August 18, 2003

# Module 1
# Historical Review of Urban Water Drainage



## Introduction

This material is mostly excerpted from: R. Pitt, M. Lilburn. S.R. Durrans, S. Burian, S. Nix, J. Vorhees, and J. Martinson, *Guidance Manual for Integrated Wet Weather Flow (WWF) Collection and Treatment Systems for Newly Urbanized Areas (New WWF Systems)*, prepared for the U.S. Environmental Protection Agency, Urban Watershed Management Branch, Edison, New Jersey, December 1999. This chapter was mostly written by Steve Burian (currently a faculty member at the University of Utah) when he was a Ph.D. student at the University of Alabama. He also presented this at the ASCE conference in Chicago in 1998.

The management of wet weather flows is an age old problem. Ancient civilizations grappled with the quandary of flood prevention and waste disposal in their cities of stone long before engineering was a recognized profession. They devised strategies to mitigate flooding in cities which resulted in occasional success and constructed drainage appurtenances such as open channels and pipes that remain intact today. It is evident from recorded histories that lessons concerning wet weather flow management can be learned from the past.

Examples of well constructed sewerage systems exist in history. From the ancient Mohenjo-Daro civilization to the Roman Empire, drainage systems proved to be sources of civic pride. Even today, the sewer system of Paris is the destination of many a tourist. The methods used in the past to lessen the impacts of stormwater can provide insight into new methods applicable today. But to find applicable concepts from the past a thorough search must be conducted. One aspect of this EPA funded project to develop a guidance manual for wet weather management in newly urbanizing areas involved just such a literature review. The literature search began with historical books which reviewed 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 wet weather management. The second part of the literature review entailed an exhaustive review of technical material from the previous 130 years. The technical literature reviewed included journals, books, reports, government documents, and other print media relevant to the subjects at hand. The purpose of this part of the literature review was to trace the development of wet weather management, possibly uncovering discarded concepts or practices that could be applicable today.

This discussion of the literature is divided into five subsections. The first subsection will detail the methodology and breadth of the literature review. The second subsection will discuss the ancient wet weather management strategies uncovered in the literature. The third subsection will detail the literature relevant to wet weather management dating from the middle ages to the nineteenth century. The fourth subsection will present the literature from the late nineteenth century to the early 1960s. The last subsection presents the recent literature from the past thirty years with special reference to current conditions. The conclusion of this module summarizes the literature review and describes the future outlook for wet weather management based on current trends in the literature.

The complete literature review (extensive bibliography) is located at the University of Alabama's student AWRA web site at:
http://www.eng.ua.edu/%7Eawra/download.htm

Additional literature reviews, covering many aspects of urban wet weather flows, are located at:
http://www.eng.ua.edu/~rpitt/Publications/Publications.shtml

Also, Bill James web site at Computational Hydraulics includes the following search engine that contains bibliographic citations for almost a thousand references:
http://www.computationalhydraulics.com/search.html

## Literature Review Methodology

One of the first steps in the development of the wet weather management guidance manual was the review of current wet weather flow management practices and historical incidents that resulted in the institutionalization of current practices. There are many ideas that have been proposed, some tried and others not, over the years that may be applicable in current conditions. We feel that a review of the historical developments may provide some insights lost over time.

Journals dating from 1860 to the present were searched for articles pertaining to municipal stormwater design and management. In addition books, reports, conference proceedings, and other forms of print were also searched. References located pertinent to wet weather flow to any degree were recorded into ProCite (Personal Bibliographic

Software, Inc. 1995), a bibliographic software application, for future reference. As references accumulated, a simultaneous critical review was conducted for each reference to determine its applicability to the current project. The critical review involved considering the title of the piece of work, possibly reading the abstract or perusing the article, and occasionally reading the entire piece. Papers of note were recorded and set aside for later synthesis with other important pieces in the development of an historical perspective of stormwater management.

In addition to the search of journals and their indices, electronic searches were conducted. The University of Alabama library system supports the Ei Page One Engineering Index for periodicals. This database was searched with key words related to wet weather management. Some of the key words used during the search were:

- sewer
- urban runoff
- stormwater
- wet weather flow
- best management practices
- detention basins
- urban hydrology

This list is just a sampling of the key words used. However, following key word searches with these terms additional searches resulted in a high frequency of repeat hits. Thus, it became fruitless to continue searching with more obscure key words in the same database and the search was discontinued. At that time other databases and search engines would be consulted for additional references.

Another computer search engine utilized was the ProQuest service for dissertation abstracts. The same key words were used as in the Ei Page One search and again the diminishing amount of new hits with additional key word searches was observed. The dissertation database was far less comprehensive than the periodical index searched, consequently far fewer dissertation and thesis abstracts were located compared to the periodical indices.

Other databases searched electronically included the National Technical Information Service (NTIS) index, COMPindex, and the Internet at large. These databases did not provide a large amount of references and even seemed counterproductive at times. For instance, the Internet search consumed a lot of time and only resulted in small amounts of literature located. Some of the poor results using these search procedures may be attributable to the search methodology implemented.

Regardless of the search methodology, be it electronic or manual, the located sources were either recorded by downloading to a disk or written by hand, depending on the type of source and if it could be uploaded directly into the ProCite database. If the source was recorded by hand it was subsequently entered into the ProCite database by hand and if it were downloaded to disk it would be uploaded into the ProCite database. Overall, slightly more than half of the references in the database were manually entered into ProCite from a printed source, whether it be an index, literature review, or some other compilation of bibliographies.

Ultimately, the goal of this initial work was to determine the general stormwater design philosophy utilized to design and manage municipal stormwater systems, and to chart the progress or regress (depending on your point of view) in the development of wet weather flow design and management strategies. Also, schisms which occurred in design and management philosophy will be apparent from the accumulated literature. It is necessary to document and understand the history of stormwater design and management to devise a future strategy. By observing past trends and decisions, prior mistakes can be avoided, previously discarded ideas can be reevaluated, and eventually future needs can be determined. A copy of the database, in both Microsoft Word and ProCite versions, is available on the www page of the Cahaba-Warrior Student Section of the American Water Works Association at: http://www.eng.ua.edu/~awra/

### *Journal Papers*

Several technical journals publish annual literature reviews or indexes divided into specific subject matter which provided an excellent starting point for this review. Specifically, the following journals were utilized in this capacity for this study:

*Journal Water Pollution Control Federation* (and its current descendents)
*Transactions of the American Society of Civil Engineers*

Overall, 124 journals are referenced in the complete ProCite database. The journal article review consumed most of the time in the early parts of this project.

Today, technical journals are ubiquitous with many publishing material germane to wet weather flow management. However, the development of the wet weather management strategies in the U.S. can be traced accurately through two organizations' journals in particular. The American Society of Civil Engineers (ASCE) and the Water Environment Federation (WEF) and its predecessor organizations have published journals dating back to the late eighteen hundreds. Since these two journals provided many sources, flow charts and explanations of the development of ASCE and WEF journals is provided below to facilitate the discussion.

**American Society of Civil Engineers (ASCE)**

ASCE has been an institution since 1852 and the published transactions for the society dating back to 1878 were readily available in the University of Alabama's library. The *Transactions of the American Society of Civil Engineers* published papers which were associated with society members. The papers in this journal provided coverage for the ASCE literature review from 1880 to the early 1950s. In the 1950s, the divisions of the ASCE began to be represented by separate journals, as is shown on Figure 3-1. ASCE publishes many other journals, but only the journals in the flow chart contained material relevant to this project.

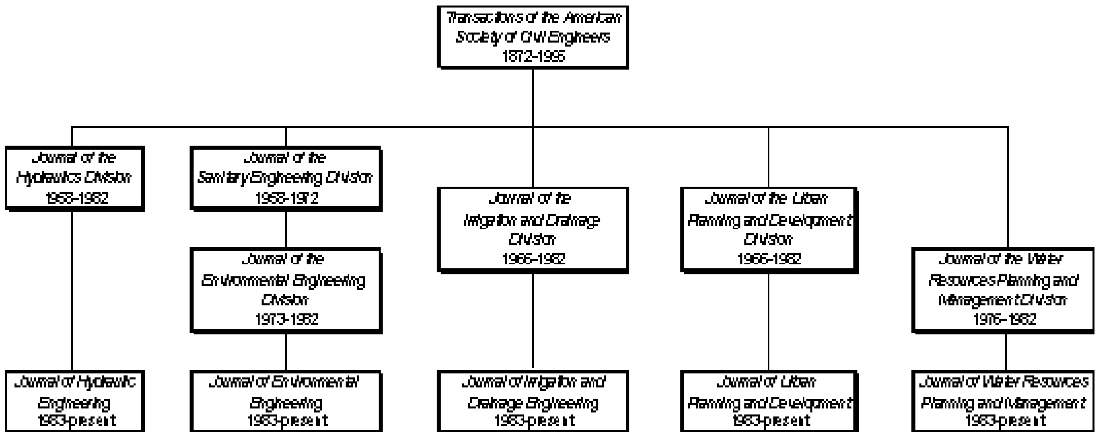


**Figure 3-1. American Society of Civil Engineers' (ASCE) Journals Reviewed.**

**Water Environment Federation (WEF)**
The Water Environment Federation evolved from the Water Pollution Control Federation. The *Sewage Works Journal* was the primary publication of the Water Pollution Control Federation from 1928 to 1949 as shown in Figure 3-2. The title of the journal was changed to *Sewage and Industrial Wastes* in 1950 and subsequently to *Journal Water Pollution Control Federation* in 1959. The journal kept this name for thirty years, until 1989, when the journal split into two journals, one a research journal (*Water Environment Research*) and the other a trade journal (*Water Environment & Technology*).

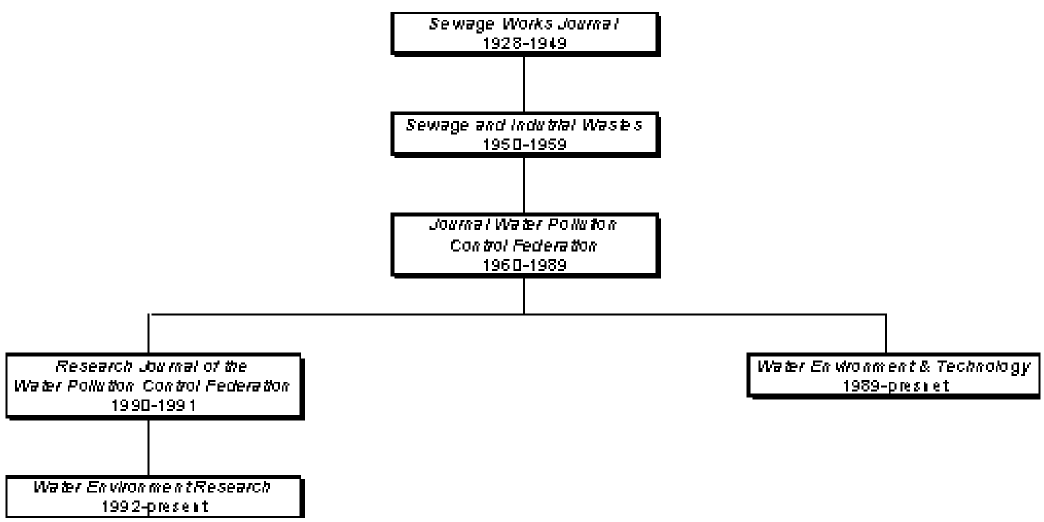


**Figure 3-2. Water Environment Federation's (WEF) Journals Reviewed.**

## *Additional Literature Reviewed*
Besides the ASCE- and WEF-sponsored journals, many other journals also contributed to the database. A complete list and their relative contributions of the more frequently referenced journals is discussed below.

The government documents database (mainly NTIS) was also searched for reports related to stormwater management. Federal agencies with major contributions to the field included: the United States Environmental

Protection Agency (EPA), the United States Geological Survey (USGS), and the Federal Highway Administration (FHWA). A good source for wet weather management reports published by the EPA is an EPA report entitled *Bibliography of Storm and Combined Sewer Pollution Control R&D Program Documents* (Field 1995). Over 340 EPA reports are cited in this document. Local and state agency reports were also documented in the database.

Conference proceedings were another area targeted for published material pertaining to wet weather management. Proceedings are not easily attainable, even if one knows the location and date of the conference. For this reason, most proceedings are considered a form of "gray" literature. Proceedings may be located in libraries, through interlibrary loan, and from authors and sponsoring agencies. This area is considered to be quite an important vein of knowledge that has been relatively unorganized in the past.

The other references examined included books, private reports, unpublished documents, theses, dissertations, and other sources discovered during the above mentioned searches. Information concerning ancient and middle age wet weather management was generally located in historical books and papers reviewing historical drainage practices.

### *Summary Statistics*

The complete ProCite database contained over 3,700 references at the time of publication. The chronological breakdown of the references is shown in Table 3-1. Almost half of all references cited were published since 1990. The large amount of material referenced during the past few years likely reflects the tremendous increase in researchers involved in wet weather flow issues and who are publishing their results.

**Table 3-1. Breakdown of References Chronologically**

| Decade | Number of References |
|---|---|
| Before 1880 | 3 |
| 1880 - 1890 | 10 |
| 1890 - 1900 | 14 |
| 1900 - 1910 | 10 |
| 1910 - 1920 | 10 |
| 1920 - 1930 | 11 |
| 1930 - 1940 | 33 |
| 1940 - 1950 | 42 |
| 1950 - 1960 | 15 |
| 1960 - 1970 | 97 |
| 1970 - 1980 | 975 |
| 1980 - 1990 | 994 |
| 1990 – 1996 ½ | 1574 |

If the number of references is further broken up into five year segments from 1970 onward, another noticeable trend is observable. As shown in Table 3-2, the second half of the 1970s showed a significant upswing in publishing followed by a steady decrease over through the 1980s. The number of publications is increasing rapidly (by a factor of 2) during the current decade. These fluctuations generally reflect the changes in national funding available for wet weather research. The 1970s were noted for significant and massive demonstration projects supported by the EPA in the area of CSO control. EPA funding abruptly ended for wet weather flow research in 1980 and did not start again until 1988. In the U.S., wet weather flow research during the 1980s was mostly sponsored by state and local governments and was not widely published. U.S. funding during the past several years has significantly increased, with a concurrent upsurge in reported research findings. In addition, European and other international wet weather flow research efforts dramatically outpaced U.S. efforts during the 1980s and current international research remains a very important source of information. For this reason, numerous international conference proceedings (such as those sponsored by the IAWQ, the International Association on Water Quality, based in London) remain extremely important to U.S. researchers.

**Table 3-2. Further Breakdown of References Chronologically**

| Time Period | Number of References |
|---|---|
| 1970 - 1975 | 313 |
| 1975 - 1980 | 662 |

| | |
|---|---|
| 1980 - 1985 | 547 |
| 1985 - 1990 | 447 |
| 1990 - 1995 | 1020 |
| 1995 - present | 554 |

The breakdown of the quantity of journal papers found within each specific journal is listed in Table 3-3. About 75 journals having contributions of less than 10 papers to the database are not listed. In sum, more than 1,600 journal papers are referenced in the ProCite database.

The database contains over 350 EPA documents and 22 USGS reports. These two government agencies are the largest single contributors, with the remaining 175 plus reports being distributed among many state, local, academic, and private entities. Over 100 conference proceedings contributing 1,350 papers are include in the database as well. Supplementary to the above references, over 100 theses and dissertations are also included.

ProCite has the capability to store very descriptive details about a reference. But not all of this descriptive capacity was available for each citation. In ProCite, each different type of media has fields that are specific to it and some that are general for all types. For instance, the author is specific to each type of reference, whether it is a journal paper, book, EPA report, etc. However, this information, like all else, is not required.

For this study, the information necessary for locating a reference was given highest priority (authors, titles, date of publication, page numbers, and publisher). Other information would also be entered if readily available. Figure 3-3 shows an example of a journal paper ProCite citation. Each field has its own line, with additional lines provided when appropriate. The input fields can be formatted by the user to display the information that is desired. The available templates in ProCite include journal paper, book, dissertation, report, patent, and many others. The user can also create their own template specific to their needs. ProCite is a Windows based application with memory requirements based on the size of the bibliography. Figure 3-3 does not display all the icons that support the use of the application.

The key words are selected based on the title, abstract, or the entire paper. In total, for the more than 3,700 references, approximately 700 different key words have been entered. Some of these are redundant, but often the words selected by different individuals will be different based on their backgrounds. Therefore, the redundancy is viewed as advantageous for the database as a whole. Several example key words include:

- CSO treatment
- toxicity
- drainage design
- detention basins
- heavy metals
- sewer solids
- infiltration/inflow
- deterministic modeling

**Table 3-3. Listing of Individual Journal Citations**

| Journal | Number of References |
|---|---|
| *American City and County* | 25 |
| *APWA Reporter* | 22 |
| *Canadian Journal of Civil Engineering* | 12 |
| *Civil Engineering,* ASCE | 65 |
| *ENR (Engineering News - Record)* | 26 |
| *Journal of the Sanitary Engineering Division,* ASCE | 10 |
| *Journal of the Environmental Engineering Division,* ASCE | 50 |
| *Journal of Environmental Engineering,* ASCE | 37 |
| *Journal of Hydraulic Engineering,* ASCE | 26 |
| *Journal of the Hydraulics Division,* ASCE | 95 |
| *Journal of Hydraulic Research* | 54 |
| *Journal of Hydrology* | 11 |

| | |
|---|---|
| *Journal of the Irrigation and Drainage Division,* ASCE | 13 |
| *Journal of Irrigation and Drainage Engineering,* ASCE | 14 |
| *Journal of the Urban Planning and Development Division,* ASCE | 9 |
| *Journal of Urban Planning and Development,* ASCE | 2 |
| *Journal of the Water Res. Planning and Management Div.,* ASCE | 27 |
| *Journal of Water Res. Planning and Management,* ASCE | 47 |
| *Journal Water Pollution Control Federation* | 112 |
| *Nordic Hydrology* | 10 |
| *Public Works* | 93 |
| *Science of the Total Environment* | 33 |
| *Sewage Works Journal* | 10 |
| *Transaction, American Geophysical Union* | 11 |
| *Transactions of the American Society of Civil Engineers* | 70 |
| *Water/Engineering and Management* | 25 |
| *Water Environment & Technology* | 59 |
| *Water and Sewage Works* | 16 |
| *Water and Wastes Engineering* | 11 |
| *Water Research* | 29 |
| *Water Resources Bulletin* | 57 |
| *Water Resources Research* | 21 |
| *Water Science and Technology* | 211 |

This sample of key words, and the remainder in ProCite, are more than adequate to conduct searches, but can be expanded by the ProCite user to provide a more expansive search capability.

The bibliographic format used for the hard copy of the reference database and within ProCite is according to a standard EPA format. Although this is the format selected, ProCite can accommodate any bibliographic format required. ProCite offers a wide range of sorting criteria, or the user can define the criteria as desired. For this report, a custom sort was constructed within the ProCite framework to organize the references. The primary sort is alphabetical, according to the author's name, or authors, if there is more than one. The secondary sort is chronological, and the tertiary sort is an alphabetic sort by the title of the work. Although this is the custom sort set in ProCite for this project, other sorting methods can be used. ProCite offers a wide variety of sorting, searching, citing, and other functions to facilitate bibliographic work. The reader is referenced to the ProCite User's Manual (Personal Bibliographic Software, Inc. 1995) for additional information.

