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THE HISTORICAL DEVELOPMENT OF WET-WEATHER FLOW MANAGEMENT

By

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Abstract: The management of wet-weather flow (WWF) is necessary to maintain the quality of urban water resources. Throughout history strategies were implemented to control WWF for many reasons, e.g., flood and water quality control, aesthetic improvement, waste removal, and others. A comprehensive literature review has been conducted to determine past strategies and to revisit the historical developments of WWF management. Understanding these past strategies and the development of WWF-management systems over time will aid current and future generations in their WWF-management efforts. This paper summarizes the historical literature review, highlighting the development of WWF management from ancient times to the present. The relationship between past developments, the current state, and the future of WWF management is addressed by identifying several lessons learned.

(**Key Words:** wet-weather flow, stormwater management, urban runoff, history, sewers)

INTRODUCTION

The management of wet-weather flow (WWF) 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. Some devised successful strategies to mitigate flooding and remove sanitary wastes, and constructed drainage appurtenances, e.g., open channels and pipes that remain relatively intact today. Other civilizations inadequately addressed drainage concerns and in several instances experienced flooding and nuisance conditions that eventually contributed to their demise. Throughout history many decisions and technological advancements contributed to the development of WWF management.

By studying the WWF-management strategies of the past, lessons can be learned to enhance future strategies. However, to uncover past strategies a thorough search must be conducted. One aspect of a project, sponsored by the U.S. Environmental Protection Agency (EPA), to develop a guidance manual for the design of WWF-management systems in newly urbanizing areas

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involved such a literature review. The initial literature searched included historical books and papers pertaining to ancient and medieval drainage practices. The purpose of this part of the literature review was to develop an understanding of the past strategies utilized in WWF management. The second part of the review entailed an extensive inspection of technical material published between 1850 and the present, including journals, books, reports, government documents, and other print media. The purpose here was to trace the development of modern WWF management, possibly uncovering discarded or, at the time, impractical concepts or practices that could be applicable today.

The goals of this paper are: (1) to summarize the findings of the literature review, and (2) to address the relationship between past strategies, the current state, and the future of WWF management. The extent of the literature prohibits an exhaustive summary, but the major highlights are discussed. The next section describes the procedures used during the literature review and the extent of the review itself. The following four sections discuss highlights in the development of WWF management for: (1) ancient times, (2) post-Roman era to the eighteenth century, (3) the nineteenth century, and (4) the twentieth century. After summarizing the literature several lessons learned from past WWF-management practices are presented. The paper concludes with an evaluation of the future direction of WWF management and how it relates to past developments.

METHODOLOGY AND SUMMARY STATISTICS

Literature reviewed included technical journals, books, reports, conference proceedings, dissertations, and other forms of print. The early work concentrated predominantly on United States (as opposed to international) sources since this literature was more easily obtainable. Future work will address the foreign literature more substantially. All relevant references were recorded into ProCite (Personal Bibliographic Software, Inc. 1995), a bibliographic software application, for future review. The ProCite database contained over 4,000 references at the time this paper was written and is continually being updated. The chronological breakdown of the references is shown in Table 1. Articles related to sewerage first appeared in the United States literature towards the end of the 1860s. Tarr *et al.*, (1984) stated that nine works on sewerage and two on drainage were seen in the popular literature between 1865 and 1875, but none were published between 1850 and 1865.

More recently, over 90% have been published since 1970, with nearly 41% from the current decade. The high quantity of recent references is attributable to three reasons: (1) the more recent literature is the easiest to locate, (2) there has been an enormous increase in the number of people publishing technical literature and publications in which to disseminate the work, and (3) more attention and research funding has been directed towards WWF management in recent times.

Of the more than 4,000 references over 2,000 are journal papers, 380 are EPA reports, and 30 are U.S. Geological Survey (USGS) reports. EPA and USGS are the largest governmental agency contributors, with the remaining 250 plus reports being distributed among many state and local entities. The remainder of the database contains more than 1,200 conference papers and 150 theses and dissertations.

WWF MANAGEMENT: ANCIENT TIMES

Several ancient civilizations constructed successful surface-water-drainage systems. In addition, some civilizations incorporated the removal of sanitary wastes into the surface-runoff system to form a combined system of sewerage. The Indus civilization of circa 3000 BC presents one example of a sewerage system ahead of its time (Webster 1962). The dwellers of the city of Mohenjo-Daro (now part of West Pakistan) used a simple sanitary-sewer system and had drains to remove stormwater from the streets. The ruins of this ancient system illustrate the care taken 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-wastewater flows, while the remaining capacity of the channel was available for WWF (Webster 1962). The masonry work and clever design of the storm-drain system show that in some instances, much more care was taken with sewerage than with some of the buildings.

The Mesopotamian Empire exemplified by Assyria and Babylonia marked great advances in civilization. The ruins of cities in ancient Mesopotamia, Ur and Babylon for example (Jones 1967; Maner 1966), include their sanitary- and storm-drainage systems, and display an advanced-technical knowledge. As early as 2500 BC, Mesopotamian engineers planned and built effective drainage and sanitary works, including vaulted sewers and drains for household wastes, gutters 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 BC. The ruins of Knossus, 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 and pipes, which carried sanitary wastewater, roof runoff, and surface runoff (Gray 1940). The expertise in drainage and sanitary engineering displayed by the Minoans far surpassed that of the contemporary Greek, Egyptian, and Chaldean civilizations. The drains emptied into a main sewer that disposed of the combined wastewater a considerable distance from its origin. The frequent and torrential rains in Crete resulted in excellent flushing of the system (Kirby *et al.,* 1990). In addition to the removal of stormwater and sanitary wastes, the Minoans also devised ways to collect rainwater and keep it pure for later use.

The ancient city of Jerusalem displayed isolated instances of WWF management. Ruins dating to about 1000 BC indicate that a separate system of sewerage was used in regions of the city (Hodge 1992). One conveyance structure was used exclusively for street drainage and household wastewater, while the other was specifically connected to sanitary waste sources. However, the majority of the city made no provision for disposal of sanitary wastes nor stormwater, only constructing occasional gutters and channels in the roadway, probably in response to flooding problems.

