engineers*, 84, 516-526. 1921.

Whipple, G. C. , *et al.* "Discussion on the advances in sewage disposal." *Transactions of the American Society of Civil Engineers*, 57, 91-140. 1906.