The progression of wet weather management as seen in the literature sources described above is presented in the following subsections.

| | |
|---|---|
| **Author, Analytic (01):** | Kuichling, Emil |
| **Article Title (04):** | The relation between the rainfall and the discharge of sewers in populace districts |
| **Medium Designator (05):** | |
| **Journal Title (09):** | Transactions of the American Society of Civil Engineers |
| **Translated Title (11):** | |
| **Date of Publication (20):** | 1889 |
| **Volume Identification (22):** | 20 |
| **Issue Identification (24):** | |
| **Page(s) (25):** | 1-60 |
| **Language (35):** | |
| **ISSN (40):** | |
| **Notes (42):** | The introduction of the rational method of storm sewer design in the U.S. |
| **Abstract (43):** | |
| **Call Number (44):** | |
| **Key Words (45):** | rational method/storm sewer design/time of concentration/rainfall-runoff/ |

**Figure 3-3. Example ProCite Citation**

## Ancient Wet Weather Management Practices

Modern engineering has become so extended and specialized in all disciplines that its relation to ancient engineering is almost inconceivable. Sophisticated computers and other design tools provide today's engineer with a decisive technical advantage over the ancient engineer. But, one must not forget that today's methods and practices have evolved from their roots in history parallel to the progress of civilization. If engineering evolution followed Darwin's theory, then the 'fittest' methods and principles would have survived. However, the 'fittest' practices have not always been those initially accepted by engineers. The literature documents incorrect practices embraced and insightful ideas ignored in the past.

The use of planned sewer systems to transport stormwater from an urban area to a receiving stream is thought by some to date back to the time people began to gather and live in cities. The drainage systems often accompanied well-planned sanitary sewage systems in an effort to provide a cleaning mechanism. Several contemporary civilizations can be credited with developing innovative wet weather and sanitary sewerage systems in the third millennium B.C.

The Indus civilization of circa 3000 B.C. presents one example of a sewerage system well advanced of their time. Evidence exists that the dwellers of the city of Mohenjo-Daro (now West Pakistan) used sanitary sewer systems and had drains to remove stormwater from the streets (Webster 1962). The discovered ruins of this ancient system show the great care used to construct the sewers which would make the engineer of today envious. Judging from the foundations of the city, archeologists have concluded that the city was laid out according to some prearranged plan. Knowing that a civic body was responsible for the planning of the city lends to the conclusion that a planning authority also influenced the development of the sewer system.

One feature of the Mohejo-Daro sewer system of note was the use of a cunette in conjunction with the storm drain (Webster 1962). This practice is seen today in allowing for normal flows to pass through wet weather structures without utilizing its entire capacity. 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 some of the buildings.

Other cities in the middle east region about 5000 years ago also exhibited wet weather management planning. For instance, the city of Ur, in present day Iraq, had an effective drainage system for stormwater control (Jones 1967). Although the system ruins did not indicate an overall system design, it did show the breadth of coverage that the system had over the whole city.

Civilizations contemporary to the Indus also had excellent sanitary and wet weather management systems. The Mesopotamian Empires of Assyria, Babylonia, and their antecedent Sumerian and Akkadian states, marked great advances in civilization. The ruins from cities in these empires have uncovered the viable sanitary and storm drainage systems implemented, displaying their advanced technical knowledge. As early as 2500 B.C., Mesopotamian engineers planned and built efficient drainage and sanitary works including vaulted sewers and drains for household waste, gutters and drains for surface runoff, and other appurtenances (Maner 1966). All the structures were built of baked brick and asphalt.

The Middle Minoan Period dates about 1000 years after the above civilizations. The ruins from this civilization located on the Aegean Sea revealed elaborate systems of well-built stone 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 ancient Crete, an island in the Minoan civilization, resulted in excellent flushing of the system. A testament to the durability of the system developed by the Minoans was a statement made by A. Mosso in describing the ruins of villa Hagia Triada (Gray 1940):

> One day, after a heavy downpour of rain, I was interested to find that all the drains acted perfectly, and I saw the water flow from the sewers through which a man could walk upright. I doubt if there is any other instance of a drainage system acting after 4000 years.

It will be interesting to see if the drainage systems constructed today, with supposed advanced technology, can function adequately after 4000 years.

The next wet weather management practice of note dates to the tenth century B.C. Ruins in Jerusalem indicate that two independent systems of sewerage, one for street drainage and household wastewater and the other for sanitary sewage, were implemented in small sections of the city (Hodge 1992). This marked a change, although at a very small scale, from the past practice in Mohenjo-Daro, which had storm drainage systems being used to convey sanitary wastes to a suitable disposal location. Arched sewers also existed in Ninevah and Babylon dating to the seventh century B.C. (Metcalf and Eddy 1928). These sewers were utilized to transport combined sewage similar to those in Mohenjo-Daro (Webster 1962).

On a scale larger than small towns or sections of cities, wet weather management in urban settings appears to have been first consistently addressed during the design of roadways. 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). But the question is did the Romans develop the drainage of roadways or did they borrow the technology from previous civilizations. It is known that roads of ample design date back to the period of Etruscan domination in Italy (800-350 B.C.) (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 streets. Therefore, some believe that the Romans developed their drainage strategies from the Etruscans. Regardless of the originator of the strategy, the intentions of both the Etruscan and Roman road drainage systems was 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 curb and gutters to direct surface runoff to open drainage channels alongside roadways. However, the ruins of Roman roadways do not indicate an abundance of curb and gutter usage and the exact date in which this drainage strategy became implemented is not clear (Hill 1984). Many Roman roadways also had rock lined open drainage channels on either side of the paved street surface. The roads would be graded in such a fashion to direct the surface runoff from the streets toward the drainage channels. Although some of the channels were lined, the most often used drainage channel was simply the open ditch.

Besides the Romans, evidence has also shown that the Greeks designed paved surfaces for travel during the same time period as well. However, mainly due to the terrain of Grecian lands, the roadway system was not nearly as intricate or finely planned as the Roman roadway system. Gutters and drains were provided and grading was done such that roadways would remain free from inundation.

The roads were not the only engineering structure that was designed for drainage. 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 where it was used as a water supply (Hodge 1992). This management practice effectively reduced the amount of surface runoff requiring control, simultaneously reducing the required size of the drainage system. A great deal of rain falling on a town, therefore, never did get drained away. This management strategy of on-site detention continues to be utilized today (Debo and Reese 1995) as a strategy to reduce surface runoff. Fewer areas continue to utilize direct reuse of stormwater on-site.

The well-known Roman aqueduct system used for water supply to the populace, was also the impetus for drainage in many parts of the Roman Empire. Once an aqueduct was brought in, and with it the overflow of unused water from street fountains and, especially the baths, then the water to be drained away could be a great amount (Hodge 1992). Therefore, it is often argued that the drainage structures constructed by the Romans were planned more for the overflow from the aqueducts than the drainage of surface runoff, nonetheless their effectiveness at managing stormwater cannot be disregarded.

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 in populace regions in the Roman Empire, domestic sewage and wastes were requiring disposal. The easiest ways were to discharge the wastes into the drainage system or develop a pipe system especially for domestic waste. The need to adequately discharge wastes initiated the development of underground sewers. Initially, open trenches or channels ran down the center of city streets to convey the stormwater and excess public water. Soon, it was discovered that disposal of wastes in these trenches removed the waste from the area. However, the trenches relied on cloudbursts to flush them of waste and debris adequately, since the overflow from the aqueducts was not sufficient to convey the wastes in great quantity. The wastes would accumulate and cause unsanitary, not to mention repugnant, conditions. The solution to this was to cover the trenches. The covered channels evolved into planned sewers. Thus, many of the early sewers were typically natural open drainage channels and streams which started to accumulate domestic wastes requiring them to be covered to prevent odors from escaping to the surrounding community.

The Romans constructed the *cloacae*, or sewers, to drain their uplands to the nearby network of low-lying streams (Gest 1963). As mentioned, sewers were originally open streams that drained most of the land prior to urbanization. The onset of paved roadways and stone structures reduced the infiltration capacity of the area resulting in flooding. The Romans understood that drainage needed to be considered in urbanizing areas to mitigate flooding caused by aqueduct overflow and rainwater. 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. This would provide alternate routes for infiltration from impervious surfaces during urbanization. As time progressed, the Romans became more elaborate with their construction of the sewers, this is evidenced by the increased care and detail given to the construction in later times. For instance, ornamental and finely crafted inlet covers have been discovered in ruins of Roman city streets (Gest 1963).

The first of the *cloacae* was the *Cloaca Maxima* (Gest 1963); constructed to drain the lowest parts of Rome, about the Forum, which were too flat to remove the stormwater easily. The *Cloaca Maxima* also had the dual purpose of draining swampland for land reclamation purposes. Therefore, constant flow of water was present with intermittent high flows during wet weather events. This provided excellent conditions for the disposal of sanitary wastes via the sewer system.

The oldest part of the existing structure dates to about the third century, B.C. (Gest 1963). The *Cloaca Maxima*, which was 4.3 meters high and 3.2 meters wide in places (Garrison 1991), discharged directly into the nearby Tiber River. Roadways, common areas, and stone structures were constructed with drains adequate to allow the stormwater to enter the sewers, thus relieving Rome of flooding problems. Besides simply removing the rainwater, the drains and sewers also acted to funnel the filth and accumulated garbage scoured from the surface of the city to the nearest waterway during wet weather events. No consideration was given to the impacts that the wet weather flows were having on the receiving water, although it most likely was minimal, due to the relatively small populations in the ancient cities.

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 wet weather management systems in the 1800s (Hodge 1992). Although the sewers were successful in their function and 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, the pinnacle of wet weather management had not yet been attained.

## Wet Weather Management Practices: Middle Ages to the Nineteenth Century

From the time of the Roman Empire to the eighteenth century, wet weather management strategies experienced few noteworthy advancements, and even regressed considerably in terms of sanitation. However, as disease epidemics occurred in major metropolitan areas of Europe, some believed proper sanitation was dependent on adequate wet weather management. The proper utilization of stormwater provided an urban area with the required flushing mechanism to remove wastes that accumulated in city streets as well as reduced the damages and dangers associated with urban flooding. The 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 cities which developed piecemeal drainage systems in response to crisis situations and funding availability. The development, from inadequate to adequate wet weather management systems required 500 years, dating from approximately 1300 (when ditches were first used to convey drainage waters) to the 1800s (the advent of modern engineering drainage design).

The first sewers to develop in Europe following the fall of the Roman Empire were simply open ditches. Previously, the inception of sewers in the Roman Empire had developed in the same fashion. Examples in Europe of this type of sewerage system is evident in both Paris and London (Kirby and Laurson 1932; Reid 1991) during the 1300s and 1400s. The open ditches used for drainage of stormwater were usually constructed in existing drainage pathways (Kirby and Laurson 1932). Besides being conveyances for stormwater, the open drainage channels became receptacles for trash, kitchen wastes, and sanitary wastes, the accumulation of which caused a great nuisance. To remedy this situation, Europeans covered the drainage channels, or sewers, which were emitting a terrible odor or providing unsightly conditions. Interestingly, this solution is also similar to that used 1500 years earlier by the Romans during the construction of the *cloaca*. It seems that strategies commonly utilized in the past to mitigate a sanitation problem was to remove it from sight; which 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. 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).

Before the covered sewer, the open sewers usually were little more than gullies running down the center of the street (Reid 1991), which a heavy downpour could turn easily into torrents overflowing their banks. Well into the nineteenth century, *pontonniers volants* appeared with planks on Paris streets during rainstorms and charged pedestrians a fee to accompany them across open sewers on their boards (Reid 1991). During dry periods, the sewers in the streets, which relied on the rainwater for cleansing, literally became garbage dumps due to the accumulation of municipal wastes. Therefore, the drainage systems functioned unacceptably during both wet and dry periods.

The few covered sewers which did exist received insufficient maintenance during the early middle ages. During periods of dry weather, the sanitary wastes remained stagnant in the sewer system, producing a repugnant odor. The maintenance problems unheeded, the municipal authorities continued to cover sewers in European metropolises. By 1663, almost one-quarter of Paris' more than ten kilometers of sewers were enclosed (Reid 1991). Maintenance of the sewers continued to be difficult to the point that blockages and backups were common. The solution in Paris during the 1700s was to build magnificently large underground sewers for the drainage of stormwater. These sewers provided enough space for a man to clean the sewers comfortably. However, opposition to the large sewers was heard from many - 'What good is such luxury underground?' (Reid 1991). The lack of government attention and the poor practices of planning, design, and construction of the sewers caused much of the deposition and subsequent clogging problems. In 1826, the Amelot in Paris had its entire six foot by five foot opening blocked with accumulated waste (Reid 1991), just one of the many recorded examples of poor maintenance of middle age civil infrastructure systems. In retrospect, the sewer systems of urban areas in Europe during the seventeenth and eighteenth centuries were grossly under-planned, poorly constructed, and inadequately maintained.

Innovations in construction practices improved sewerage systems in the early 1800s. Until the 1820s in Paris, sewers had been constructed of cut stone or brick with rectangular or roughly rounded bases, conditions conducive to deposition problems (Reid 1991). Engineers substituted mill stone and cement mortar for the hewn stone which allowed for the construction of curved sewer floors that were smooth. This innovation ameliorated the cleansing of sewers by flushing.

Another problem with the design and construction of sewers was the grade at which they were laid. Often, caution was not exercised either during design or construction and the sewers did not have a sufficient slope to transport wastewater during dry weather flow. Addressing this situation, engineers and laborers began to construct sewers on inclines sufficient to prevent ponding in the system.

The onset of numerical standards for sewer design began in the mid 1800s. The basis for the standards was both experimental results and practical experience. Bazalgette provided much of the European design standards for drainage systems in his designs for London sewerage (Metcalf and Eddy 1928). His standard of using 2 to 3 feet per second for a minimum velocity to avoid silting was well accepted throughout Europe and institutionalized in London in 1855. The minimum velocity was not arbitrary but based instead on actual tests of deposition of sand from running water. These tests indicated that a velocity of 2 feet per second would move solids along 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 or suggestions utilized included slope restrictions, materials, size, and others. However, these standards were not as universally accepted as the minimum velocity standard.

In addition to the improvements in construction, the design of the sewer pipes realized several advancements. The shape of sewers had been constrained by construction and material capabilities, but with the advent of new pipe materials mentioned above, they could be constructed curved instead of simply rectangular. As a result, new innovative shapes of sewers developed in the early 1800s that included egg-shaped, oval, and v-notched patterns for combined sewer systems. These shapes provided improved hydraulic transport efficiency over the rectangular sewer shape. Studies in England indicated that the lower part of a v-notch channel could carry sanitary waste flow along 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.

The improvement in construction practices and pipe designs didn't eliminate the problems with sewer systems in Europe. System design strategy became the focus of the next wave of innovations in sewerage practice. The precursor to the overall design of urban wet weather management systems was the improved design of parts of the system. For instance, H. C. Emmery, head of the Paris sewer system from 1832 to 1839, replaced the channels down the center of streets with gutters constructed under sidewalks which periodically emptied into sewers (Reid 1991). The sewers he constructed had a regular incline and, like sewers built later, were large enough to allow a man to move about standing up. However, even design advancements such as this could not mitigate the impacts of urbanization. The runoff caused by an increase in impervious surfaces put further strain on the sewer system causing overflows with nearly every downpour (Kirby and Laurson 1932). Also, adding to the flooding problems during this period, sewer pipe was made by 'persons not overly scrupulous, eagerly purchased, and hastily laid by parties utterly ignorant of any role of correct drainage' (Gayman 1997). As standards, regulations, and inspections became more stringent for public works projects, these problems gradually began to subside.

The next logical step in the advancement of wet weather management addressed planning for entire urban systems of drainage and sanitary sewage removal. Hamburg, in 1843, is considered to have implemented the first comprehensively planned sewerage system (Metcalf and Eddy 1928). Although previous systems had accounted for both sanitary wastes and stormwater, they were not designed with that intention. Hamburg marked the first system that from its conception was planned to manage both sanitary wastewater and stormwater runoff. The circumstances were advantageous for this type of holistic design since a large part of the city had been destroyed by conflagration in 1842. William Lindley, an Englishman in residence in Hamburg, was commissioned to plan and design the system. It was designed uniquely in that sanitary sewage and stormwater were conveyed separately, constituting a separate system of sewerage. The separate 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 it is today, economics ultimately influenced civil infrastructure system design.

London followed suit with a detailed study by many engineers of note, one of which was Sir Robert Rawlinson, 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 it 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 planned interceptor sewer concept dates to this period in Paris (Kirby and Laurson 1932).

In The United States of America, Chicago had the first comprehensive design implemented by an American city. The system was designed by E. S. Chesbrough in a report completed in 1858 (Metcalf and Eddy 1928). He soon consulted on similar comprehensive plans for many other cities. Prior to this initial design, the history of American sewage is paltry. In many of the towns, the 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 the sewers were originally constructed in 1700 but the city did not acquire control of them until 1823 (Kirby and Laurson 1932). Cumulatively, the work done by engineers and others in the laying of American sewers, at least until the middle of the nineteenth century, should not be described with the term "design."

Other important designers of sewer systems in the U.S. included Moses Lane, James P. Kirkwood, and Col. Julius W. Adams. The designs implemented in the U.S. made use of empirical data obtained from European practice as to 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.

Of all the important American engineers, 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 at least twenty-five years (Metcalf and Eddy 1928). What Adams did for "quantity" design, Hering can be considered to have done for "quality" planning. He studied European sewerage systems and wrote about the benefits and shortcomings of combined and separate systems of sewerage (Hering 1881) in terms of sanitation. His discussions brought the argument between those supporting separate systems and those supporting combined systems to a head. He offered recommendations for the use of each only in certain situations. The debate between the proponents of separate systems and those of combined systems continued into the new century. Additional discussions of Hering's ideas concerning combined and separate sewer systems continue in the *Wet Weather Management: 1860-1960* section below.

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 1930). 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. Specific considerations also included the dilution capability of the receiving stream and the location of the proper disposal location. The factors affecting sewerage design increased after Hering's trip to Europe in the late 1870s.

The amount of runoff emanating from a catchment is paramount in the design of drainage structures. The design methods utilized in the middle of the nineteenth century can be described as simple estimations or percentage calculations and sometimes weren't based on the hydrological sciences at all. For instance, the new sewers built in Paris from 1833 onward were made six feet or more high whenever possible, in the belief that the workmen employed in cleaning them would perform their duties more efficiently if they could labor without being forced to take unnatural positions (Metcalf and Eddy 1928). In London, during the same time period, an accident involving sewer workers prompted a commission to resolve that 'it shall be laid down as a first principle that no common sewer shall be so small that an ordinary sized man shall not be able to cleanse it' (Gayman 1997). Therefore, the sizing of sewers in some instances was based on human physiology rather than sound engineering calculations.