The Etruscan civilization built some of the first organized cities in central Italy around 600 BC (Scullard 1967). Marzobotto, one of the more important Etruscan cities, had a skillfully designed drainage system making use of the natural slope to keep the city dry. In addition, paved streets and stepping-stones in the roadways acted as protection for pedestrians against stormwater runoff (Strong 1968).

Some ancient Far Eastern civilizations used drainage and sanitary engineering practices in their management of WWF. Ruins in a few major cities in China indicate that a partially underground sewer system was constructed around 200 AD (Needham *et al.,* 1971). Archaeologists conjecture that the system was primarily used for stormwater removal. The Chinese also constructed the roofs of buildings with overhanging eaves to help collect rainfall. In addition, rainfall that was not collected was routed by the eaves away from the structure to prevent flooding damage (Needham *et al.,* 1971).

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, with raised sidewalks and stepping-stones at street crossings to protect pedestrians against stormwater and overflow from the aqueducts. When the Romans came to power they rebuilt the Etruscan sewers and streets. Virtually all that the early Romans knew about engineering was adapted from the Etruscans and other civilizations of the eastern Mediterranean (Kirby *et al.,* 1990).

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 a ditch. To improve drainage, the roads were graded to direct the surface runoff from the streets toward the drainage channels. The roads were not the only engineering structures designed for drainage control. Typically the disposal of rainwater depended on where it fell. For instance, if it fell on a house the roof funneled the rainwater into an interior cistern (Hodge 1992). Therefore, a great deal of the rain falling on a Roman town was never drained away.

The drainage of surface runoff and the disposal of excess water from the aqueducts were the primary functions of the sewer system. However, sanitary wastes and garbage were also deposited in the channels, which relied on cloudbursts to adequately flush them, since overflows from aqueducts were not sufficient. During periods of dry weather, the wastes accumulated and caused unsanitary conditions. As a result the channels were covered, eventually evolving into combined-sewer systems.

The Romans first planned and constructed their *cloacae*, or underground sewers, to drain their uplands to the nearby network of low-lying streams (Gest 1963). These sewers developed from open channels that drained most of the land prior to urbanization. Their philosophy was to use the existing natural drainage channels to remove WWF. The city was built over the channels and drains were provided from the surface to the underground streams. As time progressed, the Romans constructed more elaborate sewer systems displayed by their ornate inlet and drain coverings (Gest 1963).

The Roman sewers became a source of civic pride. They viewed the large-pipe, combined wastewater system as symbolic of their advanced civilization, and in the 1800s some French and English engineers tried to instill similar pride in residents during the effort to improve WWF-management systems (Hodge 1992). Although the Roman sewers were successful in their function and well constructed, they were constructed in an iterative, trial-and-error process and therefore did not epitomize the ideal sewer-design strategy.

Other ancient civilizations besides those detailed above implemented successful WWF-management systems, but space does not permit a thorough discussion here. These civilizations included the Greeks, represented by the advanced culture in Athens, the Macedonians and Greeks together under the rule of Alexander the Great (Kirby *et al.,* 1990), and the Persians to mention a few. Mumford (1961) best described the sewer systems of ancient civilizations when he observed that they were an “uneconomic combination of refined technical devices and primitive social planning”. Therefore, although successful systems had been constructed, the pinnacle of WWF management was not yet attained. The next section reviews WWF-management strategies in Europe from the fall of the Roman Empire until the late 1700s.

WWF MANAGEMENT: POST-ROMAN ERA TO THE 1700s

From the time of the Roman Empire through the 1700s European WWF-management strategies experienced little noteworthy advancement, and even regressed considerably in terms of sanitation. Several reasons have been suggested for this phenomenon. After the fall of the Roman Empire, cities experienced a significant decrease in size and population (Bishop 1968). With the shrinkage came the abandonment of municipal services - street lighting, running water, and sewer systems. In addition, during the so-called "Dark Ages" following the fall of the Roman Empire, society was observed to be indifferent and habitual in many respects (Bishop 1968). For instance, hygiene and cleanliness were completely ignored by most citizens due to their indifference. This indifference was also directed towards sanitary improvements. Several other theories and ideas have been put forth describing why the Dark Ages occurred and why sanitation suffered, but space does not permit a thorough discussion.

During the Middle Ages drainage and sanitary services were developed in response to nuisance conditions and disease outbreaks, which resulted in disjointed WWF-management systems. Paris and London exemplify European cities that developed piecemeal drainage systems in response to sanitary crises and funding availability. In general, the development of WWF-management systems from inadequate to adequate occurred in Europe during the time period dating from approximately 1300 (when planned ditches were again extensively used for the first time since the Roman era to convey drainage waters) to the 1800s (the advent of modern engineering drainage design).

The sewers implemented in Europe during this period were simply open ditches. Examples of this type of sewerage system were evident in London, Paris, and other cities during the 1300s and 1400s (Kirby and Laurson 1932). The open channels 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 drainage channels became receptacles for trash, kitchen wastes, and sanitary wastes, the accumulation of which caused a nuisance. As a remedy, Europeans covered the drainage channels, creating combined sewers. Interestingly, this solution is similar to that used 1500 years earlier by the Romans during the initial construction of their sewers. Apparently, a common strategy was to mitigate a sanitation problem by removing it from sight, which unfortunately is often the case today.

In Paris, the first planned covered sewer dates back to 1370 when Hugues Aubriot constructed the Fosse de St. Opportune (Reid 1991). This sewer, known as the "beltway sewer," discharged into the Seine River and acted as a collector for the sewers on one side of the Seine. However, the covered sewer concept was not instituted immediately throughout Europe. For instance, London did not construct a planned covered sewer until the 1600s and other areas of Paris continued to rely on open sewers well into the 1700s (Kirby and Laurson 1932).

The early covered sewers had many problems due to insufficient maintenance. During periods of dry weather, the sanitary wastewater remained stagnant because of inadequate slopes that allowed solids to settle in the sewer system, producing odors and causing repeated blockages. Maintenance problems notwithstanding, the municipal authorities continued to cover sewers in the major European cities, which compounded the problem. One solution in Paris during the 1700s was to build magnificent underground sewers for the drainage of stormwater. These sewers provided enough space for the necessary maintenance by sewer workers, but proved uneconomical for conveyance of only WWF.

For the most part, construction of sewer systems up to the 1700s lacked proper engineering design and was conducted in piecemeal fashion. In addition to the inadequate design and construction practices, maintenance and proper operation of the systems were virtually neglected. In sum, many of the sewer systems of European urban areas during the 1600s and 1700s were grossly under-planned, poorly constructed, and inadequately maintained by today's standards, resulting in poorly functioning systems with repeated blockages and frequent nuisance conditions.

WWF MANAGEMENT: 1800s

At the end of the 1700s the WWF-management outlook in Europe was improving. Society held a belief in progress, which became increasingly linked to technology throughout the 1800s (Tarr *et al.,* 1984). The early part of the 1800s was marked by a series of improvements, decisions, and technical advances related to WWF management that helped to direct its development. As a result of increased congestion and the advent of piped-in water supplies, the European and the United States privy vault-cesspool system for waste disposal became overwhelmed. Consequently, by the end of the century there was a growing public demand to replace privy vault-cesspool systems with centralized wastewater systems (Melosi 1996). The following sub-sections, complemented by Figure 1, highlight the development of modern WWF management in Europe and the United States

Improvements in Sewer Design and Construction Practices

Until the 1820s in Paris and elsewhere in Europe, sewers were constructed of cut stone or brick with rectangular or roughly rounded bases, which contributed to deposition problems (Reid 1991). Engineers substituted mill stone and cement mortar for the cut stone allowing for easier construction of curved and smooth sewer floors. This reduced the flushing effort required for sewer cleansing and improved the hydraulic efficiency of the sewer. Due to the improved construction materials a variety of new pipe shapes developed for combined-sewer systems, including egg-shaped, oval, and v-notched patterns. Studies in England indicated that the lower parts of these channel sections could carry sanitary waste well while the upper portion could provide sufficient capacity to transport stormwater (Gayman 1997). The use of concrete in the late 1800s marked the final major improvement to sewer materials in the 1800s (Metcalf and Eddy 1928). The improvement of pipe materials spawned a debate in Europe over the use of traditional large-diameter brick sewers versus the new smaller-diameter clay pipes (Rawlinson 1852).

Another problem with sewers was the grade at which they were constructed. Often, caution was exercised neither during design nor construction and the sewers did not have a sufficient slope to transport wastewater during dry-weather periods. Engineers realized in the middle 1800s that the slope of the sewers needed to be adequate for conveyance of dry-weather flow (DWF), or an effective flushing mechanism was required. This understanding resulted in improved designs and subsequent performance of sewer systems in the late 1800s.

Minimum velocity standards were instituted in most of Europe during the middle 1800s. For example, a 0.6 to 0.9 m/sec (2 to 3 ft/sec) minimum-velocity standard was established in London during the 1840s (Metcalf and Eddy 1928). The minimum velocity was based on deposition tests of sand and other materials from running water. These tests indicated that velocities of 0.6 m/sec (2 ft/sec) would entrain solids in a sanitary sewer, but that a velocity of 0.9 m/sec (3ft/sec) was needed to prevent deposition of sand, gravel, and debris washed into a combined system.

Comprehensive Sewer-System Design

Sewer-system-design strategy was the focus of another series of innovations in WWF management. Hamburg, in 1843, implemented the first comprehensively planned-sewerage system for a major city (Metcalf and Eddy 1928). The circumstances were advantageous since in 1842 a large part of the city had been destroyed by conflagration. William Lindley, an Englishman residing in Hamburg, was commissioned to plan and design the system. The system was not planned solely for the proposed sanitary benefits but also took advantage of exceptional local conditions to plan streets and sewers to meet other concerns of the community, e.g., costs (Metcalf and Eddy 1928). Therefore, then, as today, economics ultimately influenced civil-infrastructure design.

London followed Hamburg's success with a detailed study, resulting in the decision to devise a comprehensive plan of sewerage. Joseph 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 completed in 1865. Features of this ambitious enterprise were the early experiments with rainfall calculations and a version of cement. Meanwhile, until 1823 the sewers of Paris were being constructed without any coordinated plan. At this time, construction practices improved, which allowed engineers 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).

In the United States, E. Sylvester Chesbrough designed the first comprehensive WWF-management system for the city of Chicago in 1858 (Cain 1972). Not only did Chesbrough's report incorporate ideas from solicited public proposals, but also made several references to the sewer systems of New York, Boston, Philadelphia, London, and Paris. About the same time, Julius W. Adams designed a comprehensive sewer system for Brooklyn (Adams 1880). These systems were successful, but extensive construction of municipal sewers did not commence until the 1880s. Many other engineers made significant contributions to American sewerage design, but Adams was probably the most influential 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).

The comprehensive designs implemented in the United States often made use of empirical data obtained from European practice (Webster 1921). This contributed to deficiencies in the designs because of the climatologic and topographic differences between parts of the United States and Europe. Despite this use of empirical data in design, American sewerage developed many of its features predominantly through experience, rather than experiment (Metcalf and Eddy 1928).

Combined- Versus Separate-Sewer Systems

Although sanitary wastes were a constant input to European sewer systems, designs did not anticipate this component until 1843 in Hamburg. The first types of wastewater legally allowed into the storm sewers were dishwater and other kitchen wastes. When the water closet came into general use in the middle 1800s existing privy vaults and cesspools became overwhelmed. Eventually, this led to the permitted discharge of sanitary wastes into the sewers previously restricted to surface runoff only, legally creating combined wastewater. The permitted discharge of sanitary wastes did not occur in London until 1847 (Kirby and Laurson 1932) or in Paris until 1880 (Reid 1991).