The basis for the determination of surface runoff was based on empirical results. For example, the English-speaking engineering community used Roe's Table (Figure 3-4) predominantly during the middle of the nineteenth century (Metcalf and Eddy 1928).

| Inclination Fall or Slope of Sewer | Inner Diameter, or Bore of Sewer in Feet | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 2.5 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | Acres | Acres | Acres | Acres | Acres | Acres | Acres | Acres | Acres | Acres |
| Level ………….………… | 39 | 67 | 120 | 277 | 570 | 1020 | 1725 | 2850 | 4125 | 5825 |
| 1/4-in. in 10 feet or 1 in 480 | 43 | 75 | 135 | 308 | 630 | 1117 | 1925 | 3025 | 4425 | 6250 |
| 1/2-in. in 10 feet of 1 in 240 | 50 | 87 | 155 | 355 | 735 | 1318 | 2225 | 3500 | 5100 | 7175 |
| 3/4-in. in 10 feet of 1 in 160 | 63 | 113 | 203 | 460 | 950 | 1692 | 2875 | 4500 | 6575 | 9250 |
| 1-in. in 10 feet of 1 in 120 | 78 | 143 | 257 | 590 | 1200 | 2180 | 3700 | 5825 | 7850 | 11050 |
| 11/2-in. in 10 feet of 1 in 80 | 90 | 165 | 295 | 670 | 1385 | 2486 | 4225 | 6625 | | |
| 2-in. in 10 feet of 1 in 60 | 115 | 182 | 318 | 730 | 1500 | 2675 | 4550 | 7125 | | |

**Figure 3-4. Roe's Table, Showing the quantity of covered surface, from which circular sewers will convey away the water coming from a fall of rain of 1 inch in the hour, with house drainage, as ascertained in the Holburn and Finsbury Divisions (McMath 1887).**

Although some London engineers refused to use the Table, most respected Roe and therefore implemented some of his design strategies nevertheless. The Table was supposedly empirically derived from observations of London sewers in the Holborn and Finsbury divisions by Roe over a span of twenty 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 existed similar to Roe's Table in basis and function.

Bazalgette, a prominent London engineer in the 1850s and designer of the Main Drainage of London, planned for exceptional rainfall events in his design of sewer systems (Metcalf and Eddy 1928). He calculated the volume of sewerage which would be consumed by a certain frequency event then estimated the limit of overflows desired. From this information he determined the additional volume of pipe required for the system to function adequately (Bazalgette, as referenced in Metcalf and Eddy 1928). It should be noted that these calculations were implemented in the designs by Bazalgette for the Main Drainage of London in the 1850s.

Although sanitary waste was a constant input to the sewer systems of Europe, designs did not anticipate this addition until 1843 in Hamburg and the late 1800s in most areas. The sewers and drainage appurtenances were for surface waters and rainwater drainage exclusively. Of course this is not to imply that illegal connections were not present, when in fact it was often the case. The first type of wastewaters legally allowed into the sewer system were dishwater and other liquid kitchen wastes. The provision in the laws for sanitary connections from house to sewer did not come until later. Specifically, Paris did not allow legal sanitary connections to its sewer system until 1880 (Reid 1991) and London did not allow sanitary connections until the first Act made it possible it 1847 (Kirby and Laurson 1932). An increase in manpower and improved maintenance techniques, in addition to the improved planning, design, and construction, ultimately led to the Paris and London sewer systems successfully transporting stormwater and wastewater to the receiving stream. Despite the fact that wet weather management progressed in urban areas, little consideration was yet given to receiving water impacts.

The wet weather management systems of many European cities required years of attention and effort from many individuals to develop them to the standards they attained in the late 1800s. Even though the systems functioned with marginal success by today's criteria, once in a completed stage, society viewed them with amazement and considered them a grand achievement of their time (Reid 1991). Some cities touted their sewerage systems in an effort to rally public support. This enthusiasm was exemplified by the introduction of tourism to the sewer systems. In Paris, for instance, guided boat tours through the sewers offered the tourist an opportunity to view the mysterious underground labyrinth (Reid 1991). London had a similar trip for tourists wishing to view the sewers and drainage tunnels. An open air trolley conducted interested riders under the Thames and to various parts of the drainage and sewer system (Gayman 1997). The fascination with the Paris sewer system continues to this day and a guided tour is still possible.

Additional sewer system design improvements came in the latter part of the nineteenth century with rainfall-runoff predictions, hydraulic calculations and sewage disposal practices becoming infused into the wet weather system designs. These advancements are discussed in the following section.

## Wet Weather Management Practices: 1860-1960

The above section discussing the middle ages culminated in the development of wet weather management strategies to the point of comprehensive design for sewerage systems at the conclusion of the nineteenth century. Hamburg, in 1843, is considered the first city to be designed according to comprehensive planning with other major European cities such as London and American cities such as Chicago following soon thereafter. Although the comprehensive planning was a definite step forward, the design practice remained empirically based and often improperly conducted. Much work was still needed in advancing design strategies for quantity, but in addition, the quality issues required attention. The technical literature from 1860 to 1960 addresses these topics as well as others and this portion of the review will detail those advancements. Since the literature sources originate mostly from U.S. publications, a bias toward American sewerage development is unavoidable. It is noteworthy that American sewerage among the branches of engineering is exceptional for the overwhelming influence of experience, rather than experiment, upon the development of many of its features (Metcalf and Eddy 1928). We shall keep this in mind as the development of wet weather management is explored.

In the second half of the nineteenth century the hydrologic and hydraulic design methods used to size sewers became enhanced. Most notably, the rational method was developed in this time period by Mulvaney (1851), Kuichling (1889) in the United States, and Lloyd-Davies (1906) in Great Britain. The major advancement to the determination of runoff quantity with the rational method of Kuichling was the introduction of the time of concentration as a design parameter. Essentially, Mulvaney assumed a constant rate of rainfall and was concerned with the maximum rate of runoff, whereas Kuichling discussed the need to incorporate the relation between rainfall intensity, drainage area. and the time of concentration. 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 size of the pipes directly from the input parameters. Some of the equations used can be attributed to Adams, McMath, Hering, Parmley, Gregory, Burkli-Zeigler, Roe, and Hawksley (Hoxie 1891; McMath 1887; Buerger 1915). These equations all were derived based on site specific data and conditions, consequently they provided poor results when applied to other drainage basins (Buerger 1915), especially in the U.S.

Some of the more popular equations used to design sewer systems in the U.S. during the early 1900s are presented below (Buerger 1915):

**Hawksley (or Bazalgette):**

$$\log d = \frac{3\log A + \log N + 6.8}{10}$$

where *d* = diameter of sewer (inches);
*N* = length of sewer per foot of drop; and
*A* = drainage area (acres).

**Adams:**

$$q = CR^{0.83}\frac{S^{0.083}}{A^{0.167}}$$

where q = discharge (cubic feet per second, cfs);
C = an empirical coefficient;
S = slope (feet per 1000 feet);
A = drainage area (acres); and
R = rainfall (inches per hour).

**McMath:**

$$q = CR\frac{S^{0.20}}{A^{0.20}}$$

**Burkli-Ziegler:**

$$q = CR\frac{S^{0.25}}{A^{0.25}}$$

The Hawksley equation is distinct from the other three displayed in that it calculates the size of the sewer directly. This formula reflects the older attitude in design more in line with Roe's Table (shown above) in that the formula calculates the size of the pipe. The other three formulae, which were develop to replace Roe's Table and other formulae such as the Hawksley, calculated the discharge from the drainage basin for a storm event of a particular intensity. This flow was then used to design the size of the pipes.

The Adams, McMath, and Burkli-Ziegler formulae are very similar, especially the McMath and the Burkli-Ziegler. The equations were derived from empirical observations, consequently they reflect the specific situations from which they were derived. This results in the small amount of variance noticed in the formulae. The differences between each provide the reason why one method is more accurate for a specific set of conditions, but less accurate for a different situation. The older literature that compares these methods displays the observation that in some situations the Adams formula is the best, but in others the McMath is the best, and so on (Gregory 1907; Grunsky 1908;

Buerger 1915). This indicates that a formula can be derived to fit some situations, but it most likely will not be the best for all the situations.

The application of the equations and tables required knowledgeable and experienced engineers, because, in addition to the usage of the calculations, certain contingencies had to be anticipated in designing the system. Therefore, not only were the formulae influenced by the site conditions, but the influence of the design engineer was also imparted on the results.

Buerger (1915) presented a formula method that was not based on site specific criteria. He compared his method to much of the observed data that was available at the time and concluded that his method was superior to previous formula methods. The results obtained from the rational method are used for comparison because at that time it was considered to produce the best results. He reasoned that his method was preferable to the rational method since it is a singular formula, although it was complicated in form.

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

Drainage became a legal concern as well as an engineering concern in the middle 1800s. Courts found municipalities liable for the damages caused by negligent drainage design. In Wisconsin, The State Supreme Court ruled that if a sewerage system was constructed without a properly adopted plan, the city was liable for any damages that may result (Metcalf and Eddy 1928). It was also ruled that the city was not liable for defects in construction or materials, but only for improperly planned systems. Although the courts did find some municipalities liable, they also ruled in favor of the city on occasion. The Missouri Supreme Court supported the sufficiency of a sewer system although several failures had resulted in three occurrences of floods on a commercial property (Metcalf and Eddy 1928). The court ruled that since the floods were caused by unusual storm events the municipality couldn’t have planned for, no liability existed. In other words, exceptional storms did not have to be taken into account by the engineer designing sewerage systems.

Combined sewerage was the usual method of removing wastes from urban areas in Europe during the late nineteenth century, but separate sewerage systems had proven successful, for example at Hamburg, Germany (Metcalf and Eddy 1928). The combined sewers were not originally designed for sanitary wastes, but the ease of which sanitary wastes could be disposed of in the sewers became apparent resulting in the practice of adding sanitary waste to storm sewers creating combined sewers. A debate began in the late nineteenth century between the use of combined versus separate sewerage systems in the U.S. and elsewhere. Bourne (1966) provided 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 U.S. was Col. George E. Waring, Jr. (1878 and 1879). He designed several of the early separate systems including one for the City of Memphis in 1880 (Odell 1881). 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). This small size in comparison to other designs of six inches or more is what many believed to be the root of failures in Waring’s systems. To learn more about separate and combined sewer systems, Rudolph Hering visited Europe in the late 1870s 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 1881a; Hering 1881b). 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 rain-water did not need to be removed underground. Despite Hering’s report and the support of his conclusions (White 1886), the discussion continued, some may say even till today.

The turn of the century ushered in a change of philosophy in terms of waste treatment. Typically sewage and stormwater were simply discharged into a stream or river of adequate capacity to dilute the waste. The dilution of waste was an engineering discipline with design calculations determining if a stream had the capacity to dilute the waste to prevent objectionable conditions from developing. The sewerage systems would be designed such that the maximum amount the receiving system could dilute would be discharged. The placement of the outfalls would be changed to accommodate this requirement, not the actual amount of waste being discharged. Unfortunately, the dilution strategy completely ignored any unseen impacts imparted on a receiving water system.

Besides the increased attention given to treatment of sanitary waste, stormwater treatment was also being addressed. Whipple, *et al.* (1906) discussed the stormwater treatment operations being utilized in the U.S. The usual method instituted for combined sewer systems entailed sending as much of the storm flow/sanitary sewage mixture to the treatment plant by way of the intercepting sewer. The plant capacity was the limiting design factor for this action. 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, in most cases. Treatment plants and collection systems were typically designed to treat twice or more the 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 designed for economically, thus the sewage flows greater than the design capacity of the conveyance system would result in frequent overflows. Alternate treatment methods for combined sewage and stormwater discharges included spreading the flow on beds of coarse rocks or spreading on land (Whipple, *et al.* 1906). It should be stated that municipal sanitary sewage treatment was still in its infancy and therefore, the application of these concepts to wet weather flows was rather rudimentary.

Intensive efforts in rainfall data collection and analysis occurred in the second half of the nineteenth century in the U.S. (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).

The rain gage was the instrument used to record rainfall data. Rain gages have been in existence since man first began studying the weather and hydrology. They have developed from their beginnings as simple containers that could capture and hold rainwater. The measurement would be done manually following a storm, or a specific period of time. Gradually, the gage became more of a standardized instrument. In the mid 1800s, detailed records began to be kept for daily, monthly, and annual rainfall amounts at many stations throughout the U.S. The U.S. Weather Bureau became responsible for the administration of these stations. By the early 1900s, the rain gauge had become standardized by the U.S. Weather Bureau. The standard rain gage used consisted of a cylinder 8 inches in diameter and 2 feet high (Steel 1938). In the upper end was a funnel which discharged into a collecting tube. The tube had a cross-sectional area one-tenth that of the cylinder. A measuring stick was used to determine the height of the water in the tube. This type of measurement only provided rainfall between daily readings. Automatic recording gages were also in use in the early 1900s to determine rainfall during short periods of time (Steel 1938).

The early twentieth century witnessed the attempt to describe the rainfall-runoff process more accurately (Rafter 1903; Gregory 1907; Hoyt 1907; Grunsky 1908; Justin 1914; Buerger 1915; Meyer 1915; Grunsky 1922, to mention a few). 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 accumulation 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 others modified it or applied in different manners subsequently (Pettis 1938; Brater 1939). Since reliable rainfall-runoff data were rare, it was difficult to develop unit hydrographs for most drainage basins. To solve this problem, others developed methods to utilize the UH principles on ungaged watersheds. The derivation of these synthetic unit hydrographs was typically based on the characteristics of the watershed (Snyder 1938; Clark 1945).

Economical and adequate design of wet weather sewer systems was possible with a knowledge of only 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 (UH), no design strategy had considered using the runoff hydrograph and storm hyetograph, only the peak rate of runoff was utilized.

Following from the UH applications, a renewed interest in the rainfall-runoff process was observed in the 1940s. Methods for determining runoff from rainfall had been based on coefficients of some type to account for the losses of rainfall that were observed. In the late 1930s and early 1940s, the abstractions from rainfall became a concentrated topic of research. This extended the idea of using hydrograph techniques for design in lieu of the peak discharge rational methods. Horner and Flynt (1936) first applied the 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. Horner and Jens (1942) developed a methodology to mathematically describe the process of infiltration, among other abstractions and apply the hydrograph techniques to a small basin, with the opportunity for application to a larger basin. Linsley and Ackerman (1942) also presented rainfall losses as being an important part of the rainfall-runoff process that had previously been dealt with using coefficients.

Procedures for UH synthesis from watershed characteristics were developed by Snyder, Clark, and others (Snyder 1938; Clark 1945). The idea that urban runoff hydrographs could be synthesized was originally developed by Hicks. He determined correlation's of certain drainage area properties that could be utilized in the estimation of runoff hydrographs for the City of Los Angeles (Hicks 1944). Practical applications of hydrograph techniques to wet weather design in urban areas also were reported for Chicago and Cleveland soon after Hicks presented the method applied to Los Angeles (Stanley and Kaufman 1953). Hicks' method was criticized because it was too complicated for practitioners to apply, but a revised methodology was utilized in the Chicago and Cleveland applications (Eagleson 1962).

Progress in sewer design during the 1950s was realized in the improved inlet hydrograph and maximum sewer flow rate predictions. Tholin and Keifer presented information and techniques which permitted estimation of runoff from urban areas of various physical properties for a range of storm rainfall characteristics (Tholin and Keifer 1960; Eagleson 1962). In addition, the routing of the flows through the wet weather system (gutters, lateral sewers, main sewers, etc.) to the outfall was conducted. Essentially, the hydraulics of each component of the system were described thus removing most of the fundamental objections to the rational method of design (Eagleson 1962). However, the method was too complicated and found little application amongst most practitioners, although cities such as Chicago, Baltimore and Philadelphia applied the ideas with some success (Tholin and Keifer 1960).

By the 1940s and 1950s, formulae relating rainfall intensity and duration were extended by researchers to include a term for the frequency of occurrence of specified storms (Williams 1978). Such knowledge permitted the selection of a design storm according to the extent of flood damage which might be tolerated in the event of inadequacy of the sewers. This methodology coupled with the advancements in the intensity-duration-frequency curves greatly improved the drainage design strategy. Another advancement in rainfall-runoff modeling was presented in the 1950s. Miller and Paulhus (1957) presented a technique for interrelating antecedent precipitation with season, rainfall depth and runoff response, but routine urban drainage design practice failed to reflect their contribution.

The 1930s and 1940s also became years for research into the pollution of receiving waters from overflows of combined sewage. Intercepting sewers had been the answer to limit the number of overflows, but now designs for retrofits or replacement systems were being designed with sufficient interceptor capacity to limit overflows to a predetermined amount based on receiving water quality impacts (Howell 1930; Gregory, *et al.* 1934; Stegmaier 1942). The impact on the receiving water system was based on the ability of the receiving stream to dilute the waste stream discharged. This and other environmental concerns would become increasingly important as environmental awareness increased. The development of the quality aspects of drainage design and the continued advancement of quantity aspects from 1960 to the present is detailed in the next section.

## Wet Weather Management Practices: 1960 to the Present

Much of what occurred in the late 1960s and early 1970s is still being debated and updated today. Therefore, a chronological discussion of wet weather management similar to that above is not prudent. Instead individual subjects must be addressed from their inception, documenting their development to the present day. The remainder of this section will therefore be divided into subsections pertaining to a general subject within the wet weather management genre. These subject headings are considered to be the major topics in wet weather management over the previous thirty years. The evolution of each subject heading will be discussed chronologically within the subsection. Overall, legislation, planning and design, control and treatment, best management practices, modeling, CSO and stormwater characterization, sampling and monitoring, receiving water impacts and urban hydrology constitute the major categories related to wet weather management over the previous thirty years discussed below. This list is in no way all-encompassing of the literature and topics germane to the wet weather field, but the amount of material available is extremely voluminous and consequently prohibitive to an exhaustive coverage.

The main purpose of the following discussions are to shed light on some of the major topics in wet weather management and to display chronologically the development of these topics. The review of these topics provide researchers with insights to facilitate the development of future strategies. The review of the literature should indicate areas that need improvement, areas that are saturated with attention with only small gains, and the areas that will become important in the future. Another benefit of the literature review is to accommodate researchers with a head start in their own personal work. The reviews combined with the database of references developed as part of this work, eliminate much of the library time and footwork necessary in the literature review process. This will allow researchers to conduct more thorough and detailed searches given that the preliminary work has already been done.

### *Legislation Affecting Wet Weather Management Practices*

In order to fully appreciate the development of wet weather management an overview should be conducted of important relevant legislation. Since it is sometimes difficult to tell whether the legislation brought about the scientific studies or if the scientific studies initiated the legislation and what influence public opinion had, these points are not investigated here. Rather, a review of the basic environmental laws and regulations and how they impacted wet weather management strategies shall be presented regardless of the impetus for the law.

The first environmental law passed in the United States is considered to be the Refuse Act of 1899, which made it unlawful to discharge wastes into navigable waters. The lack of improved legislation required this law to be utilized in a regulatory capacity well into the 1960s.

The original Water Pollution Control Act of 1948 (PL 80-845) provided for the organization of several water pollution control agencies within the Federal Government, but provided little in terms of regulatory "teeth." The act was amended several times from 1948 to 1972 authorizing, among other things, several environmental research centers, the Division of Water Pollution Control within the Public Health Service, and provided for some government control over water pollution (Novotny and Olem 1994).

In response to the increased environmental awareness of the 1960s on the part of its citizens, the United States passed *The Federal Water Pollution Control Act of 1972* (PL 92-500), later renamed the *Clean Water Act (CWA)*). Specific goals set forth by the act included (Lager, *et al.* 1977):

> 1. "To restore and maintain the chemical, physical and biological integrity of the Nation's waters." [Section 101(a)].
>
> 2. "Where attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983." [Section 101(a)].

This act defined a national water quality management plan and required the federal government to lead the pollution control efforts with the assistance and participation of the states. The act also required EPA to set water quality standards and develop the National Pollution Discharge Elimination System (NPDES) permitting program (Dodson

1995). Initial efforts to control pollution focused on traditional point sources of pollution, such as discharges from industrial manufacturing processes and municipal wastewater treatment plants. Although the act was meant to be a comprehensive water quality program, in practice the majority of the attention was given to point sources, while nonpoint sources of pollution received less attention (Novotny and Olem 1994).