The United States was rapidly urbanizing during the 1800s. In 1840 only 11% of all Americans lived in urban areas, but by 1860 the percentage increased to 20% and by 1880 had risen to 28% (Tarr and McMichael 1977). As in Europe, water-supply systems and the use of the water closet increased the consumption of water and consequently increased the quantity of wastewater, which eventually overwhelmed the privy vault-cesspool system. City councils, sanitary engineers, and health groups agreed, although not without dissent, that water-carriage systems of sewerage provided the most benefits and the lowest costs compared to other disposal options.

The question then became which type of sewerage should be constructed: separate or combined. Tarr (1979) addressed this question in detail, elucidating several of the key people and decisions that influenced the choice of implementing separate or combined sewers. Tarr (1979) iterated that the primary difficulty in deciding between separate and combined sewers was the "newness" of comprehensive systems. Consequently, practitioners had yet to agree on basic criteria, including such issues as removal of stormwater, disposal and treatment of wastewater, and potential sanitary benefits of the respective systems.

The combined-sewerage scheme became widely implemented, in spite of opponents who thought it sensible to keep sanitary wastes and stormwater separate. Edwin Chadwick and John Phillips, both from England, were two early proponents of the separate system of sewerage. Phillips proposed the separate system for London in 1849, but a few years later Bazalgette's combined system was selected (Metcalf and Eddy 1928). Although supporters for separate sewerage existed, early systems were mostly combined because: (1) there was no European precedent for successful separate systems, (2) there was a belief that combined systems were cheaper to build than a complete separate system, and (3) engineers were not convinced that agricultural use of separate-sanitary wastewater was viable (Tarr 1979).

Bourne (1866) made one of the first American arguments for separate sewerage. He advocated the separate system for reasons of sanitation. Another adamant supporter of separate-sewer systems in the United States was Colonel George E. Waring, Jr. (Waring 1879). He constructed the first separate-sewer system in the United States for the small Massachusetts community of Lenox (Tarr 1979). Waring argued that the separate system was better because it could transport sanitary wastes faster, a characteristic he deemed important to prevent the release of "objectionable gases" that he and other anticontagionists considered the cause of diseases.

Waring designed several other separate systems, including one for the city of Memphis, Tennessee in 1880 after yellow fever had ravaged the city in previous years (Odell 1881). The Memphis system was credited with dramatically improving the sanitary conditions and reducing the incidence of yellow fever in the city, which helped promote Waring's system (Tarr 1979). However, in general, some of the separate systems performed adequately, but others failed with repeated blockages and backups in the sanitary lines. Even the Memphis system was later determined to have been a relative failure due to repeated blockages and flooding, which required costly retrofits to correct (Hering 1887).

Rudolph Hering, an American engineer, visited Europe in 1880 at the behest of the U.S. National Board of Health to investigate European sewerage practices. In his report he suggested a model for the choice between combined and separate systems (Hering 1881). Hering's model recommended 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. Ultimately Hering concluded that neither system had sanitary advantages, therefore the final decision should hinge on local conditions and financial considerations.

Despite Hering's report and the support of many engineers and sanitarians, the debate continued for several years between the advocates of the two types of sewerage (Tarr 1979). But by the end of the century engineering practitioners embraced Hering's ideas and combined-sewer systems were recommended for most urban areas. This philosophy did not waver until more wastewater treatment was required and costs correspondingly increased. This resulted in the transfer from recommending combined sewers to separate sewers as the system of choice for urban areas in the 1930s and 1940s (Hey and Waggy 1979).

Identification of Waterborne Diseases

Several individuals through history have conjectured that wastes and unsanitary living conditions were linked to diseases (Tarr and McMichael 1977). However, due to the limited knowledge of bacteriology it was difficult to scientifically validate their beliefs. During the early and middle 1800s the concepts of bacteriology became better understood and scientific evidence started to demonstrate a link between wastewater discharges, polluted-receiving waters, and disease outbreaks. The key factor was the new knowledge that had come from the works of Louis Pasteur, Robert Koch, Robert Warington, and others into the nature and activities of bacteria.

A publication by Dr. John Snow in 1849 discussed the communication of cholera by contaminated water. In 1854, he also helped identify the source of the Broad Street cholera epidemic in London. William Budd's studies of typhoid fever in the 1850s marked another landmark development in the epidemiology of waterborne disease (Dworsky and Berger 1979). 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 this theory was firmly established by Koch and others. This time period, appropriately labeled the Great Sanitary Awakening, led to filtration of drinking water to prevent waterborne 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 under the direction of William T. Sedgwick identified the relationship between typhoid fever and wastewater-polluted waterways (Tarr and McMichael 1977). These studies and others raised serious questions about the safety of discharging wastewater directly into receiving waters, especially those that were used as a drinking water source.

Treatment of Wastewater

Regardless of the type of sewerage (combined or separate), the control and treatment of discharges was very limited during the 1800s. Typically, combined and sanitary wastewater and stormwater were simply discharged into a stream or river of adequate capacity to dilute the waste (an average of 0.17 m^3/sec (6 ft^3/sec) stream flow per 1,000 persons (Fair and Geyer, 1954)). The sewerage systems were designed to discharge the maximum amount that the receiving water system could dilute. The locations of the discharge points were planned to accommodate the dilution capability of the receiving water body.

In the late 1800s, wastewater was treated primarily by three methods: land application and irrigation of farmlands (wastewater farming), filtration, or chemical precipitation (Whipple *et al.,* 1906; Tarr and McMichael 1977). These treatment types were more conducive to the smaller and more easily controlled separate-sanitary-wastewater flows. Although numerous sewer systems were constructed in the late 1800s, the use of centralized municipal wastewater treatment facilities was still in its infancy. By 1892, the United States had only 27 cities with wastewater treatment works (21 used land application methods and 6 used chemical precipitation) (Tarr 1979). Of these 27 cities, 26 had separate-sewer systems, which indicated a lack of treatment for combined wastewater.