Section 208 of the act provided for a comprehensive land-use planning process to be institutionalized. Although many planning reports were completed because of the legislation, actual implementation of them was not as ambitious. Planning and enforcement tools were extensive for point sources, but nonpoint sources became neglected in terms of regulatory enforcement (Novotny and Olem 1994).

In 1973, EPA issued its first stormwater regulations. EPA recognized stormwater discharges as point sources, but understood that stormwater discharges could not be easily controlled by traditional, "end-of-pipe" controls. Also the daunting task of issuing permits for all stormwater discharges was considered impractical (Dodson 1995). Therefore, EPA selected particular discharges considered to be significant contributors of pollution (Dodson 1995; 38FR 13530 (May 22, 1973)). Court decisions altered the regulations to require the permitting of other discharges such as municipal stormwater outfalls in 1975 (Dodson 1995).

The CWA is periodically "re-authorized" by Congress, which is usually accompanied by amendments to the act. One such reauthorization was the *Clean Water Act of 1977* (PL 95-217). This piece of legislation affected the combined sewer problem through the innovative and alternative provisions section. This act clearly established Congress' intent to encourage the development and use of alternative and innovative technology in wastewater treatment (General Accounting Office 1979). Although the act primarily mentioned treatment facilities, EPA stated that its provisions would apply to combined sewer treatment facilities as well (General Accounting Office 1979). However, the application of the act to combined sewer collection systems was never clear.

Another important set of amendments to the *Clean Water Act* was the *Water Quality Act of 1987* (PL 100-4). Important points from this act included the establishment of the National Storm Water Program (NSWP) and Section 402(p) which required a NPDES permit for separate storm sewers (Novotny and Olem 1994). The NSWP consisted of two phases (Dodson 1995):

1. Phase I provides for the regulation of the following discharge categories:
    - Discharges permitted before February 4, 1987;
    - Discharges associated with industrial (and construction) activity;
    - Discharges from large (population > 250,000) municipal separate storm sewer systems (MS4s);
    - Discharges from medium (population between 100,000 and 250,000) MS4s;
    - Discharges which the director of the NPDES program designates as contributing to a violation of a water quality standard or as a significant contributor of pollutants to the water of the United States.

2. Phase II is to conduct studies on stormwater discharges other than those covered under phase I. The studies are to characterize the pollutants in the discharges and establish procedures and methods to control the discharges as necessary to mitigate receiving water quality impacts (Dodson 1995). The EPA and state and local officials will decide the additional discharges to be permitted. Phase II was originally scheduled to begin October 1, 1992, but due to delays did not begin on schedule. It is anticipated that additional permit requirements will be made for small municipalities and urbanized areas, as well as some commercial businesses that handle industrial-type materials (e.g. gas stations) (Dodson 1995).

The EPA published its control strategy for combined sewer overflows (CSO) in 1989 (*Federal Register*, August 10, 1989). The control strategy was dependent on the NPDES permitting system. The goal was to bring all CSO discharges within compliance of the technology-based standards promulgated in the *Clean Water Act*. Other considerations of the control strategy include compliance with state standards and the minimization of water quality, aquatic biota, and human health impacts from wet weather overflows (Novotny and Olem 1994).

EPAs *National Water Quality Inventory, 1994 Report to Congress* noted that pollution from wet weather discharges was cited by States to be the leading cause of water quality degradation. Based on this report and others, EPA has concluded that wet weather discharges, both point and nonpoint sources, are one of the largest inhibitors of water quality. EPA believes that urban wet weather discharges, such as stormwater discharges, SSOs, and CSOs, should be addressed in a coordinated and comprehensive manner. To remedy this, EPA has established the Urban Wet Weather Flows Advisory Committee with an SSO subcommittee and a NSWP Phase II subcommittee. The committee will address urban wet weather problems consistent with the principles identified in the March, 1994, NPDES Watershed Strategy (Wet Weather Advisory Committee 1995). These include a place-based focus for identifying sensitive areas, targeting monitoring and watershed assessment resources to achieve the most cost effective environmental benefits, involving both watershed stakeholders and the public, and measuring progress in environmental terms (Wet Weather Advisory Committee 1995).

Wet weather discharges of concern often occur in urban areas from both point and nonpoint sources. Currently, wet weather sources which must be authorized by NPDES permits include the following (Wet Weather Advisory Committee 1995):

- Municipal and industrial stormwater discharges;
- Sanitary sewer overflows (SSO), which occur when the municipal separate sanitary sewer system's capacity is exceeded due, in large part, to unintentional inflow and the infiltration of stormwater;
- Combined sewer overflows (CSO), which occur when a combined sewer system, consisting of storm and sanitary sewage, is overwhelmed during wet weather events; and,
- Wastewater treatment bypasses, which may be used during wet weather events to prevent treatment process hindrance.

Nonpoint sources, such as agricultural runoff and drainage, are not regulated under NPDES.

The legislation pertaining to wet weather flows appears to have originated from environmental acts of Congress not specifically directed towards wet weather management. But the previous ten years has seen the expansion of the NPDES permitting system for many discharges of stormwater (MS4s, constructions sites, etc.) as a result of specific mention of stormwater in regulations.

One piece of legislation that has recently gained attention that could influence wet weather management strategies in the future is the Total Maximum Daily Load (TMDL) Program. The TMDL Program's basic goals are to identify remaining sources of pollution and allocate loadings in those places where water quality goals are not being achieved (EPA 1997). The background of the program is rooted in the CWA. The CWA has a number of provisions to restore and maintain the quality of the nation's water resources. One of these is for the States to establish water quality standards for desirable conditions of their water bodies.

Despite many provisions to improve water quality, there are still waters in the nation that do not meet State water quality standards. CWA Section 303(d) addresses the remaining waters by requiring States to identify the waters and develop TMDLs for them, with oversight from EPA. Currently, EPA is developing implementation plans for the TMDL program. The development process is incorporating feedback from States, Tribes, and the public to meet the requirements of the TMDL program. This program will impact wet weather management in areas that discharge to water bodies that do not meet State water quality goals.

### *Wet Weather Management Planning and Design*

Planning in the late 1960s was not conducted in a holistic sense. Some strategies had been presented to plan wet weather management comprehensively, but few had actually been implemented. For instance, Boyce (1949) presented a methodology for engineering planning of sewage and addressed stormwater and wastewater in the same paper, but observed them as separate systems, not in conjunction. The concept of watershed management took shape in the 1960s with the formation of Departments of Watershed Management at Colorado State University and the University of Arizona (Renard and Hawkins 1995). Additionally, the American Society of Civil Engineers (ASCE) sponsored task committees devoted to watershed management. These early institutions primarily focused on rural regions and the development of forested land to agriculture. Symposia organized by the committees covered many diverse subjects, including urbanization, water quality, and watershed development and management. Most of the topics are considered applicable today even though more than thirty years have elapsed (Renard and Hawkins 1995).

Comprehensive urban drainage became a primary concern in many metropolitan areas in the late 1960s when it was evident that different sections of a municipality had sewer systems designed by different methods and according to different standards. Often times, the surrounding communities would not organize a regional drainage plan because of competitive and antagonistic attitudes between nearby communities. The situation in Denver and surrounding suburbs displayed such characteristics and to compound the problem was expanding at a rapid rate. In the late 1960s, the Denver Regional Council of Governments contracted Wright-McLaughlin Inc. to develop a standard method of practice for drainage design in the Denver Metropolitan region. The result was a design manual for the area to encourage design engineers to use identical methods and standards during the design process resulting in a more cohesive system. The manual entitled *Urban Storm Drainage Criteria Manual* (Wright-McLaughlin Inc. and Wright Water Engineers, Inc. 1969) was used not only in the Denver region but became a template for other manuals throughout the country (Urbonas and Stahre 1993). Although the manual was thorough in its consideration of quantity control, stormwater quality control was given low priority, which is to be expected since the manual was devised for use in a flood concerned region such as Denver. But, recent improvements and updates to the manual have addressed water quality concerns.

The passage of the *Federal Water Pollution Control Act of 1972* (PL 92-500) provided for areawide planning by virtue of Section 208 of the act. The areawide planning concept was enthusiastically embraced by the planning community. Regional planning boards were organized and began to initiate the planning process in the early 1970s. The areawide, or watershed, planning philosophy became pervasive in government and community institutions. For instance, the U.S. Army Corps of Engineers invoked an *Urban Studies Program* in 1973 to develop, in conjunction with local government, realistic plans which would solve regional water resources problems (Fulton 1974). Others researched particular aspects of the planning process and how it interacted with the watershed planning concept. Walesh (1973), from a practitioners perspective, stated that hydrologic and hydraulic simulations complemented the comprehensive watershed planning technique and should be considered effective tools. One interesting environmental planning philosophy was instituted in The Woodlands subdivision, located north of Houston, during its construction in 1973 (Everhart 1973). The McHarg planning technique (McHarg 1969 and 1970) was utilized to develop a plan that observed environmental constraints in addition to the usual economic and engineering constraints. The utilization of the natural drainage corridors of the land, regardless of the cost effectiveness, constituted a major adjustment in design practice for the time (Everhart 1973). It was the philosophy that an environmental design might cost more in the short term, but over the long term would prove the most cost effective.

The EPA influence in areawide planning took the form of a voluminous planning strategy and design manual entitled *Areawide Assessment Procedures Manual* (EPA 1976). The objective of this series of documents was to provide a "unified technical framework for the analysis of complex areawide wastewater problems." In addition to this manual, other published planning guides influenced the regional planners in addressing wet weather management concerns. For example, *SWMM Level I: Preliminary Screening Procedures* (Heaney, *et al.* 1976) documented a simplified approach to permit preliminary screening of alternate urban stormwater quality management plans, which included the 208 plans. Another planning guide entitled *Water Quality Management Planning for Urban Runoff* (Amy, *et al.* 1974) provided planners with a tool to obtain a first approximation, or assessment of the magnitude of the stormwater management problem. Other planning strategies continued to be presented (Field, *et al.* 1977a), some became implemented, others not.

None of the manuals published addressed design or implementation extensively. Examples of 208 planning projects began to surface in the late 1970s in the literature (Spooner, *et al.* 1978). However, problems still existed concerning implementation of the developed plans. McPherson (1978b) outlined considerations needed for planning agencies to better understand the concerns of local governments to facilitate implementation of areawide plans for stormwater management. McPherson (1978a) also addressed the fractionalized authority of administrative agencies and balkanized governments in metropolitan areas as causes of some of the problems with 208 implementation. The gap in communication between the local governments implementing stormwater management plans and the regional planning agencies is still in existence today. Whipple (1980) later reviewed the 208 planning projects and determined that most had been poorly done. He attributed this to the inadequate data used in the planning process and the lack of anticipated technological advances. His recommendation was to define the environmental objectives prior to optimizing the system from the economical standpoint. Although much of the 208 planning did not produce anticipated results, some did. Poertner (1980) discusses some of these innovative successes in drainage planning.

The late 1970s saw the relationship between land use and stormwater management being defined. Much was published indicating that land use had an impact on the surrounding environment, therefore management schemes could be developed specific to certain land uses. However, the pollution and hydrologic characteristics of each land use had to first be described (Grigg 1985). Papers and reports were prepared, exemplified by the American Public Works Association (APWA) publication *Urban Stormwater Management* (APWA 1981).

The impact of urbanization was a recurring theme in much of the land use studies. It was shown that increased urbanization had a myriad of adverse impacts to the hydrology, water quality, geomorphology, and other characteristics of the watershed. Therefore, it was important to address wet weather management in urbanizing areas to mitigate the impacts caused by the urbanization. A study was undertaken by Berwick, *et al.* (1980) sponsored by EPA with the purpose of formulating planning strategies for residential developments to reduce the documented impacts of urbanization. The report discussed several aspects of the planning process from the wet weather management perspective including: estimating pollutant accumulation and washoff from street surfaces, the development of production functions for evaluating stormwater control options, stochastic models, cost models, and the evaluation of political and social problems concerning wet weather management in residential areas.

Besides improvements in the overall planning strategy, improvements were also realized in design, particularly of storm sewer networks. However, quantity consideration was the common improvement researched. Optimization techniques to determine the optimal cost designs of sewer networks developed in the late 1960s. Linear programming optimization was an early method utilized to determine the least cost sewer network design (Hollang 1966; Deininger 1969; Dendrou, *et al.* 1978; Froise and Burges 1978; Elimam, *et al.* 1989). Elimam, *et al.* (1989) presented a recent method applying a heuristic approach to determine the optimal cost design by linear programming. The early applications stressed wastewater collection systems, but the methodology was applicable to storm sewer networks as well.

Dynamic programming also became a tried method for optimization of sewer networks by a number of researchers (Tang, *et al*. 1975; Mays and Yen 1975; Miles and Heaney 1988). Miles and Heaney (1988) implemented a dynamic programming algorithm on a spreadsheet showing that the spreadsheet was a tool capable of performing engineering design calculations.

The new methods of optimization improved the design of sewer networks, but the major innovation in design was, of course, the development of computer applications and models in the late 1960s. The advancement of wet weather management modeling is discussed below so only a brief mention will be made here. Yen and Sevuk (1975) compared two computer models (ILLUDAS and SWMM) with several other calculation methods and simple routing procedures. Their results indicated that supposedly innovative methods such as the British RRL (a method from England that was applied to U.S. storm sewer network design in the early 1970s (Terstriep and Stall 1969; Stall and Terstriep 1972)) and the Chicago Method did not perform better than the simple routing procedure, although they entailed more complex calculations. In addition, they also determined that the computer models produced the most accurate results consistently, supporting the contention that computer simulations were superior to empirically derived relationships for design purposes.

Although these new methods for sewer network design had been developed, design engineers continued to use the simpler methods such as the rational method (Yen, *et al.* 1974). A survey conducted in 1969 of design engineers throughout Wisconsin attempted to document the storm drainage design practices of 32 cities in Wisconsin (Ardis, *et al.* 1969). The survey indicated that comprehensive planning of cities was taking place, but some plans did not consider urban drainage (Ardis, *et al.* 1969). The design of storm sewers in the 32 cities was primarily done (95.8%) by city engineering departments, under the supervision of a professional engineer. The dominant design strategy employed was the rational formula, however, only a small fraction of the cities utilized it correctly. The primary problem in the application of the rational method involved the runoff coefficient and the time of concentration and its relation to the intensity of rainfall (Ardis, *et al.* 1969).

As part of this current project, a survey has been conducted of many design engineers similar to that conducted twenty-eight years ago by Ardis, *et al.* (1969) except this survey is on a national scale. The results of this survey are presented in Section 4 of this report and provide interesting comparisons between current practices and those of thirty years ago.

Since the late 1970s, sewerage design research has stressed quality considerations more than quantity. The last decade and more has witnessed little improvement in the capabilities design engineers have in the sizing of sewer pipes in networks. However, major advances have been made in the use of these older methods through the use of computer methods (such as the EPA's Storm Water Management Model, or SWMM). New methods have been developed, but often the practitioner is content to remain with the old method that addresses the quantity issue adequately. More emphasis is placed on management practices to reduce the impact of pollutants on the receiving water systems. Since quantity and quality concerns are often competing ends, an optimal point must be attained whereby the most cost effective design procedure is devised to address the quantity and quality issues optimally for a given watershed. Appendix A presents a detailed discussion of integrating quality and quantity objectives in drainage design.

The traditional design storm concept of wet weather management has been criticized for the better part of thirty years. Yet, the rational method and other design storm concepts continue to be applied. The design storm method does not provide an ecosystem-sensitive design, and over long terms could be detrimental to the environment (James 1994 and 1997). James concludes that the attainment of eco-sensitive stormwater drainage design demands the use of continuous modeling (James 1994 and 1997). Many applications of continuous simulation in wet weather design have been documented. Continuous simulation has been shown to be applicable to watershed management (Ellis, *et al.* 1981) and to the design of detention structures (James and Robinson 1982; Loganathan, *et al.* 1985; Ormsbee 1987). Ormsbee views the most lacking aspect of design storm methodologies as being the ignorance of antecedent moisture content, resulting in the assumption that the runoff event has the identical frequency as the rainfall event. Klemes looked at this problem and found that the assumption is, in fact, not true (Klemes 1987) and the runoff event frequency rarely is equivalent to the rainfall event frequency. The motivation and capabilities for continuous simulation design procedures exist, yet many practitioners fail to embrace the technology in wet weather design strategies.

The recent emphasis in wet weather planning continues to include watershed management considerations which were introduced in the 1960s. This is evidenced by the numerous conferences that have convened over the previous five years dedicated to watershed management (e.g. National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels (1993); Watershed '96: A National Conference on Watershed Management (1996); Watershed Management: Planning for the 21$^{st}$ Century (1995); Effects of Watershed Development and Management on Aquatic Ecosystems (1996)) not to mention the numerous papers and reports presenting watershed management techniques. Current issues related to wet weather management being addressed at many of these conferences and symposia include:

- Geographic information systems
- Remote sensing
- Decision support systems

- Sustainability and risk analysis
- Watershed planning
- Ecological planning
- Integrated water resource planning and design

Although the watershed management terminology has been around for twenty five years, it does not retain exactly the same definition. Previous watershed planning strategies accounted for wet weather management on a watershed scale for both quantity and quality. However, currently, the trend is watershed management in an integrated fashion. Field (1993) presents a description of what is meant by integrated stormwater management. He indicates that the most effective solution for wet weather management problems must consider (1) wet weather pollution impacts on receiving water systems, (2) structural versus non-structural techniques for control, (3) integrating dry and wet weather control/treatment systems to maximize the usage of dry weather facilities during wet weather events and conversely wet weather facilities during dry weather, and (4) the optimally cost-effective degree of control/treatment required dictated by load discharge or receiving water requirements (Field 1993). Overall, the flood and erosion control technology must be integrated with pollution control technology to provide comprehensive planning that is effective. Research addressing the topic of integrated wet weather management is also taking place in Europe (Harremoës and Rauch 1996; Rauch and Harremoës 1996). Their comprehensive plans entail considering the sewer systems, treatment plants, and receiving waters in a coordinated fashion.

### *Wet Weather Control and Treatment Practices*

This section will focus on the development of downstream, or "end-of-the-pipe," control and treatment technology in wet weather management. The next section pertains to best management practices consisting of source controls, regulations, and education. Many control and treatment options can be implemented at the end of a sewer system to provide flood and pollution mitigation benefits. The mechanisms used to control or treat the wet weather flow can be physical, chemical, biological, or some combination of these. The process is generally structural and man-made, but nonstructural, natural techniques such as wetlands have been applied successfully. With these thoughts in mind, the highlights of the development of wet weather control and treatment options will be presented.

The impacts of CSO and stormwater discharges on receiving waters became increasingly apparent in the early 1960s. Prior to 1960, the impacts of the CSO problem on receiving waters had been studied by some (Stegmaier 1942; Hess and Manning 1950; Palmer 1950; Camp 1959), but was not accepted as a problem by all. The proponents of the dilution strategy still existed (Adeney 1928). The main thrust of the research was water quality studies and the effects that CSOs imparted to the receiving system. The CSO problem was viewed by some to be a nationwide problem in the 1950s (Palmer 1950; Camp 1959), but the funding was not available to remedy the situation.

Increased public environmental awareness in the 1960s spirited by, among other things, the publishing of Rachel Carson's *Silent Spring* (1962) and a general outcry for cleaner water provided the impetus for additional research into water pollution control. The CSO was targeted as a significant pollution source, and thus required attention. The above discussion of wet weather management from 1860 to 1960 mentioned the primary method for treatment during the late 1800s through the first half of the 1900s of combined sewerage was to intercept a certain amount and transport it to the dry weather wastewater treatment plant. The inability of the intercepting sewer to adequately transport the entire combined sewage load during wet weather events resulted in CSO. The only way to guarantee the capture of all combined sewerage was to build uneconomically large interceptor sewers. This was not practical so researchers sought alternate solutions that restricted the occurrence of CSOs to a minimum. Alternate solutions included separating the sanitary sewer system from the stormwater system, in-system storage, ponding, holding tanks and screening and chlorination of remaining CSOs (Dunbar and Henry 1966). Similar to increasing the size of the intercepting sewer, these methods also proved uneconomical, impractical, or ineffective. In turn, physical, chemical, and biological treatment techniques, some borrowed or adapted from dry weather wastewater treatment technology, became applied to CSO and stormwater discharges as unit processes or as part of an overall treatment train.

The remainder of this subsection is divided into four categories depicting the major areas of control and treatment of wet weather flows. The categories are based on the underlying processes that result in the control and treatment of the flow. The four sections are physical control and treatment, chemical treatment, biological treatment, and storage/release systems. There is overlap between these sections by many of the techniques utilized in managing wet weather flows, but processes are only discussed in one section when applicable. For instance, a detention basin relies on the physical process of settling to remove suspended material, but under certain circumstances, biological activity can occur that further treats the runoff. The same can be said of storage/release systems which might utilize physical processes in detention, then chemical and biological processes during treatment. Appendix D of this report details the literature pertaining to many of the control and treatment processes briefly introduced here, as they are applied in the Source Loading and Management Model (SLAMM).

**Physical Control and Treatment Processes**

Physical treatment processes offer several advantages for the treatment of wet weather flows (Field 1990). First, they are adaptable to automatic operation, including rapid startup and shutdown. Second, their resistance to shock loads is a requirement when considering wet weather events. And third, physical treatment methods have the ability to consistently produce a low suspended solid (SS) effluent. Physical treatment unit operations include screening, straining, filtering, settling, and flotation. The application of these processes are incorporated into many control techniques.

One type of physical control technique involved the application of swirl and vortex technologies. Smisson utilized a cylindrical vortex-type CSO regulator/settleable-solids concentrator in England during the 1960s (Smisson 1967; Field and O'Conner 1996). The U.S. Environmental Protection Agency (EPA) funded a series of research projects in the mid 1960s through the early 1970s investigating swirl technology (Sullivan, *et al.* 1972; 1974; 1976; 1977; 1978; and 1982). The EPA-sponsored projects developed the swirl concentrator/regulator for controlling CSOs (Sullivan, *et al.* 1972). The dual functioning swirl concentrator/regulator could achieve both quantity and quality control of CSO and stormwater discharges. Settleable solids removals have been observed in field studies to be as high as 40-50% (Field 1990) for the swirl concentrator. Combine these benefits with the fact that the swirl has no moving parts, and the result is a viable option for CSO and stormwater discharge control.

A product of the EPA-sponsored studies included several general conclusions regarding the application of swirl technology in controlling and treating CSO and stormwater discharges. It was concluded that the swirl technology in principle could be utilized to obtain clarification of wastewaters, including CSO and stormwater discharges (Sullivan, *et al.* 1978). The absence of moving parts in the swirl concentrator made it an easily maintainable device with minimal operation and maintenance costs (Sullivan, *et al.* 1982). Another benefit observed during the studies was the effective use of limited space by the swirl concentrator. Generally, areas requiring CSO or stormwater discharge control and treatment are urban and therefore space constrained. A device such as the swirl concentrator utilizes a minimum of space to accomplish its task, which is highly desirable (Sullivan, *et al*. 1978). Other control technologies similar to the swirl concentrator include the helical bend regulator/concentrator and several commercial products such as the Storm King and Fluidsep vortex-hydrodynamic separators (Field and O'Conner 1996). Unfortunately, swirl concentrator technology alone seldom results in large improvements in CSO quality.

Additional research in the 1970s and 1980s supplemented the findings of the Sullivan-led research group. Some of these researchers include Field and Masters (1977) and Pisano, *et al.* (1984). The use of the swirl technology continues to be refined today (Moutal, *et al.* 1994; Field and O'Conner 1995; Field and O'Conner 1996).

Other physical control and treatment options that were researched included filtration and screening. Filtration, using different media types and arrangements, was shown to be a viable option for the treatment of CSO and stormwater discharges in the early 1970s (Accoustica Associates, Inc. 1967; Fram Corporation 1969; Rand Development Corporation 1969; Harvey and Fan 1972; Lee, *et al.* 1972). Applications included both flow rates utilized in conventional dry weather wastewater treatment and high flow rates tailored to the wet weather event (Lager, *et al.* 1977). Dual media high-rate filtration was found to be effective in reducing the suspended solids and heavy metal concentrations in wet weather flows (Field 1990). Currently, the use of filtration is being targeted for upland and source controls in addition to 'end-of-the-pipe' controls.

The screening of wet weather flows, similar to filtration, proved effective at reducing the suspended solids loading and loading of pollutants associated with suspended solids (Cornell, *et al*. 1970; Envirogenics Company 1970; City of Portland 1971). Screens of various types and with various size openings were implemented with varying degrees of success. Benefits of screening were also realized by applying the process as pretreatment for other processes such as microstraining, dissolved air flotation and disinfection (Rex Chainbelt, Inc. 1972; Gupta, *et al.* 1977; Meinholz 1979). Advantages of dissolved air flotation over conventional settling include higher overflow rates, shorter detention times, and the ability to remove particles with densities higher and lower than the liquid flotables such as oil and grease (Field 1990). The advantages of dissolved air flotation are especially apparent in applications to CSO control and treatment.

The retention or detention of stormwater and CSO was also researched to determine its efficacy for treatment (Springfield Sanitary District 1970). Storage in one form or another is the best documented abatement measure, and can equalize flows and reduce flood peaks as well as facilitate the removal of pollutants through settling. Storage has been a planned element of wet weather management since the 1800s (Chittenden 1918). It was originally applied in the form of detention basins in Germany and England before being implemented in the U.S. Wet weather storage facilities can be classified as either in-line or off-line. In-line storage requires no pumping, and consists of storage within the sewer system itself or in-line basins (Field 1990). Off-line facilities for storage include basins and tunnels, and typically require pumping facilities for operation (Nix and Durrans 1996).

Currently, detention in one form or another is the most often implemented form of wet weather control (Urbonas, *et al.* 1994). Planning methods for detention on both the small scale and large scale have been developed over the previous thirty years (Wenzel, *et al.* 1976; Mays and Bedient 1982; Ormsbee 1983). Besides planning, the design of detention basin has also been an oft researched topic (Rao 1975; Ormsbee 1987; Segarra-Garcia and Loganathan 1994). The use of detention for the dual purpose of flood control and pollutant removal has been studied in more recent times (Whipple 1979; Jones 1990). The topics introduced here are only a brief indication of the ubiquity of the practice of detention in stormwater management. Further support is observed in the number of textbooks and design manuals that have been published pertaining to the subject, Urbonas and Stahre (1993) for example and conferences covering the topic, DeGroot (1982) for example.

In addition to traditional detention devices, underwater storage and in-receiving water storage were determined to be marginally successful in the control of CSO and stormwater discharges (Melpar 1970; Karl R. Rohrer Associates, Inc. 1971). Karl Dunkers, from Sweden, developed unique and effective in-receiving water approaches to wet weather management to protect lake water from pollution (Field 1990; Forndran, *et al.* 1991). The technology has since been applied in the United States (Field, *et al.* 1992). Tunnel storage has also become an option for some large urban areas that need storage space but do not have the real estate to devote to detention. Chicago is a prime example of this type of alternate strategy for detention (Robinson 1986).

Alternative techniques for CSO treatment have continued to develop up to the present. One alternative disinfection technique which requires short detention times and precludes the development of toxic by-products is disinfection by ultraviolet (UV) light irradiation (Scheible and Forndran 1986; Scheible, *et al.* 1991). Other alternative treatment techniques that can attain high pollutant removal rates include high gradient magnetic separation (Allen 1977; Allen 1978) and powdered activated carbon (Lager and Smith 1974). These advanced techniques are cost prohibitive and therefore are implemented only in cases when the effluent quality must be very high.

**Chemical Treatment Processes**
Chemical disinfection had been the traditional method for treatment of sanitary wastewater, but stormwater and combined sewage were generally not treated in a comparable manner due to the assumption that disinfection of dry weather flow resulted in effective protection of receiving water systems (O'Shea and Field 1993). Several studies which addressed the treatment and disinfection of stormwater and CSO were conducted during the 1960s providing evidence that treatment should be required and that the large variations in flows were the principal problems to be overcome for the chlorination procedure to be effective (O'Shea and Field 1993). The use of chlorine ($Cl_2$) and chlorine dioxide ($ClO_2$) and other chemical disinfectants was shown in several applications of high-rate disinfection processes to result in significant bacterial population reductions in CSO (Cochrane Division, Crane Company 1970; Roy F. Weston, Inc. 1970; Moffa, *et al.* 1975; Drehwing, *et al.* 1979). Other chemical oxidizing agents that can be applied include bromine and hydrogen peroxide and their compounds.

To improve the disinfection process, microstraining and screening and various other unit processes were added to the treatment train to remove and/or fragment particulate and organic matter containing bacteria prior to disinfection (Cochrane Division, Crane Company 1970; Shuckrow 1973; Glover and Herbert 1973; Maher 1974; Drehwing, *et al.* 1979). The reduction of coliforms across the microstrainer were found to be minimal, but the effluent required less chloride for disinfection and shorter detention times (O'Shea and Field 1993). Drawbacks with the screening process included operational problems during start-up and initial performance (Drehwing, *et al.* 1979). However, overall, the research into the application of high-rate physical and chemical treatment processes was found to be a viable and economical technology in most situations (Drehwing, *et al.* 1979).

**Biological Treatment Processes**

Biological methods also garnered some attention for CSO treatment (Storm and Combined Sewer Pollution Control Branch 1970; Welch and Stucky 1974; Agnew 1975). Due to the random, intermittent nature of wet weather flows, CSO and stormwater discharges are a difficult waste stream to treat, especially with biological methods which require a specific range of conditions to remain viable. Biological treatment methods applied to CSO and stormwater treatment include rotating biological contactors (Welch and Stucky 1974), contact stabilization, trickling filters (Homack, *et al.* 1973; Parks, *et al.* 1974) and treatment lagoons (Connick, *et al.* 1981). Biological treatment methods can have high pollutant removal efficiencies although they are susceptible to shock loadings. The biological treatment processes are typically termed secondary, and depending on the situation, can remove 70-95% of the $BOD_5$ and SS for ranges of 30 to 10 times dry weather flow, respectively (Field 1990). The biological treatment processes utilized for wet weather management are typically part of dry weather treatment facilities.

Wetlands are becoming an increasingly popular method for the control and treatment of wet weather flows. They have the advantage of providing flood control and pollutant removal capability similar to the detention basin. Natural wetlands can be used for stormwater management, but in most situations engineered and constructed wetlands provide for the best compatibility between the system and the desired control and treatment. Another advantage of the wetland over most other control and treatment technologies is the fact that it offers a sustainable option for wet weather management which is becoming more and more important. A thorough review of the literature pertaining to stormwater wetlands was conducted by Strecker (1993) therefore the reader is directed to this source for additional references.

**Storage/Release Systems**

During the 1970s, the prominent means of control of urban stormwater quantity and quality was through some type of storage/release system (Heaney, *et al.* 1977; Lager, *et al.* 1977; Finnemore 1982). The storage/release system remains an integral part of wet weather management strategies in the present day. Storage/release systems provide storage to capture a portion of the highly variable stormwater flows and pollutant loads and a release process through which the contents are released in a more controlled fashion (Nix 1982). If the release is input to a wastewater treatment plant or a treatment unit process, the terminology storage/treatment is applied to the system. The storage of wet weather flows can also act as a treatment process, with settling and biological mechanisms improving the water quality. Therefore, often the terms storage/release and storage/treatment are used interchangeably. Although detention basins are the primary structure used for storage/release systems other appurtenances, such as rooftops, parking lots, catch basins, and sewer systems, can be utilized in this capacity (Nix 1982).

An example of a successful implementation of a storage/release system in the late 1960s was documented by EPA for a site located in Chippewa Falls, Wisconsin (City of Chippewa Falls 1972). The demonstration was undertaken to determine if CSO could be mitigated by storing the overflow and subsequently pumping it to a dry weather wastewater treatment plant. The results indicated that storage with ensuing treatment was a viable alternative for wet weather management.

The benefits of storage/release combinations for controlling wet weather flows continued to become evident. The progression during the 1970s resulted in the inclusion of storage/treatment options in the state-of-the-art update for urban runoff pollution control compiled by Field and Lager (1975). At that time, storage/treatment strategies were considered the most promising approach to urban stormwater management. Following the study conducted at

Chippewa Falls, other investigations were conducted and resulted in additional support for the effectiveness of storage/release systems (Consoer, Townsend, and Associates 1975; Lager, *et al.* 1977).

The storage/release system might have been shown to be a viable alternative by these case studies, but the incremental amounts of storage constructed and treatment capacity provided were not being determined in an optimal fashion in most cases. Original methods of determining the best combination were characterized by trial and error economic calculations and design storm calculations (City of Chippewa Falls 1972; Field and Lager 1975). The application of optimization techniques to determine the most cost effective combination of storage and treatment for a specified performance standard came in the mid 1970s.

The central focus of most of the research into optimization of the storage/release alternatives involved the application of microeconomic theory, of which a characteristic was the production function. The production function, as applied to the storage/release system, was represented by a series of plotted curves depicting the combinations of storage and treatment required to attain specified levels of system performance. These curves were termed isoquants and could be used in combination with cost data and an optimization algorithm to determine the least cost design for a specified level of pollutant control.

Storage/release system optimization applying microeconomic theory became a thoroughly researched area during the 1970s (Heaney, *et al.* 1976; Howard 1976; Heaney and Nix 1977; Heaney, *et al.* 1978; Flatt and Howard 1978; DiToro and Small 1979; Small and DiToro 1979; Howard, *et al.* 1981; Medina, *et al.* 1981a and 1981b; Nix 1982). A cost effective use of storage and release or treatment strategies was sought that would optimize the runoff attenuation and pollutant removal capabilities of the system for the minimal cost. The effectiveness of a storage/release strategy is based on the long-term pollution control performance. Methods to estimate this performance can be divided into three categories: (1) empirical relationships, (2) statistical techniques, and (3) deterministic simulation (Nix 1982; Nix *et al.* 1983; Nix and Heaney 1988). Sediment trap efficiency curves developed by Brune (1953) and others exemplify empirical relationships. Performance data from a number of reservoirs were used to derive the trap efficiency curves.

Statistical approaches were developed, based on several simplifying assumptions concerning the statistical nature of runoff events as well as the operation of a storage/release system (Howard 1976; Flatt and Howard 1978; DiToro and Small 1979; Hydroscience, Inc. 1979). Howard (1976) introduced a statistical methodology to analyze the long-term performance of storage/treatment systems for controlling CSO. In the procedure, probability distribution functions of precipitation volume, duration, and interevent time were derived. Together these functions coupled with other estimated parameters determined the probability distribution function of overflow volume. From this derived distribution, the frequency of overflow and the magnitude of overflow volumes were derived. This method, in combination with other analyses, was useful for estimating the overall cost of pollution control alternatives.

In the same time period as Howard, others were also developing statistically based methods to analyze storage/release systems (DiToro and Small 1979; Hydroscience, Inc. 1979). Adams and Bontje (1983) extended the principles of these researchers in developing analytic probabilistic models to predict the performance of storage/release systems. This technique was formulated into a computer package, termed Statistical Urban Drainage Simulator (SUDS) (Guo and Adams 1994). SUDS was expanded in the early 1990s to include water quality aspects of wet weather management (Li 1991; Li and Adams 1993).

Another extension of the statistical methods developed in the late 1970s used to determine the optimum storage/release strategy was presented by Segarra and Loganathan (1989). This method was based on a first-order pollutant washoff model for defining the pollution control isoquants. Enhancements to this methodology continued to be developed in the 1990s (Segarra-Garcia and Loganathan 1994; Segarra-Garcia and El Basha-Rivera 1996).

Computer simulation approaches were developed prior to Howard's statistical approach in the early 1970s (Howard 1976). The U.S. Army Corps of Engineers developed a model titled Storage, Treatment, Overflow, Runoff Model (STORM) (U.S. Army Corps of Engineers 1977). This model was developed with the intent to simulate stormwater storage/release systems for performance analysis purposes. The early versions of the EPA Storm Water Management Model (SWMM) did not have the capability to perform the continuous simulations required to conduct the proper analyses, therefore STORM was predominantly used in research efforts in the 1970s. As SWMM was updated in the late 1970s and the early 1980s, it became the preferred tool compared STORM.

One computer simulation approach, presented by Heaney, *et al.* (1976) introduced a preliminary screening model to determine the optimal use of storage-treatment options in wet weather pollution control. They used the production function to devise optimal combinations of storage and treatment based on unit costs of storage and treatment alternatives (Nix 1976 and 1982; and Heaney and Nix 1977). Nix (1976) extended the storage/treatment optimization approach applied by Heaney, *et al.* (1976) to include other wet weather management options such as source controls, best management practices, and other structural and non-structural controls. Additional adjustments to the computer simulation approach introduced by Heaney, *et al.* (1976) were made by Heaney and Nix (1977), Heaney *et al.* (1978), and Heaney (1979). Nix (1982) reviewed most of the statistical and simulation approaches developed in the 1970s and developed an improved Storage/Treatment Block for SWMM. Nix and Heaney (1988) capitalized on the improved electronic spreadsheets and spatial analysis software available to enhance the optimization procedure.

Computer modeling capabilities continued to improve in the early 1980s which enhanced the application of the optimization methods developed in the 1970s (Medina, *et al.* 1981a and 1981b; Nix 1982; Huber, *et al.* 1984; Huber and Dickinson 1988). The EPA SWMM (Huber and Dickinson 1988) and STORM (U.S. Army Corps of Engineers 1977) models remained the two more popular models utilized to simulate storage/release systems.

The traditional strategy of storage/release system implementation revolved around the construction of additional storage and treatment facilities. Field, *et al.* (1994) adjusted this focus somewhat by stressing the use of in-system storage and improving current treatment plant operating efficiency prior to constructing additional units of storage and treatment. This "integrated" optimization strategy attempts to minimize the construction of additional storage and treatment facilities by (Field and O'Conner 1997):

- Maximizing storage and treatment in the current system through operational and low-cost inline improvements,
- Considering the sedimentation which occurs when storage tanks overflow,
- Selecting design capacity of control options in the most economical fashion by choosing the point of diminishing returns on the curve of pollution control versus cost, and
- sizing the storage/treatment system in the most optimal fashion.

The strategy stresses that the cheapest potential wet weather management components should be analyzed first, and then the less economical retrofits and additional construction options should be evaluated. This is similar in theory to a strategy that has been implemented in Europe for the previous ten years which involves optimizing the location and then size of controls. In addition, the European method concentrates on improving short-term control goals providing a platform for long-term goal achievement (Wildbore 1994). Wildbore (1994) explains that implementing smaller structures higher up the system allow much less pollutant load per unit of expenditure and that system wide searches for improvements should be conducted to provide overall cost savings.