Whipple *et al.,* (1906) discussed the combined-wastewater-treatment options in the United States at the beginning of the 1900s. The usual method instituted for combined systems entailed sending as much of the storm-flow/sanitary wastewater mixture to a dry-weather-wastewater treatment plant, if one existed, by way of an intercepting sewer. The plant capacity and interceptor size were the limiting design factors for this action. The WWF that could not be transported via the interceptor was discharged directly into the adjacent receiving water through constructed storm-overflow devices, creating combined-sewer overflows (CSO). Treatment plants and collection systems were typically designed to treat twice or more the mean daily DWF (Whipple *et al.,* 1906). During wet weather, flows were observed to increase in sewer systems by a factor of one hundred over DWF. However, economic limitations constrained the design capacity of combined sewers below what was needed for these extreme events.

Although research uncovered the connection between polluted waters and disease, wastewater treatment was not widely practiced. The debate centered on whether it was more economical to treat the wastewater prior to discharge or treat the water source before distribution as potable water. Most sanitary engineers subscribed to the editorial stance taken by the *Engineering Record* in 1903 (Tarr *et al.,* 1984):

> "… it is often more equitable to all concerned for an upper riparian city to discharge its sewage into a stream and a lower riparian city to filter the water of the same stream for a domestic supply, than for the former city to be forced to put in wastewater treatment works."

Sanitary engineer Allen Hazen supported this concept and added that wastewater purification was only required to prevent nuisance conditions in the receiving water (Hazen 1907). Although most sanitary engineers supported this position well into the 1900s, it is now known that the dilution theory ignored impacts to the recreational uses and the habitat of the receiving water.

Urban Hydrology

In the middle 1800s, the estimation of surface runoff in urban areas was based on empirical results. For example, much of the European engineering community used Roe's Table to size sewer pipes (Metcalf and Eddy 1928). The table was supposedly empirically derived from Roe's observations of London sewers in the Holborn and Finsbury districts over a span of 20 years. It tabulated the catchment areas that could be drained by sewers of various sizes on various slopes, as indicated by his experience. Several other equations and tables similar to Roe's were developed during the same time period for specific locations.

In the second half of the 1800s the hydrologic- and hydraulic-design methods used to size sewers were enhanced. The most notable of these was the rational method developed by Mulvaney (1851) and introduced to the United States by Kuichling (1889). The rational method was based on the assumption that a realistic flow of the chosen frequency was obtainable if the rainfall intensity of duration similar to the travel time of water from the farthest ridge line (time of concentration) in the sewer system was applied to the drainage catchment. The calculated flow was subsequently used to select the size (as a function of slope) of the sewer pipes.

Prior to the rational method, runoff determinations took the form of empirical equations. Most of these equations 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 were attributed to Adams, McMath, Parmley, Gregory, Burkli and Zeigler, and Hawksley (Adams 1880; McMath 1887; Buerger 1915). These equations were 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 United States during the second half of the 1800s (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-drainage design. Talbot, in 1899, performed some of the initial work, using U.S. Weather Bureau records at 499 stations to plot storm intensities versus duration on a cross-section paper. Two curves were drawn, one depicting the very rare rainfalls, and the other displayed ordinary rainfalls. These curves became the forerunner of the present day intensity-duration-frequency (IDF) curves for drainage design. Since Talbot constructed his curves, many cities, public agencies, and engineering firms have developed similar curves and equations for specific locations (Berwick *et al.,* 1980).

WWF MANAGEMENT: 1900s

Urban Hydrology Continued

As stated in the previous section, the design of sewer systems in the 1800s usually involved the use of an empirical equation to determine the sizes of the required pipes. The engineering community did not accept the rational method immediately after its introduction in the late 1800s. In fact, well into the 1900s the older empirical equations 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 United States and worldwide.

In the early 1900s there were several attempts to describe the rainfall-runoff process more accurately (Rafter 1903; Gregory 1907; Buerger 1915; Grunsky 1922). Prior to this time, drainage-design equations had not considered the rainfall-runoff process in detail; instead empirical relationships were used which related pipe size to watershed characteristics based on observed data (Roe's Table or Hawksley's formula, for instance). By the 1920s the accumulation of raingage records enabled "design storms" to be used, in which rainfall intensity rose to a peak and then died away. The identification of design storms led to the use of runoff hydrographs as design runoff events.

The unit hydrograph (UH) concept is an example of a procedure involving runoff hydrographs. Sherman (1932) developed the UH concept 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 UHs for many drainage basins. To solve this problem, others developed methods to utilize the UH principles on ungaged watersheds. These derivations of the synthetic UH were 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 (1962), Eagleson and March (1965), Viessman (1968), and Roa *et al.*, (1972).

After the UH concept was initially introduced in the early 1930s the study of the rainfall-runoff process intensified. Rainfall abstractions including interception (Horton 1919) and infiltration became the focus of several researchers. The work of Green and Ampt (1911) and Horton (1933), in particular, defined the concept of infiltration in relation to rainfall and runoff. This pioneering work was later incorporated into deterministic models of the rainfall-runoff process.

Economical and adequate design of WWF-management systems was possible only with the knowledge of the magnitude and timing of the expected peak flow. The proper sizing of more complex systems and the testing of the capacity of existing systems required a knowledge of the time-history of flow in the sewers (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 (Eagleson 1962). They considered the variability of rainfall both spatially and temporally in their design method.

Building on the UH techniques of the middle 1900s, the U.S. Department of Agriculture Soil Conservation Service (SCS) published a simple, effective method to determine runoff from rainfall, the well-known Technical Release No. 20 (TR-20) (SCS 1982). TR-20 used hydrologic soil-cover complexes to determine runoff volumes and a UH to determine peak rates of discharge for single event simulations. In 1986 SCS published Technical Release No. 55, *Hydrology of Small Urban Watersheds* (TR-55) (SCS 1986), which detailed a tabular and graphical method for determining runoff. TR-55 and the rational method continue to be very popular methods to determine runoff characteristics from small watersheds.

Technical Tools and Design Methods

In the late 1960s and early 1970s advancements in computer technology had a significant impact on the development of WWF management. The use of computers ranged from simple calculations to complex modeling approaches, e.g., the Urban Runoff: Storage, Treatment, and Overflow Model (STORM) (HEC 1973) and the Storm Water Management Model (SWMM) (Metcalf & Eddy Engineers *et al.*, 1971). SWMM could simulate flow and pollutants through complex urban watersheds, while STORM offered a tool to analyze several urban stormwater runoff control alternatives. Although computer models were introduced in the 1970s, the rational method remained the most popular technique for estimating design flows in urban drainage design. However, the use of the rational method was shown in the 1960s and 1970s to result in over-design of drainage structures, which is unacceptable given the high cost of urban drainage control. The advent of the computer provided engineers the opportunity to design drainage systems using continuous simulation, which was determined to be the most satisfactory method for urban drainage design (Linsley and Crawford 1974; McPherson 1978; James and Robinson 1982). Continuous simulation using both STORM and SWMM was applied extensively in the analysis of WWF-control alternatives (Heaney *et al.*, 1977).

In addition to computers, advanced mathematical and statistical techniques were directly applied to WWF management. Mathematical optimization methods, e.g., linear programming (Dendrou *et al.*, 1978) and dynamic programming (Tang *et al.*, 1975; Mays and Yen 1975) were utilized in the 1970s to find cost minimized designs of WWF-management systems. Statistical methods were also used in the planning and design of WWF-management systems, specifically to analyze long-term simulation results; rainfall, runoff, and water quality data; and urban runoff control system configurations (Howard 1976; Di Toro and Small 1979; Hydroscience, Inc.

1979). There are numerous other applications of mathematical and statistical techniques in WWF management, but space limits this discussion to those mentioned above.

Most of the technology essential for WWF management was introduced before the late 1980s. Several methods existed to plan, design, construct, maintain, and rehabilitate WWF-management systems. But all facets of the technology had room for improvement and innovation. Much of the work in the 1980s centered on the improvement of the technology and ideas initially introduced in the previous two decades. For example, the advancement of the personal computer resulted in the application of computer methods to perform functions that had been previously accomplished without computers. In a short period of time, the personal computer advanced to the state that adequate design of WWF-management systems hinged on its use. This is evident today by the importance given to results from computer models.

Computational aids, e.g., geographical-information systems (GIS), spreadsheets, databases, and model pre- and post-processors have seen many advances during the 1990s. These aids have improved the planning, design, and operation of WWF-management systems significantly. The use of these aids has also made the computer model technology developed in the 1970s and 1980s more "user-friendly", consequently the excuse that computer-based techniques are too esoteric to utilize is no longer valid.

Environmental Awareness and Receiving-Water Impacts

During the 1960s, WWF was identified as a major cause of receiving-water-quality degradation. To mitigate the problem, methods of control and treatment for urban storm-runoff discharge and CSO were devised. Controlling WWF was necessary to reduce the problem and in certain situations was more cost effective than increasing the capacity of wastewater- treatment facilities. WWF management in the 1960s shifted to include water-quality concerns in addition to the traditional quantity concerns. Planning and design philosophies began to promote the preservation of natural-drainage systems and the increased use of storm-runoff-quality controls in addition to traditional flood abatement (Jones 1967).

Interest in reducing receiving-water impacts through control and treatment of WWF led to numerous research projects sponsored by the EPA (and its predecessor agencies) in the 1960s and 1970s (Field and Lager 1975). The main focus of these projects was to evaluate the adverse characteristics and control and treatment alternatives for WWF. The evaluated control and treatment alternatives included physical/chemical, e.g., detention, swirl separation, filtration, screening, and disinfection; biological methods, e.g., rotating biological contactors, contact stabilization, trickling filters, treatment lagoons, and activated sludge; and storage/treatment combination methods (Field and Lager 1975; Lager *et al.,* 1977).

The next step in the 1970s was the attempt to evaluate problems on a larger scale. This was manifested in 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-storm runoff and wastewater discharges on a watershed-wide scale instead of looking at a single outfall or a single stream reach. Unfortunately, the Section 208 studies and implementation projects of the late 1970s resulted in few documented successes.

In the early 1980s, attention concentrated on the relationships between wet-weather discharges and receiving-water impacts. Specifically, data was collected to characterize the pollutants of concern and the impacts they had on receiving waters. One of the major research efforts was the Nationwide Urban Runoff Program (NURP), conducted in the United States predominantly supported by the EPA (EPA 1983). The overall goal of NURP was to collect data and develop information for use by local decision-makers, states, EPA, and other interested parties.

There is abundant description in the literature of the impacts of WWF-induced pollution, and recently descriptions have been in terms of biological or habitat impacts including those by Porcella and Sorenson (1980), Field and Turkeltaub (1981), Pitt and Bozeman (1982), Heaney and Huber (1984), and Herricks (1995). Many of these references indicated a significant impact on receiving waters downstream from urban areas. However, the habitat degradation caused by WWF is often attributable to the synergistic effects of a myriad of waste discharges and modifications to urban streams. For example, habitat improvement will be unlikely if the receiving water system has been modified significantly (channelization projects, removal of debris, and straightening of streams). Consequently, improvement in habitat is usually possible only after addressing all problems contributing to the degradation of habitat. Therefore, documented cases of habitat improvement as a result of only improved or newly constructed WWF-management systems are rare.