**Control and Treatment Planning**

As individual treatment techniques developed, comprehensive strategies for mitigating CSO and stormwater discharges progressed. The discussion of CSOs continued in the literature with more refinement in treatment techniques, including increased case studies of bench and full scale applications (Field and Lager 1975; Lindholm 1976; Larson 1979). Due to the increased knowledge pertaining to CSO control and treatment, efforts of the engineering community could be directed towards the development of planning strategies to mitigate CSO and stormwater impacts from a watershed perspective. This ideology supplemented the watershed planning schemes already being advanced from the 1960s. The previous subsection discussed wet weather planning and design from a general perspective, therefore only a brief mention of specific planning for CSO control and treatment will be made here.

There was enough knowledge being gathered to facilitate the initiation of conceptual planning for CSO control (Field and Struzeski 1972; Parks, *et al.* 1974; Field and Lager 1974; Giessner, *et al.* 1974; Labadie, *et al.* 1975;

Mahida 1975; Janson, *et al.* 1976; Griggey and Smith 1978). Giessne, *et al.* presented a master plan for wastewater management in the San Francisco area (Giessner, *et al.* 1974). The main goal of the plan was to adequately and economically treat dry weather flows, provide for flood protection from the 5-year frequency design storm, and to mitigate the combined sewer overflow impacts on the receiving water system. These goals could be applied to most urban areas which have combined sewerage systems. Some of the other strategies included such topics as real-time control.

Comprehensive planning of wet weather management systems can be implemented in a number of ways. One way, which is the most popular, is to insert control and treatment options throughout the urban watershed that operate as standalone units with some collaboration. Another, improved but more expensive, manner to implement a planning strategy is through real-time control (Anderson 1970; Labadie, *et al.* 1975; Roesner 1976 Coffee, *et al.* 1983; Grigg and Schilling 1986). Real-time control refers to the control of a wet weather systems during a wet weather event by using monitoring and remote control of control and treatment units in conjunction. The optimal use of this technology has indicated that it can be an effective means to manage wet weather flows (Nielsen 1994).

### *"Best Management Practices"*

"Best management practices" (BMP) are the first line of action to control wet weather pollution. By treating the problem at its source, or through appropriate regulations and public education, multiple benefits can be derived (Lager, *et al.* 1977). Some of the benefits realized as a result of BMP implementation include lower costs for downstream controls and treatment, lower cost for conveyance and collection systems, erosion and flood control benefits, and an improved and cleaner neighborhood. BMP success is dependent on many factors, but primarily on legislation or ordinances promulgated to force or encourage conformance with the intended BMP, and a concerted effort to monitor compliance and educate not only those responsible for regulation, but the public as well (Lager *et al.* 1977). The greatest difficulty faced by BMPs is that the action-impact relationships are almost totally unquantified. The reader is referenced to Appendix D of this report for a thorough discussion of source quality controls and the literature pertaining to selected stormwater management controls.

### *Wet Weather Modeling*

A mathematical model can range in sophistication from the very simple empirical equation to complex physically based equations. Countless models are in existence, but a few have had a significant impact on wet weather management. Mathematical models were developed many years ago, and range in complexity from the so called rational method (Mulvaney 1851; Kuichling 1889) to the unit hydrograph procedures (Sherman 1932; Snyder 1938) up to comprehensive computer models. The application of computers over the past thirty-odd years to the modeling procedure greatly improved the capabilities to manage wet weather flows. The use of mathematical equations in the planning and design of wet weather controls constitute elementary models. The advent of the computer greatly enhanced the capabilities of these elementary mathematical models as well as opening doors to improved approximations of the physical processes shaping the hydrology of a watershed. Besides computer models, planning and desk top models also were developed in the 1970s that had a significant impact on wet weather management. But, since some of these models are discussed in other sections of the literature review, this section concentrates solely on computer modeling.

The early applications of the computer to modeling wet weather systems involved using the swift calculating ability of the computer to perform the calculations previously done by hand. However, this process was rarely applied in practice since computers were expensive and mostly inaccessible to practitioners. Watershed modeling applications did develop at university settings during the early 1960s.

Early model developments highlighted by the Storm Water Management Model (SWMM) (Metcalf and Eddy, Inc., *et al.* 1971) had the capability to simulate individual storm events. The optimal solution to a problem was not found by the model, but rather numerous alternatives would be simulated separately and the user would have to select the optimum solution. One drawback with the individual storm event simulations was that the storm event selected did not represent the random occurrence and probabilistic nature of the real hydrologic phenomena (Metcalf and Eddy, Inc. 1971). Others were discussed in an earlier section of this report (See the *Wet Weather Planning and Design* subsection). It became apparent that most planning efforts required data on the probability of occurrence of events of various magnitudes. In most urban situations this could only be provided by the use of continuous simulation models.

Continuous simulation models differ from single event and other simulation models in that they operate under the necessity of a water balance (Linsley and Crawford 1974). In order to execute on rainfall data over long time periods, the model must contain a feedback mechanism that continuously updates and modifies various processes of the model which are dependent on the quantity of water in storage. The earliest of the modern, computer-based continuous simulation models was the Stanford Watershed Model (Linsley and Crawford 1960; Crawford and Linsley 1966), better known as the Hydrocomp Simulation Program (HSPF). In the late 1960s, numerous modifications and various applications of the model were elaborated (James 1965; Drooker 1968; Lichty, *et al.* 1968; Ligon, *et al.* 1969). This model was originally developed to simulate runoff from mostly rural basins, thereby reducing its applicability to urban drainage design. Linsley and Crawford (1974) discussed its applicability to urban watersheds.

The true dawn of the modern computer modeling age directly applied to urban drainage concerns can be placed at the time of development of SWMM in the late 1960s (Metcalf & Eddy Engineers, *et al.* 1971). Throughout the 1970s and 1980s SWMM was adjusted and updated (Heaney, *et al.* 1973; Huber, *et al.* 1975; Huber, *et al.* 1984; Huber and Dickinson 1988) developing it into the forefront of technology utilized in wet weather management. As a testament to its popularity, there are numerous proceedings from user group meetings sponsored by EPA that contain papers pertaining to practical and theoretical applications of the model (for example: EPA 1980a; EPA 1980b). In addition to SWMM, other computer models included the U.S. Army Corps of Engineers Storage, Treatment, Overflow, Runoff Model (STORM) (Hydrologic Engineering Center 1973; Hydrologic Engineering Center 1977) and the Illinois Urban Drainage Area Simulator (ILLUDAS) (Terstriep and Stall 1974). These models all contained the capability to generate runoff hydrographs and pollutographs as well as perform simple routing, which are important in the designing of drainage systems (Nix 1994). SWMM was more advanced, with the capacity to perform more sophisticated routing.

In the 1980s, computer models began to appear that would perform more than the cursory functions of generating hydrographs and pollutographs and simple routing. Models such as the updated EPA SWMM (Huber and Dickinson 1988; Roesner, *et al.* 1988) and the Quantity-Quality Simulator (QQS) (Geiger and Dorsch 1980) developed which had the capability to route flows through gutters, channels, and sewers in addition to developing hydrographs and pollutographs (Nix 1994). Many other models perform similar functions, but are not mentioned here. Brandstetter (1976) provided a thorough review of the models available for urban stormwater management modeling. Other sources should also be consulted for a more thorough review of the available commercial models (Whipple, *et al.* 1983; Huber 1986).

Applications of computer models to wet weather management had various purposes and results. The application to CSO control and treatment was a necessary step to supplement the monitoring studies that were being conducted during the mid 1970s. As far as applications, Cermola, *et al.* (1979) presented a study using the EPA SWMM model (Huber *et al.* 1975) to investigate CSOs for the City of New Haven, CT. The study investigated a plan to reduce the discharges by implementing various control measures. It was concluded that site specific characteristics and storm data were required for proper calibration and utilization of the SWMM model (Cermola, *et al.* 1979). Additional information on modeling CSO impacts and control and treatment alternatives can be found in various sources (Nix 1990; Nix, *et al.* 1991).

The 1990s witnessed the proliferation of models being integrated with geographic information systems (GIS) and graphical pre- and post-processors which greatly enhanced the input and output capabilities, but did not change the internal structure or theoretical basis of the models to any noticeable extent. Examples include XP-SWMM (XP Software 1993) which has a graphical interface for pre- and post-processing the input and output data from EPA SWMM version 4 (Huber and Dickinson 1988; Roesner, *et al.* 1988). These advancements in wet weather modeling do not impact the accuracy or theoretical basis of the models, but attempt to increase the efficiency in which the models can be utilized. Thereby, the computer models of today are more user friendly for those learning the model, but some still consider the graphical interfaces and GIS packages to be unnecessary some of the time.

Besides the modeling of the actual runoff process in the urban drainage system, models were developed to simulate loading of pollutants and others were developed to simulate the impacts of the pollutants on the receiving water system. Source models such as the Source Loading and Management Model (SLAMM) (Pitt and Voorhees 1996) were originally developed to evaluate the effectiveness of source controls.

Receiving water quality models include the Hydrological Simulation Program - Fortran (HSPF) (Johanson, *et al.* 1980; Johanson, *et al.* 1984; Bicknell, *et al.* 1993). This model includes a complete water balance accounting for both surface water and groundwater and for interactions between them. HSPF has an exceptional water quality modeling capability represented by the ability to simulate a suite of pollutants and lower level organisms. Medina (1979) developed a simplified receiving water quality model that provided continuous simulations. Its purpose was to provide preliminary screening of areawide wastewater treatment strategies for planning decision making. The model can simulate the response of a steam or tidal river system to effects from wet weather sources, dry weather sources and upstream sources. The model output included a dissolved oxygen sag curve and dissolved oxygen profiles at selected points downstream.

The EPA developed some stream models in house for determining the effects of stormwater runoff on the receiving water system (Smith and Eilers 1978). These mathematical models simulated the physical, chemical, and biological reactions that occur in a flowing stream. The pollution loads on the stream could be specified as steady-state or transient. One model computed the dissolved oxygen (DO) deficit in the stream as a function of time and distance along the stream caused by specified stormwater overflows. The other model simulated the hydraulic effect on the stream from large overflow volumes.

Many other models are in existence, some developed by commercial software companies and some developed by government agencies (U.S. Army Corps of Engineers, EPA, for example) that are more than adequate for wet weather modeling. The studies that have tried to compare the accuracy of the models have resulted in inconclusive results. Usually it is recommended that the model be selected to meet the needs of the user. It is also often mentioned that the model cannot replace reliable data gathered with careful monitoring and sampling.

### *CSO and Stormwater Characterization*

Logic would dictate that prior to attempting to solve a problem, the problem must first be defined. Following this philosophy, in order to address a stormwater runoff or combined sewer overflow problem, an investigator must have knowledge of the characteristics of the problem. The characteristics of stormwater runoff and CSO can be divided into source characteristics and quality characteristics, among other ways. Sources of pollutants can originate from the air, land, or other water sources. The source of pollution known, measures can be implemented to mitigate the impacts caused by the source, through source controls, best management practices, etc. In addition, if the stormwater quality characteristics are known control measures specific to those quality parameters can be implemented in-system or at the "end-of-the-pipe." Detailed studies to determine the sources and quality of wet weather flows originated in the late 1960s, parallel to the development of specific treatment techniques for CSO.

An understanding of the potential sources of wet weather pollutants is of primary importance when studying the impact of urban runoff. Several early studies concentrated on runoff from roadways and other impermeable surfaces. Runoff from impermeable surfaces in an urban environment has been shown to be a significant source of pollutants. Sartor and Boyd (1972), for instance, developed relationships for the accumulation and washoff of pollutants from street surfaces. They also characterized the quality of the stormwater from several types of land uses. Pitt and Amy (1973) characterized the toxic pollutants that originated from the surface of streets in urban areas. Other studies around the United States determined the quality of stormwater runoff (Davis and Borchardt 1974; Colston 1974; Black, Crow & Edisness, Inc., *et al.* 1975; Betson 1976; Mason 1977) in specific cities. The conglomeration of data from different cities eventually provided a diverse database from which other localities in the vicinity of a studied area could use the data previously collected for management purposes. Much of this runoff quality data was gathered into the *Urban Rainfall-Runoff-Quality Data Base* in the late 1970s by Huber *et al.* (1977; 1979). This database was eventually inserted into the STORET system under the control of EPA. Much of this data is summarized in Appendix B.

In Europe, researchers have also been characterizing the pollutants that originate from urban roadways. J. B. Ellis, working in the UK, has conducted and reported several investigations describing the characteristics and pollutants of wet weather flows (Ellis 1977; Ellis and Revitt 1982; Ellis 1985). One of his motivations was to correlate the pollutants found in stormwater and the impacts that these pollutants were having on the receiving waters. Brunner (1975) found that roadways in Germany could erode at surprisingly rapid rates, showing an increase in erosion as the traffic intensity increased. Others throughout Europe have also conducted studies characterizing the quality of wet weather flows.

Another major pollutant source from impermeable surfaces, for cold climate regions specifically, is material used for ice control such as salt, sand, etc. Field, *et al.* (1973) reported a study investigating the water pollution caused by street salting. Street salting can have adverse impacts on several species of fish in waters receiving high quantities of snowmelt in urban regions (Ellis 1985a). It has been shown that chlorides can be detrimental to roadside vegetation as well (Field 1973). Some regions use sand and dirt in an effort to mitigate the impacts of harsh weather on driving conditions. These materials also can contribute to significant increases in suspended sediment observed in receiving water systems (Lorch 1997). Overall, ice control in urban areas can contribute several pollutants to the runoff from those regions.

There are many different types of pollutants that can emanate from the sources discussed above. Whipple, *et al.* (1983) classified the pollutants into the following nine types:

- suspended sediment
- oxygen-demanding substances
- heavy metals
- toxic organics
- nutrients
- microorganisms
- petroleum products
- acids
- humic substances

Other types of pollutants exist which might not fit exactly into one of these categories. For example, thermal enrichment of receiving waters (Xie 1994) caused by stormwater discharges can have detrimental effects and does not fit into any of the above categories explicitly.

Preul and Papadakis (1976a; 1976b) conducted investigations into analytical and field methods to characterize stormwater runoff. Their findings were compiled into two published reports by EPA detailing the project. The microbiological components of stormwater also were investigated in the late 1970s. Olivieri, *et al.* (1977) determined that runoff from urban areas contained high densities of microorganisms and high levels of bacterial indicators of fecal contamination. The impacts of these findings were debated since storm runoff is usually not consumed and is diluted in the receiving system prior to any possible contact. Qureshi (1977) investigated the microorganism characteristics of separate storm sewers in Toronto, Canada. The findings of this investigation were similar to those found by Olivieri, *et al.* Ellis and Yu (1995) have recently investigated the microbiology of sewers and runoff in an attempt to describe the sewer from the perspective of a bacterial reactor.

The Nationwide Urban Runoff Program (NURP) administered by the U.S. EPA and the USGS in the late 1970s and early 1980s produced great amounts of runoff quality data (EPA 1983). The overall goal of the study was to collect data and develop information for use by local decision makers, States, EPA, and other interested parties. The information ultimately would provide a basis for determining whether or not urban runoff is causing water quality problems, and if it is, for planning and implementing water quality management schemes and control options (EPA 1983). Of the priority pollutants monitored at the numerous study sites, heavy metals were by far the most prevalent (especially copper, lead and zinc). Additionally, coliform bacteria were found to be in high concentrations in receiving waters during and immediately after storm events and total suspended solids were high as well (EPA 1983). The final report provides a summary characterization of urban runoff appropriate for use in estimating pollutant discharges from sites where monitored data are lacking at the planning level. Appendix B summarizes some of the NURP data.

Bannerman, *et al.* (1996) have conducted a recent comprehensive study to characterize the quality of urban runoff. Their study identified several pollutants as potential problems in Wisconsin stormwaters including lead, zinc, copper, silver, cadmium, PAHs, DDT, atrazine, suspended solids, and others. This long list of possible contaminants is indicative of many studies. This shows that the accurate characterization of runoff water quality is difficult due to the site specific pollutant sources that must be considered and the suite of pollutants that can become part of runoff.

The many other studies conducted are too numerous for a thorough coverage. These studies, both large and small, continue to refine and expand the characteristics of stormwater discharges and CSOs. In the recent past, the toxicity of stormwater has become a much studied subject. Along with these ideas came the need to perform proper sampling and monitoring to accurately identify the sources and the pollutants themselves. The next subsection details the development of sampling and monitoring for the purposes of wet weather management.

## *Wet Weather Sampling and Monitoring*

Sampling and monitoring are important topics to review since many of the other topics discussed in this report are dependent on reliable sampling and monitoring data. For instance, computer modeling requires accurately recorded data to perform a calibration process. In addition, the wet weather impacts on receiving waters can only be quantified adequately by an organized and thorough sampling and monitoring program. Indeed, each of the sections contained in this section of the report require consideration of sampling and monitoring either during planning, design, or implementation. Despite this importance, it seems that much of the other technology has advanced more rapidly. But, with the NPDES regulations requiring monitoring of stormwater outfalls more attention has recently been given to sampling protocols and methods and monitoring programs during wet weather events.

This subsection will introduce some of the literature discussing sampling, measurement, and monitoring for wet weather management. First, sampling and measurement devices will be briefly introduced. Second, sampling and measurement protocols will be discussed. The last part of this subsection will touch on some sampling and monitoring planning strategies and guidelines for use in wet weather management.

### Sampling and Measurement Devices

Before the advent of discharge permits, the sampling of wastewater and wet weather flows was inelegant. Sampling was conducted when convenient or on an as-needed basis. The instruments used consisted of cans, bottles and other containers that held water without leaking. Rigorous quality control techniques were unknown. The samples collected were manually collected in a grab fashion. Although some cities and industries used automatic samplers for process control in the 1930s, it was not until the 1950s that automatic sampling became popular. The main reason was the fact that sewer use charges became a revenue producer. Naturally, the collection of 24 hour composites required by permits called for new and more frequent composite samplers. This was the impetus behind the development of the commercial automatic samplers in the late 1960s and early 1970s. In the early 1970s, the need to perform composite sampling and more frequent sampling of wet weather flows prompted the automatic samplers used in the wastewater industry to be applied to wet weather sampling and monitoring. However, the durability requirements and other needs required that adjustments be made to the samplers for sewer applications. New samplers were also developed specifically for use in sewer sampling.

The EPA became involved in the development of sewer sampling and monitoring devices not to mention flow measurement devices during the early 1970s. The state-of-the-art in sewer flow measurement was discussed by Shelley and Kirkpatrick (1975). This report detailed the reason for accurate sewer flow measurement and then reviewed over 70 generic devices and methods for determining wastewater flows. They observed that the state-of-the-art in flow measurement, especially from the electronics standpoint, was advancing very rapidly.

Foreman (1979) developed and tested an innovative sewer flow measurement device. The device was designed by Grumman Aerospace Corporation (GAC) for EPA in the mid 1970s (Foreman 1976). This device can be described as a passive, nonintrusive flowmeter based on acoustic theory. The flowmeter utilizes the local, nonpropagating sound resulting from the partial transformation of flow pressure loss at a discontinuity in a channel or conduit. The field testing of the instrument during wet weather flow events had the goal of determining the durability and accuracy of the measurement device. The investigation verified the operational principles of the acoustic emission flowmeter under actual environmental conditions. In addition to testing the instrument, the researchers also investigated the validity of calibrating the instrument to lab-scale data and using the sewer manhole as sensor installation locations.