WWF MANAGEMENT: LESSONS LEARNED FROM THE PAST

The beginning of this paper indicated that much might be learned from past WWF-management practices. Indeed, the literature review provided helpful insights that will prove useful in developing future WWF-management strategies. Several lessons learned are listed here and then discussed below:

- WWF-management techniques have been developed in response to societal demands or existing problems
- efficient technology transfer is needed
- “user-friendly” design methods and tools are required
- designs must consider political, social, and economic ramifications
- WWF-management systems must be designed for sustainability
- combined-sewer systems are viable WWF-management systems in densely populated areas
- the literature is a valuable resource to engineers

One lesson learned from reviewing the development of WWF management is the propensity of society to demand progress in response to perceived problems. This is seen in other technical fields, but with WWF management it is manifested in cities where both combined sewers and separate sewers were constructed in piecemeal fashion from the late 1800s to the early 1900s. The resulting disjointed systems, and associated problems, were then passed on to future generations. This lack of comprehensive planning, design, and construction caused by public pressure for results must be avoided today and in the future.

McPherson (1975; 1978) voiced concerns over 20 years ago concerning another lesson learned: the importance of reducing the development-to-implementation (technology transfer) time lag. Professional societies have published monographs with the purpose of bridging the gap between research and practice (Kibler 1982). Efforts must continue to insure that developing technology is rapidly disseminated to engineers. The prediction of runoff from a watershed serves as an excellent historical example of the technology transfer time lag. The “formula” methods, e.g., Adams, McMath, Roe, and Burkli-Ziegler, dominated sewer design in the late 1800s and early 1900s throughout Europe and the United States, although the rational method for estimating stormwater runoff had been introduced by Mulvaney (1851) and Kuichling (1889). 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 can be considered the method that engineers are continuing to embrace while new technology is being ignored. 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 considerable judgment." This again is a popular reason expressed today for the lack of application of other techniques, e.g., the UH, physically-based models, and continuous simulation.

The methods and tools that have gained application throughout history were simple to implement and easy to understand, although not necessarily the most accurate or appropriate. Today, "user-friendly" design aids include model pre- and post-processors, GIS, spreadsheets, and other computational tools. The progression of the SWMM model presents an example of "user-friendly" enhancements in WWF management. The addition of GIS capabilities and pre- and post-processors in XP-SWMM (XP Software 1993), PCSWMM '97 (CHI 1997), and the SWMM-Windows Interface (EPA 1997) have aided the user in the modeling process. Judging by the engineering community's tendencies in the past and present, new technology in WWF management must be "user-friendly" and perform the desired task efficiently and effectively for it to be accepted.

The need to consider social, political, and economic ramifications of WWF management is another lesson learned from the past. Throughout history, especially in the 1800s and early 1900s, proponents of sewerage cited the improvements gained socially and economically by installing a sewer system. The engineers in Paris and London in the 1800s pointed to the example of ancient Rome two thousand years earlier as a flourishing civilization due in part to its public works projects, including the sewerage system. This sentiment was again expressed by engineers in the United States in the late 1800s and early 1900s, but this time they pointed to the refined European cities, e.g., Paris and London as examples of the social and economic benefits of sewerage (Schultz and McShane 1977). Today, WWF-management systems remain vital to the social and economic fabric of a community. This is illustrated by continued public demands for flood control and improved water quality in urban areas.

The past literature indicates that a sustainable development will have the benefit of significantly reducing the environmental impacts over time associated with a project, while also promoting economic stability. The literature is replete with examples of entire systems (for example Paris in the Middle Ages and Cincinnati in the 1800s (Schultz and McShane 1977)) or parts of systems that were designed without considering the long-term sustainability of the project. The systems performed poorly and required considerable resources for rehabilitation shortly after completion.

The ancient and recent past indicate that combined-sewer systems (CSS) can be effective WWF-management systems. Of course, most past CSS did not require the treatment of the wastewater prior to discharge to the receiving water, consequently they were much simpler to design and operate. However, today the trend is to design mostly separate-sewer systems in newly-urbanizing areas to solve pollution problems (Carleton, 1990), but unfortunately separate systems are not a panacea. For instance, separate sewer systems also experience such pollution problems as overflows and infiltration/inflow (EPA 1996), and in addition, must conform to regulatory constraints under the NPDES program.

Currently, there is renewed interest in the use of CSS in the United States and elsewhere under specific conditions. The use of CSS (in conjunction with improved treatment facilities) may result in reduced, and more cost effective, WWF control. Carlton (1990) for example, determined the pollution impact of separate-sewer overflows (SSO) in Sydney, Australia are only slightly less than the CSS overflows in Lyon, France. Based on a field study, Kaufman and Lai (1978) concluded that the use of separate sewer systems might not always be the proper sewer system to mitigate WWF pollution. Similarly, Heaney *et al.* (1997) found that CSS may discharge a smaller pollutant load to the receiving water than separate systems in cases where the stormwater is discharged untreated and the sanitary wastewater is well treated. They present an example in southern Germany where CSS are being designed with extensive infiltration components to reduce the inflow of stormwater to the drainage systems, reducing the frequency and magnitude of CSO events. Similar systems are also used in Switzerland and Japan with similar results. In addition to these recent studies, DeFilippi and Shih (1971) concluded, based on a study comparing combined- and separate-sewer discharges, that the implementation of separate-sewer systems can still result in significant pollutant loading to receiving waters.

Proposed construction of new CSS would be very controversial in the United States and it would be very difficult to overcome resistance to their construction. The main areas of resistance relate to the massive efforts in the last several decades in reducing the number and severity of CSO, usually under court order. In addition, current interest and massive correction efforts to control SSO 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 CSS. The political resistance to the construction of new combined sewers in the United States is therefore considered almost insurmountable. Nevertheless, it still may be interesting to list a few considerations for the future use of combined sewers:

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

One final lesson learned in the review of the literature was the value of the literature itself. By spending time reviewing the literature, design engineers will gain valuable insights improving their own designs. Recognizing this, many of today's professional engineering organizations, including the American Society of Civil Engineers and the American Public Works Association, strongly encourage the study of past engineering practices by reviewing the literature.