Shelley (1976) was also involved in another EPA sponsored project to develop an automatic sewer sampler. Four commercially available samplers were tested under the same flow conditions in a side-by-side fashion. The sampling consistency was erratic for each of the samplers, especially when an appreciable bed load was present. A prototype sampler was developed as part of the study and was shown to be capable of collecting reasonably representative samples compared to those commercially available. Many of the recommendations in this early report have been implemented by current manufactures of automatic sampling equipment, especially the use of “super-speed” pumps and small diameter tubing to maximize particulate transport in the sampler.

Before, during and after the EPA sponsored research effort, other automatic samplers were being developed by private organizations. However, the market for automatic sampling was not that lucrative for wet weather management in the late 1960s and early 1970s. But, with the increased concerns for the environment and more stringent regulations, monitoring efforts were undertaken to collect data for a number of purposes. In addition, monitoring required as part of the National Pollutant Discharge Elimination System (NPDES) for point sources necessitated the use of automatic samplers for effluents from industrial and manufacturing wastewater treatment plants, as well as municipal wastewater treatment plants. The expansion of the NPDES program to cover urban stormwater initiated widespread application of the automatic sampler in the wet weather field (Baily 1993).

Currently, a wide assortment of commercial automatic sampling products are available suiting a number of needs. The reliability and quality assurance associated with many of the automatic samplers has risen dramatically. The reason for this can be attributed to the increased demand for higher quality products from the vendors due to the more stringent permitting and increased concern for the environment. Many companies, such as N-CON Systems Co., Inc., Isco, Inc., and YSI Incorporated to mention a few, have divisions which specialize in providing equipment that can be tailored to a specific water or sewer sampling or monitoring situation. Research continues to develop innovative devices with the added benefit of being economical, such as a flow-weighted culvert sampling device (Dowling and Mar 1996).

In many instances, the needs of the user are not as advanced as the technology has developed. The operator should choose equipment that suits his or her basic needs without the expense of special features that will remain unused. In essence, the sampling and monitoring equipment should match the requirements of the sampling and monitoring program.

The need for quality monitoring equipment reaches beyond the water sampling needs. Besides water quality, another category of data required for many wet weather analyses is precipitation. As mentioned in a previous section, rainfall records are much more available than streamflow records and thus the need for rainfall-runoff relationships in design. There are numerous types of recording and non-recording rain gages that can be implemented. There are also numerous ways in which the rain gage network can be arranged. It is important to organize the network to best suit the needs of the study. The most common rain gage used in the U.S. is the 8 inch diameter, sharp edged gage placed 3 feet above the ground surface (Elliot 1995). There are variations for different climatic conditions. It is noteworthy that this type of rain gage has been in use for nearly one hundred years. However, technological advances have improved the recording and data management capability of the instrument.

**Sampling and Measurement Protocols**

The development of instruments utilized in sampling and monitoring efforts was introduced above. But, in order for the equipment to serve their purpose it must be used properly. The proper use of most equipment is detailed in instructions provided when the equipment is purchased. The additional protocols required depend on the constituent being measured or sampled. Government regulating agencies have stipulated specific procedures for sampling and analysis of water and wastewater when sampling and analysis were required. Prior to that time, sampling and analysis methods were left to the person performing the actual work. In the 1960s and 1970s environmental regulations became increasingly more stringent and therefore the required sampling and analysis procedures likewise became increasingly more stringent. *Standard Methods for the Examination of Water and Wastewater* (1992) has become an institution in terms of water quality analysis and basic sampling protocols. Additionally, sampling and monitoring protocols have been developed by EPA and other regulatory agencies. Keith (1992 and 1996) provides a compilation of the EPA sampling and analysis methods according to parameters being measured. These procedures are general to environmental studies but have applicability in wet weather situations. Keith (1991 and 1996) also provides additional information concerning environmental sampling which again can easily be applied to wet weather scenarios.

Wet weather sampling and analysis has its own specific regulations suited to the unique situations encountered that are not experienced in municipal and industrial wastewater and water quality sampling efforts. For instance, EPA (1992 and 1993) published a guidance manual for stormwater sampling. This document was prepared specifically to address the issues surrounding the NPDES permitting program. NPDES permits require specific sampling and monitoring plans that are often tailored to the individual site characteristics. The manual has the purpose of assisting operators/owners in planning and fulfilling the NPDES storm water discharge sampling requirements for permit applications and other needs.

**Planning of Sampling and Monitoring Efforts**

The planning of sampling and monitoring efforts is highly dependent on the type, resolution, and accuracy of results desired. To meet regulatory requirements requires a certain level and frequency of sampling, while the planning and design of wet weather controls will require a different level. The data needs can often direct the monitoring effort or in the least provide constraints from which the monitoring effort can be devised. Models have been developed to facilitate the development of sampling programs with the use of computers (Reinelt, *et al.* 1988).

Planning requirements include selecting the data needs and instruments to be used, developing protocols for sampling and analysis, and devising strategies for organization and management of the monitoring network. Once again the regulating agencies and other references can be sought for information concerning the planning of a sampling and analysis effort.

In 1994, a conference was entirely devoted to NPDES sampling and monitoring (Torno 1995). The conference had several important topics addressed by papers, including sampling (Dudley 1995), monitoring (Cave and Roesner 1995; James 1995), toxicity (Herricks, *et al.* 1995), and illicit connections (Lalor, *et al.* 1995; Minor 1995) to mention a few. The occurrence of such a conference exemplified the recent attention given to sampling and monitoring of wet weather flows for a variety of reasons. With the importance of regulations and modeling in wet weather management, sampling and monitoring will continue to be one of the more important topics in the future.

## *Receiving Water Impacts*

To begin discussions on receiving water impacts, the term impact must first be defined. The term impact is subjective in nature depending on the viewpoint of those doing the defining. In a previous study conducted by Heaney and Huber (1984), the impacts of urban runoff on receiving water systems were defined as resulting in the loss of beneficial use. They considered beneficial uses to be comprised of those listed in local, state, and federal laws such as drinking water use, fishing and shellfishing, swimming, boating, manufacturing process water use, etc. To develop a more general definition the inherent values of water quality and wildlife should also be included when considering impacts to the receiving water systems in addition to the economic ramifications from the human standpoint.

The possible impacts of urban runoff on receiving water systems are well documented in the literature. However, some still disagree with the results of those studies, claiming that the myriad sources of pollution (point and nonpoint) in an urban environment are difficult to separate. To combat this argument, many researchers have painstakingly insured that urban runoff was the major contributor of pollution to the receiving water thereby validating their investigation. The results and conclusions from studies following this methodology can be reviewed with confidence. But, one must be cautious when considering the conclusions from a receiving water impact study without knowing the circumstances of the investigation in full.

Prior to 1960 the water quality impacts of wet weather pollution received almost no attention (EPA 1983). However, as point source discharges were brought under control the nonpoint sources such as urban runoff were noticed to be significant contributors to the degradation of water quality. Extensive research was conducted in the 1970s to determine the impacts of urban runoff and to develop mitigation measures. The culmination of much of the decade's efforts to characterize urban runoff is manifested in the EPA-sponsored Nationwide Urban Runoff Program (NURP) mentioned above (EPA 1983). One of the goals of NURP was to characterize urban runoff in order to describe its impacts on receiving water systems.

The effects of urban runoff on receiving water quality are highly site specific. It depends on the type, size and hydrology of the water body; the urban runoff quantity and quality characteristics; the designated beneficial use; and the concentration levels of specific pollutants that affect the beneficial use (EPA 1983). In addition, as was mentioned above, the effects of urban runoff are difficult to distinguish from the other pollution sources present in an urban environment.

In evaluating the effects of urban runoff, one must discern between two types of impacts. One type is the short-term, or acute, water quality deterioration imposed during the wet weather event, such as turbidity, dissolved oxygen depression, toxicity and others. The second type is long-term, or chronic, impacts related to the bioaccumulation of contaminants in wildlife and the corresponding accumulation of contaminants in the sediment of the receiving water. Both types of impacts are included in this discussion. One must also consider the fact that urban runoff contains a suite of pollutants whose individual impacts are not easily identifiable. Therefore, the combined, and often synergistic, impacts of urban runoff pollutants is also evaluated in the ensuing discussion. The following discussion provides a highlight of some of the studies conducted and the results discovered. Therefore, this review should not be considered exhaustive of the literature available.

Generally, impacts can be divided into categories depending on the type of receiving water body into which they discharge. Many types of water systems exist, but most can be classified into two general categories: surface water systems and groundwater systems. Of course, surface water systems interact with groundwater systems, but for the sake of discussion the classification below will be based on which type of water body that initially experiences impacts from urban runoff. The following two subsections will highlight some of the more prominent literature covering the past thirty-odd years pertaining to surface water and groundwater impacts from urban runoff. The modeling of receiving water impacts was briefly mentioned in the *Wet Weather Modeling* subsection above, therefore it is neglected in this section.

**Surface Water Impacts**

Wanielista, *et al.* (1982) found that urban runoff was the sole cause of lake degradation in Lake Eola in Orlando, Florida. The primary reason for the degradation was attributed to nutrients (phosphorus in particular). Nutrients contributing to a receiving water system can lead to accelerated eutrophication, especially in stagnant lakes or ponds. Additionally, phosphorus is often a limiting nutrient in algal production, therefore an increase in phosphorus should concomitantly increase the algal production leading to increased eutrophication.

Porcella and Sorensen (1980) compiled a survey of literature pertaining to urban nonpoint surface runoff to determine the effects of that source of contaminants to stream ecosystems. They discovered that very little information existed on detailed studies of ecosystem effects caused by urban runoff. They did however compile a review of literature found that discussed the impacts of flooding, pollutants, and runoff on stream ecosystems. They also introduced a methodology to conduct future experimental studies to elucidate the effects of urban runoff impacts on stream ecosystems.

Pitt and Bozeman (1980 and 1982) carried out a series of studies investigating water quality and biological impacts of urban runoff. Their study concentrated on Coyote Creek, a creek which passes through an urban area in California. The preliminary report (Pitt and Bozeman 1980) presented some initial results from their study. Specific characteristics of urban runoff, effects of urban runoff and the potential controls for urban runoff were all addressed in the report. It was noticed that the urbanized reaches of the creek were degraded in comparison to the non-urbanized reaches. This conclusion was based on short- and long-term biological sampling and water and sediment sampling for a period of several years. The final report (Pitt and Bozeman 1982) further supported the conclusions of water quality degradation in urban reaches. Quantitatively, they observed pollutants such as lead and nitrate in concentrations more than seven times greater in urban reaches of the stream compared to the non-urban reaches. Dissolved oxygen in the urban reaches was also noticed to be lower compared to that observed in the non-urban reaches.

In their studies, Pitt and Bozeman also discovered that bioaccumulation of lead and zinc had occurred in many of the samples of algae, crayfish and cattails (Pitt 1995). The measured concentrations of these metals in organisms (mg/kg) exceeded concentrations in the sediment (mg/kg) by up to a maximum factor of six and exceeded concentrations in the water column by factors of 100 to 500 times, depending on the organism.

Besides Pitt and Bozeman, others were also investigating the impacts of CSO and stormwater discharges with EPA sponsored projects. McConnell (1980) investigated the impact of urban runoff on stream quality near Atlanta, Georgia. This investigation detailed how rapid urbanization was impacting stream water quality. Also, Moffa, *et al.* (1980) were observing the impacts of CSOs on Onondaga Lake in Syracuse, New York.

Field and Turkeltaub (1981) stressed the need to identify the impacts of urban runoff in order to develop control technologies. Quantification of the impacts was also noted as a key point. This paper reviewed several studies investigating various impacts of urban runoff. Specifically, the paper addressed dissolved oxygen depletion, pathogens, biological investigations, nutrients and toxicity. Each of these subject areas was briefly introduced followed by a discussion of recent studies performed investigating the specific topic. The paper concluded that dissolved oxygen (DO) depletion could not be directly attributed to wet weather events based on several studies (Ketchum 1978; Keefer, *et al.* 1979; Stiefel 1980) although lower DO readings were measured in urban areas compared to non-urban areas. Additionally, the presence of bacterial indicator organisms in CSO in several studies (Meinholz, *et al.* 1979; Moffa, *et al.* 1980; Tomlinson, *et al.* 1980) suggested that viruses could be present in receiving streams. It was also mentioned that the fauna in urban reaches of streams were observed in several studies to be dominated by pollutant tolerant species compared to the more diversified organisms residing in non-urban reaches of the same stream (Tomlinson, *et al.* 1980; Pitt and Bozeman 1982; Shutes 1984). Field and Turkeltaub (1981) used these conclusions and others to develop an urban runoff control methodology.

Heaney and Huber (1984) summarized their efforts searching for case studies demonstrating the cause-effect relationship between urban runoff and the impairment of receiving waters. Part of their work classified the receiving waters of the 248 urbanized areas in the U.S. according to what type they were and how much dilution capacity they had (Heaney, *et al.* 1981). For instance, it was determined that 84% of the primary receiving waters in urban areas were rivers, 4% were lakes, and 11% were estuaries or oceans. Their conclusions indicated that documented case studies of receiving water impacts were scarce for a number of reasons. Some of the reasons for this conclusion included that receiving water impacts were not important from a regulatory viewpoint, impacts of urban runoff and CSO difficult to separate from other sources of pollution, impacts could be subtle, uniform definition of impact did not exist, and others.

Ellis (1979; 1982; and 1985b) has studied the impacts of urban runoff on receiving water systems in a number of investigations. Some of his findings concluded that 40-50% of the annual biochemical oxygen demand (BOD) loading to benthal sediments in London receiving water bodies was contributed by storm sewered runoff. The increased BOD in the sediment presents a problem, especially when the sediment is disturbed. Ellis also concluded that urban runoff caused water quality degradation due to substantial pollutant and shock hydraulic loadings discharged from stormwater outfalls. This was based on his own investigations as well as those of others.

Conferences proceedings can be the location of a plethora of papers pertaining to a particular subject. This possibility was considered when searching for literature discussing receiving water impacts. Conferences found which had the theme of receiving water impacts would have many papers concentrating on the subject contained in the proceedings. One such conference was held in Orlando, FL in November 1979 (Yousef, *et al.* 1980). This large proceedings was published as an EPA report and consisted of more than 25 papers, some of which are mentioned individually in this review.

It was stated above that it is difficult to discern the effects of urban runoff and CSO in an urban environment since many pollutant sources contribute to the receiving water systems. To solve this dilemma some studies have not attempted to separate the impacts of urban runoff from the other sources in order to observe the cause-effect relationship of the wet weather sources explicitly, but rather studied the effects of urbanization in general (McPherson 1972). It is understood that a major component of urbanization is the creation of increased runoff that contributes to the degradation of water quality. Therefore, reviewing a few of the studies documenting impacts on receiving waters due to urbanization will be time well spent.

Graf (1975) studied the Denver area fluvial system and noticed that the region was largely impacted by suburban development. A large part of the problem was attributed to large quantities of sediment and the increased amounts of impervious surfaces contributing higher surface runoff rates and volumes. He observed that the increased surface runoff caused increased erosion to the streambed leading to incision of the stream in many areas. Consequences of this action include upsetting the delicate balance of the ecosystem and loss or alteration of property due to erosion of streambanks and the deposit of sediment in specific locations of the stream.

Klein (1979) studied 27 small watersheds having similar physical characteristics, but different land uses, and found definite relationships between land use and water quality. It was found that stream aquatic life problems were first identified in watersheds with impervious area comprising at least 12% of the watershed. Other studies have supported this 12% impervious ratio, with the range of 8 to 15% being documented by the cumulative results of many studies (Claytor 1996b; Schueler 1996; Stephenson 1996). It was also observed that at more urbanized sites with a steady sediment source, sand covered the natural stream bed in 2 to 3 months. Sand, when it is of the shifting, unstable variety, provides one of the poorest substrates for benthic life (Klein 1979). Klein (1979) also observed that generally urban streams exhibited a paucity of life characterized by inhabiting organisms being of the pollution resistant variety. These findings are similar to those observed by others investigating the impacts of urban runoff (Pitt and Bozeman 1980 and 1982; Shutes 1984).

Many other individuals and organizations also investigated the impacts of urbanization on the receiving water system. Most of these studies attempted to characterize the impacts associated with the quantity of water. For instance, some quantified the alterations to peak runoff rate and runoff volume which occur during the urbanization of a watershed (Bras and Perkins 1975; Task Committee on the Effects of Urbanization 1975; Walesh and Videkovich 1978; Beard and Chang 1979). These studies confirmed the expected outcome that increased impervious surfaces increases surface runoff volume and peak rate and concomitantly decreased subsurface flow and infiltration. Essentially, studies have shown that the hydrology of a watershed is altered, sometimes severely, during the urbanization process.

The water quality impacts of CSO and stormwater discharges on receiving water systems became a widely studied subject (Pitt and Bozeman 1980 and 1982; Field and Turkeltaub 1981; Heaney and Huber 1984). Gradually a shift from water quality impacts to the impact on aquatic life and fauna began to occur. Studies of urban runoff began to observe the impacts on specific aquatic organisms. For instance, Pitt and Bozeman (1980 and 1982) and Shutes (1984) determined that receiving water impacts from urban runoff included a less diverse species population downstream from wet weather discharges. As described above, these studies were significant because they quantified the effects, not just stating that the wildlife and/or water quality was observed to be impacted. This method of determining impacts has continued to evolve such that presently assessing stormwater impacts is much more complex. Biological assays are needed to determine if the urban runoff impacts are toxic to wildlife in the short-term and long-term.

Burton (1994) observes that due to the complexity of assessing receiving water impacts it is imperative that wet weather evaluations use an integrated approach. He recommends focusing on toxicity, indigenous biota, and habitat during initial surveys, followed by focused contaminant analysis of sediments and runoff from impacted areas. For the toxicity testing, it is recommended that a tiered toxicity testing approach be utilized (Burton 1994). Pitt, *et al.* (1996) also propose the use of toxicity testing in assessing stormwater impacts. They compared a relatively simple toxicity evaluation procedure to the more rigorous alternatives and concluded that the simpler test provided accurate results for preliminary assessment purposes. For more detailed analysis they suggested using multiple complementary tests, instead of any one test method (Pitt 1996).

Johnson, *et al.* (1996) and Herricks, *et al.* (1996) describe a structured tier testing protocol to assess both short-term and long-term wet weather discharge toxicity. These researchers have developed and tested the assessment procedure. The procedures recognize that the test protocol must correspond to the time-scale of exposure during the discharge event. To solve this problem, three time-scale protocols were developed, for intraevent, event, and long-term exposures. Additional results from the investigations indicated that standard whole effluent toxicity (WET) tests overestimated the potential toxicity of stormwater discharges.

Another approach for assessing receiving water conditions was summarized by Claytor (1996a). This methodology was developed by the Center for Watershed Protection as part of their EPA-sponsored project on stormwater indicators (Claytor and Brown 1996). The stormwater indicators were divided into six broad categories: water quality, physical/hydrological, biological, social, programmatic, and site. The goal of these indicators is to measure receiving water impacts, to assess the water resource itself, and to evaluate runoff control program effectiveness.

**Groundwater Impacts**
An often neglected destination of urban runoff is the groundwater. Runoff can be directed to the groundwater either intentionally (infiltration basins, unlined detention basins, grass swales, etc.) or unintentionally (leaking sewers, breached linings in control structures, etc.). Regardless of the means by which runoff reaches the groundwater, it must be considered in wet weather management strategies. Investigations have concentrated specifically on the impacts associated with stormwater infiltration, both intentional and unintentional and some are introduced in the following discussion.