SUMMARY AND FUTURE OUTLOOK

The purpose of this literature review was to determine past WWF-management strategies and to document the issues, developments, and technological advancements that influenced current strategies. The first part of the paper mentioned several of the ancient civilizations that constructed successful sewer systems. Most of the systems were developed independently and did not influence future designs. But their existence indicates that modern technology and practices were not required to provide adequate WWF management. However, today's systems are far more complex than those required in ancient times. Therefore, the improved technology of today must provide the extra advantages needed to develop WWF-management systems that will meet future needs.

The second part of the paper discussed chronologically some of the issues, developments, and technological advancements that directed the development of modern WWF management. These important points can be grouped into three major categories:

Advances in Design and Construction of Sewer Systems

- Introduction of Comprehensive Sewer-System Design
- Improvements in Pipe Design and Construction Materials
- Combined Versus Separate Sewerage Debate
- Inline versus Off-line Storage

Advances in Tools and Methods used in Design of Sewer Systems

- Urban Hydrology Advances
- Computer Applications

Advances in Environmental Considerations

- Identification of Waterborne Diseases
- Treatment of Sanitary and Combined Wastewater
- Receiving-Water Impacts
- Toxicity and Habitat Impacts
- Legislation

The above list indicates many of the important topics in past WWF-management practices. Although they reflect topics that were important in the past, many are still important in the present and will remain important in the future. In a report titled *Risk Management Research Plan for Wet Weather Flows* (Field *et al.*, 1996), the future directions for WWF research as seen by the EPA's Urban Watershed Management Branch (of the Water Supply and Water Resources Division, National Risk Management Research Laboratory (NRMRL)) are discussed. The report specifically describes five-research areas: characterization and problem assessment, watershed management, toxic-substances impacts and control, control technologies, and infrastructure improvement. Several of these areas correspond to topics that were highlighted as important in the literature review.

Although there are many common themes between the literature and the future research plan, several differences also exist. One major difference is the consideration of toxic substances in the future. Research has been conducted only recently concerning toxic substances, and the impact of this research is yet to be noticed on a widespread scale in WWF management. In conclusion, several lessons were learned from the literature review concerning the management of WWF. These lessons will enhance future strategies and help delineate future research objectives.

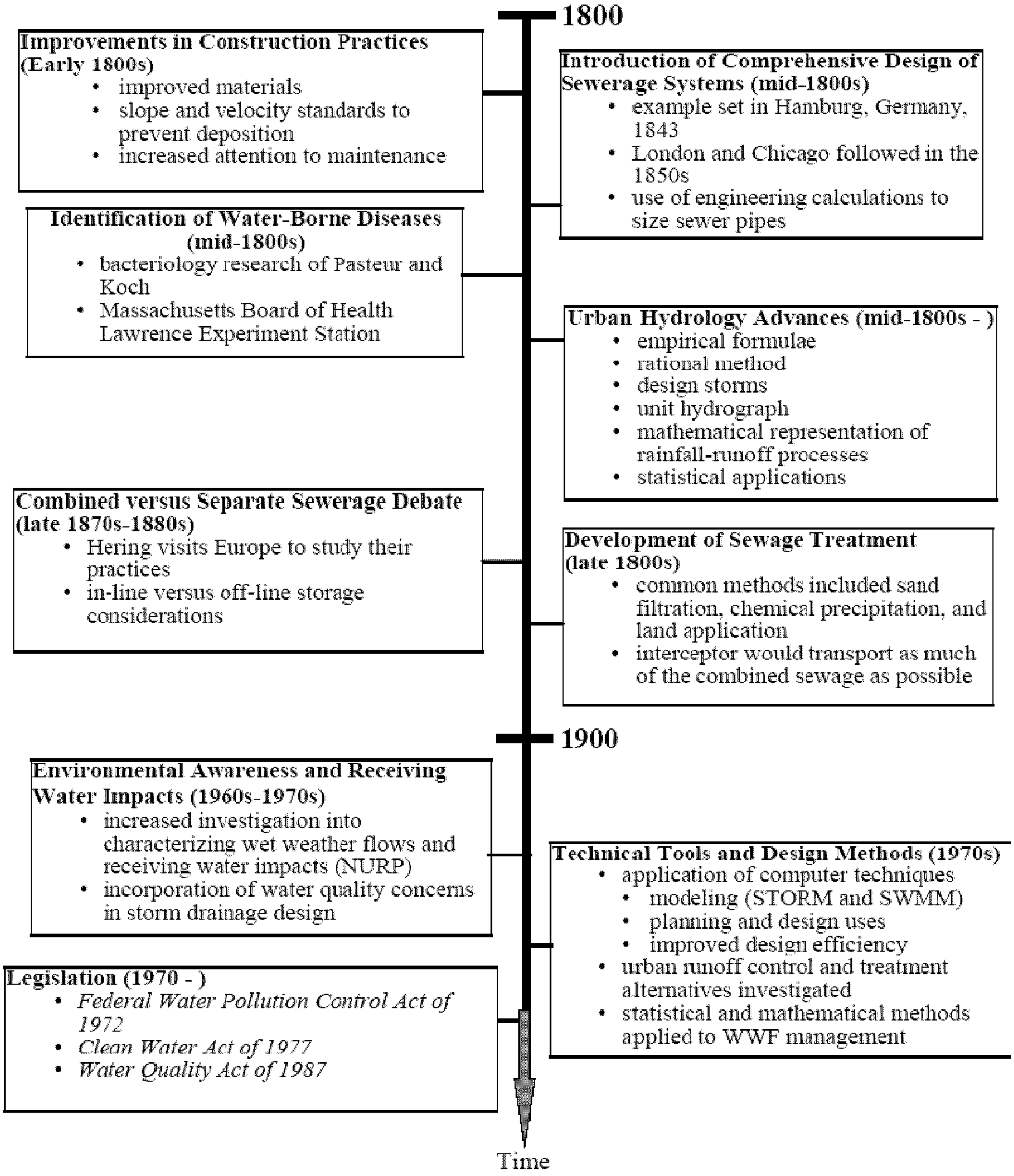

Figure 1. Development of Modern WWF Management.

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