Nightingale and Bianchi (1977a; 1977b) studied the impacts of artificial recharge of stormwater and other sources on the groundwater quality. Part of these studies focused on how the inorganic chemical quality of the recharge water related to the changes observed in groundwater quality beneath recharge basins and in nearby urban water wells. Other focuses of the study included investigating the soil and groundwater characteristics and their relationship with the impacts caused by the recharge water.

Nightingale (1975) and Wigington (1983) investigated the accumulation of contaminants in soils beneath recharge and infiltration facilities. They documented the accumulation of arsenic and trace elements (lead, zinc, copper, and cadmium) in the soils. The accumulations at the time of the study did not pose a threat, but eventually the levels could become unacceptable (Nightingale 1987). Another concern is the classification of the soils as hazardous material if they contain a level of contaminant of a sufficient level. This would pose a management problem during maintenance and for future use of the soils in the recharge zone.

Eisen and Anderson (1979) looked at the impacts of urbanization in general on the quality of groundwater. They observed trends in groundwater quality that supported the results of other researchers. It was found that chloride and sulfate were the principal products of urbanization which affect the quality of groundwater. Evidence pointed to the causes of this contamination being road salting, leaking sewer pipes, and infiltration of contaminated surface water. Stormwater is a common link between each of these contamination avenues and therefore must be considered in prevention plans.

Ku and Simmons (1986) studied the aquifer system beneath Long Island, New York to determine if the high density of stormwater infiltration facilities on the island were contaminating the groundwater. They concluded that many of the contaminants were filtered out in the soils beneath the recharge basin and therefore never reached the groundwater. This conclusion was in agreement with the results observed in Fresno, CA during a study associated with NURP (U. S. Environmental Protection Agency 1983b).

Pitt, *et al.* (1994 and 1996) conducted a study to review the groundwater contamination literature as it related to stormwater. They developed a methodology to evaluate the contamination potential of stormwater nutrients, pesticides, other organic compounds, pathogens, metals, salts and other dissolved minerals, suspended solids, and other contaminants. The potential for contamination was based on factors such as their mobility through the unsaturated zone above infiltration facilities, their abundance in stormwater, and their treatability. Conclusions from their study highlighted salts, some pathogens, 1,3-dichlorobenzene, pyrene, fluoranthene, and zinc as having high potential to contaminate groundwater under certain conditions.

The application and research of stormwater infiltration basins is more intense outside the United States. Studies have concentrated on the use of infiltration basins as CSO and stormwater runoff control strategies rather than simply groundwater recharge basins (Jacobsen 1991; Geldorf, *et al.* 1993; Jacobsen and Mikkelsen 1993; Mikkelsen, *et al.* 1994). The infiltration of polluted flows increases the contamination potential of the underlying aquifer. Therefore, more intensified research is required to investigate the contamination potential of groundwater from infiltrating polluted wet weather flows.

Mikkelsen, *et al.* (1994) state that although infiltration systems have several advantages they are rarely installed on a large-scale in urban areas because of the uncertainty associated with the risk for groundwater contamination. They offer recommendations that the most cost effective manner to prevent groundwater contamination is by controlling pollutants at the source. However, due to the short time-scale the environmental impacts of the pollutants must be assessed by documenting the potential contaminants in stormwater and their likely sources. Some of this need has been filled by Pitt, *et al.* (1996). Geldorf, *et al.* (1994) espoused the use of infiltration because of its positive impacts on the receiving water system. They stated that infiltration basins constructed correctly offer a design option that is environmentally sustainable.

Mikkelsen, *et al.* (1996a and 1996b) continued to be involved in a series of tests to examine the effects of stormwater infiltration on soil and groundwater quality. Their results indicate that pesticides and other highly mobile contaminants are of the greatest concern. On the other end of the spectrum, metals and PAHs present little concern for groundwater contamination during stormwater infiltration due to their high affinity for soils.

### *Urban Hydrology*

The path of water in an urban environment follows the hydrologic cycle. An urban environment has, by definition, been altered such that many of the natural processes constituting the hydrologic cycle are altered. The management of the effects of these alterations on wet weather flows in newly urbanizing areas is part of the focus of this report. The need to address the topic is clear and one particular aspect that must be addressed is the changes to the hydrology in the urban area that must be reckoned prior to devising the management strategies. Within this section, some of the specific characteristics of urban hydrology, as presented in the literature, will be discussed.

Earlier in this section, the ancient strategies for urban drainage were discussed, from which it became apparent that the consideration of hydrology in the urban setting had an early beginning. However, despite the early beginning, urban hydrology is still lacking in refinement. Jones (1967) pointed out at that in the 1960s the rational method (Kuichling 1889) for drainage design had been the last major development in urban hydrology. It can still be argued today (thirty years later) that the rational method remains one of the last major developments in urban hydrology. Of course, computer models have developed markedly in that time and improved physically-based rainfall-runoff models exist, but all indications are that practitioners still predominantly utilize the rational method or similar techniques developed decades ago in one form or another.

A major economic consideration in drainage design is the mitigation of flood damages. To promote effective designs flood frequency analysis is needed. In an urban setting, the flood frequency characteristics will differ from those observed in a rural or natural setting. Numerous researchers have examined the flood frequency characteristics of urban settings. Some of the early urban hydrology work in the late 1950s and early 1960s addressed the effects of urbanization on the flood potential of small watersheds. The conclusions of this work were that urbanization had increased flood peaks by one and one-half to five times (Espey and Winslow 1974). Some of this early work included Ramey (1959) who determined that floods in the Chicago area had increased at least two and one-half times due to urban development. Wiitala (1961) found that the flood peaks in Michigan were approximately three times the peaks observed in undeveloped watersheds. Van Sickle (1962 and 1974) observed that urban development in Houston, Texas would increase peak discharge rates two to five times over those expected from the same watershed for undeveloped conditions. Savini and Kammerer (1961), Espey, *et al.* (1965 and 1969); and Espey and Winslow (1968) found similarly affected peak discharges, unit hydrograph shapes and other hydrologic characteristics in urban watersheds compared to undeveloped watersheds as previous research had observed. It should be noted, however, that numerous investigators pointed out that the dramatic increase in peak discharge becomes less significant for floods of increasing magnitude (Curtis, *et al.* 1964; Wilson 1967; Espey and Winslow 1974).

Espey and Winslow (1974) applied the Log-Pearson Type III distribution to 60 relatively small urban watersheds located throughout the United States. Applying the distribution to data indicated that the flood discharge would be significantly increased due to urbanization. An increase of 200% in some instances was predicted by the flood frequency analysis. They suggested that the flood frequency equations developed should be updated after the collection of more data.

Jones (1971) continued to stimulate urban hydrology in the engineering profession. It was anticipated that increased attention would act as a precursor to improved practice. In this paper he discussed urban drainage design, precipitation recording and analysis, runoff quantity estimations, as well as other aspects of urban hydrology and water quality. He discussed the current status of the subjects and then provided reasons for the problems and directions for advancement.

Starting in 1975 and continuing annually, for 10 years thereafter, a conference was held at the University of Kentucky addressing the topics of urban hydrology, hydraulics and sediment control. The contribution of these papers is too lengthy to discuss in detail, but it should be noted that the compiled papers of the conferences provide an excellent resource for urban hydrology. A list of all the papers is printed in *Current Practices in Modelling the Management of Stormwater Impacts* (James 1994). General topics covered at the conference included modeling, urban hydraulics, urban hydrology, stormwater management and many others. These conferences covered subjects related to many of the categories discussed in this report.

In terms of precipitation characteristics and analysis, major advancements and insights were provided from the late 1960s onward by the work of Keifer and Chu (1957), Huff (1967) and others. Keifer and Chu (1957) specifically investigated storm patterns for use in the design of drainage structures and systems. They realized that with the increased technical knowledge and computational capability, the only facet of drainage design that needed to be improved was precipitation and storm event analysis. Huff and others constructed a dense rain gage network in the Chicago for conducting comprehensive hydrometeorological research. Huff (1967) analyzed data from this network for heavy rainstorms and developed time distribution patterns. The network was updated for different projects throughout the 1970s trying to improve the utilization of meteorological data in drainage design (Huff 1969; Huff and Changnon 1977). Huff, *et al.* (1981) used the comprehensive rain gage network to develop and evaluate real-time monitoring-prediction system for facilitating and improving the operation of urban sewer systems.

The rational method is used for the design of some types of facilities in small drainage basins, where an estimate of only the peak rate of runoff is required. Rainfall information used with the rational method consists of intensity-duration-frequency (IDF) curves. The IDF curve concept was developed in the late 1800s in the United States in an era of intense precipitation analysis (Berwick, *et al.* 1980). IDF curves were eventually developed for most regions from recorded rainfall data. For use with the rational method, IDF curves are typically developed for a particular locality using the procedures set forth in TP 40 (Hershfield 1961) and HYDRO-35 (Frederick, *et al.* 1977). These two publications provide maps of the United States displaying rainfall data for different regions of the country in a graphical format.

More recent research into precipitation analysis has been conducted at the Danish Meteorological Institute (Mikkelsen, *et al.* 1996c and 1996d). This study began by changing the old rain gages for measuring extreme precipitation originally constructed as early as 1933 with modern systems of gages linked electronically to a central computer (Harremoës and Henze 1981). The data collected has revealed a geographic variability in rainfall patterns that calls for the revision of current engineering design uses of rainfall data (Harremoës and Mikkelsen 1995).

During the 1970s, the rainfall-runoff process was being studied with the intent of developing models. The EPA sponsored research to observe the process in both urban and rural settings. Brater and Sherril (1975) authored a report on the findings of this project. They discussed the rainfall-runoff process in the context of stormwater management and drainage design. Many others conducted research with the goal of describing the rainfall-runoff process. Sarma, *et al.* (1973) compared excess rainfall-direct runoff conceptual models at several urban watersheds. The instantaneous unit hydrograph (IUH) model performed the best of the conceptual models tested. Todini (1988) reviewed rainfall-runoff modeling of the past, evaluated the present models, and predicted the characteristics of rainfall-runoff modeling in the future.

With the proliferation of computer models in the 1970s came the need for large amounts of data for calibration and model process development. To answer this call, Huber and Heaney (1977) compiled a database of urban rainfall, runoff, and water quality data. Updates and additions to this database occurred later (Huber, *et al.*. 1979; Huber, *et al* 1981). The data in the database was from several catchments located in several cities. Many sources were reached during the accumulation of the data, which was eventually entered into a database. The collected data became part of the EPA STORET data retrieval system for increased accessibility.

The physical description of the rainfall-runoff process has been increasingly described in research projects as nonlinear. However, most of the traditional drainage design methods utilize linear runoff responses for modeling purposes. Improvements are needed in future research to provide methods that become implemented in design practice.

## Summary of Literature

Granted, all the literature pertaining to wet weather management could not possibly be entered into the ProCite database. Moreover, the literature which is contained in the database could not possibly be exhaustively reviewed in the above discussion. However, more than enough of the literature has been reviewed and documented above to provide an accurate chronological development of wet weather management from ancient times to the present day. The purpose of this review, as stated earlier, was to determine past wet weather management strategies and to observe how they influenced the current strategies. The progression of wet weather management discussed above indicates decisions, ideas, and experiences in the past which resulted in the current state of wet weather management. This knowledge of past events provides insights into the future methodology which will enhance it. Another benefit of the literature review is the observance of research trends. The literature is an excellent reflection of the research that is being conducted. A review indicates areas that have been overwhelmed with research without much gain in knowledge and on the other hand areas that have been relatively neglected by research. This short summary describes some of the major trends in wet weather management as displayed in the literature as well as identifying areas that have been thoroughly researched or that have been neglected.

The history of wet weather management is indeed ancient. Strategies have developed from the elegant systems of the Romans to the pitiful systems of the middle ages to the advanced systems of today. Judging by this progression, the passage of time does not necessarily mean advancements of wet weather management strategies. In fact, engineers in London during the early eighteenth century tried to instill the same pride in drainage concerns as the Romans had displayed two thousand years before them, but many thought it was foolish to concern themselves with ancient concepts since civilization had advanced much since ancient times.

The methodology used in modern drainage design is approximately 150 years old and is now developing at a much faster rate than at any previous time. Ancient methods of design did not involve engineering calculations or experiments, but were based on judgment and trial and error. The 1800s are considered to be the beginning of modern drainage design. It was during this time period that experiments were conducted with the intent of deriving empirical relationships between design parameters (such as precipitation, watershed characteristics, etc.) and the size of drainage appurtenances.

Improved methods of planning sewerage systems were the next major step in the development. Lindley developed the first planned sewerage system for Hamburg in 1842, Bazalgette designed the Main Drainage of London in the 1850s, Chesbrough designed the first comprehensive sewerage system for Chicago in the 1850s, and many others also planned systems comprehensively during this time period (Metcalf and Eddy 1928). The comprehensive planning of sewerage systems ushered in the debate concerning combined versus separate systems of sewerage (Hering 1881a). Reasons could be offered for use of either, but a definite choice was not discernible. Therefore, the debate over which type of sewerage system to utilize was argued in the technical literature and at technical gatherings.

Once drainage systems were being planned and designed comprehensively, improved empirical formula methods for sewer system design were instituted. In addition to the formula methods of design, the rational method for drainage design was being developed (Mulvaney 1851; Kuichling 1889). As mathematics improved, enhanced descriptions of the physical processes (rainfall, runoff, treatment, and others) inherent in wet weather management developed. These improvements resulted in equations describing infiltration and other abstractions as well as the rainfall-runoff process in general (Linsley and Ackerman 1942).

Research in developing mathematical descriptions of the physical processes continued to occur through the early to mid 1950s and became manifested in wet weather management through models, treatment techniques, and general understanding of underlying relationships. The computer age, which has developed over the last forty years has advanced the use of the physical descriptions of processes in certain aspects of wet weather management, especially models. Computer models have developed such that now they are required tools in the wet weather management profession.

In the same time that computers were improving wet weather management, water quality was becoming a concern. The knowledge that urban runoff was having severe impacts on receiving water quality completely altered the philosophy of wet weather management. Before this time the strategy was to remove stormwater as expeditiously as possible from the urban area. But more recently, the dual purposes of removing stormwater and promoting receiving water quality have led to more comprehensive management techniques. This has ultimately resulted in management techniques that address traditional quantity concerns and the newer water quality concerns. These dual purpose concerns were iterated in the literature throughout the past thirty years (Wanielista 1978; Geiger and Dorsch 1980). To further support the fusion of quantity and quality concerns in wet weather management evidence can be found in the technical conferences (Whipple 1975).

The advancement of technology in the previous thirty years is evident in the quantity of technical literature published in that time frame. However, although technology was advancing at a rapid rate, it was noticed that there existed a long lag between the significant developments and the applications in urban water resources practice. The slow "technology transfer" experienced in wet weather management was addressed by several individuals (McPherson 1975 and 1978b), but the problem persisted. Now it appears to be easier to advance technology and improve wet weather management on the research and development front, yet see years before these improvements are implemented in practice. The technology transfer phenomena is still in need of attention.

In addition to the technological advancements, such as with models, monitoring and controls, the improved technology has benefited the presentation, analysis, and other related aspects of wet weather management through instruments such as GIS, databases, word processors, and so on. These improvements have given researchers and engineers tools to make the more mundane tasks of engineering simpler and quicker, which facilitates the direction of time and energy toward implementation of the technological advancements.

It seems that as technology and understanding of the physical world has improved, there has been a corresponding advancement in wet weather management. It is anticipated that this correlation between technology and knowledge with wet weather management practices will continue in the future, albeit with a technology transfer time lag.

## Future Outlook

The trends in wet weather management were generalized in the summary, and described in the literature review. This subsection considers these trends in the present day and attempts to forecast their future. Most of this section is based on material read or observed in the past few months and is an indication of topics currently gaining attention throughout the United States and the world. The topics mentioned are considered important factors to improving the wet weather management concepts.

This literature review has indicated that the technology has advanced many fold the last thirty years. However, problems still result from the lack of implementation of this technology. This was experienced for the 208 planning studies, in which many studies were conducted by regional planning boards, but few were actually implemented in their original form. Problems facing the wet weather management community in the future will not be entirely technical in nature. Technology is improving each year and providing for methods that are more than sufficient to produce excellent designs. However, the real problem lies with the implementation of this technology and methodology as was explained in the previous section. McPherson (1975 and 1978b) championed these concerns twenty years ago and offered suggestions to reduce the development to implementation lag time. Some of these suggestions and ones made since should be reevaluated and applied to today's circumstances. As mentioned in the introduction to this report, the goal of this project is to develop a design methodology that is effective yet simple to apply for a design engineer. This type of design philosophy will circumvent many of the detractors that usually impede the transfer of technology, thereby gaining implementation more swiftly.

Design engineers and planners will be forced to consider the environmental, socioeconomic, political, and legal ramifications associated with their plans and designs. These topics are the main inhibitors to the implementation of innovative technology and in the future must be addressed for progress to be made. Berwick (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. Problems also exist in the regulations and ordinances forcing design engineers to comply with standards that are either outdated or do not promote sustainability. Researchers and design engineers alike need to become more in tune with the political, socieconomic, and legal fabric of the urban community in order to better develop strategies that can be implemented.

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 of the 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 utilized method until much later. A paper by Charles Buerger (1915) states:

> "It (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 would 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 offers for the lack of implementation is even more interesting. He states that the rational method has not received the widest use because it is relatively laborious, and requires a material exercise in judgment. This again is a popular reason expressed today for the lack of application of other techniques, but now the rational method is the popular method because of its simplicity and not the formula methods of Buerger's day.

The future is anticipated to be no different. If the trend of today mimics that of the past, it may be another twenty or more years before a method that has been introduced recently replaces an entrenched technique such as the rational method. Or, such as with the method Buerger was introducing in his paper, a new technique might never truly be implemented by practitioners regardless of the benefits and improvements that could be gained.

As one might conjecture from the above mention of the need for consideration of social, economic, and political concepts, the wet weather management field is also becoming increasingly multidisciplinary. It is not just a sanitary or civil engineer that is needed to design drainage structures. Disciplines that have become integral parts of the wet weather management field include biologists, ecologists, economists, computer scientists, geographers, geologists, sociologists, political scientists, and many others. Granted, an expert in each of these disciplines is not needed to design a wet weather system for a small-sized subdivision, but for the planning and design of a large urban region or the planning on a regional scale the input of experts in many of these fields might be required.

Although implementation of the technology is considered a major component for improving wet weather management, the improvement of technology cannot be entirely ignored. The future of modeling seems to be GIS and graphical pre- and post-processors. But the actual theory behind model applications needs to be addressed as well. In addition, the wet weather pollution problem is divided by models into several categories, e.g. sources, drainage system, receiving water, etc. Only recently have models begun to be integrated to better evaluate the system on a holistic scale. In the future models will need to continue to be developed in this fashion in order to advance wet weather management technology.

The use of the Internet will increase in the future. Already spatial data are being accumulated at certain sites in the forms of maps and databases that can be downloaded and used in wet weather management. The future direction of the Internet seems to be heading towards interactive applications in which users can perform functions remotely without actually having the data or necessary tools at their location. Examples of this include Intranet setups in large design firms in which information and tools are shared from a common server amongst engineers at several, sometimes remote locations. Along these same lines, interactive maps are now being implemented on the Internet for use at large. Future design, modeling, and management efforts could rely on such information being easily accessible.

The improvement in computer and modeling applications is definitely important for the advancement of wet weather management, but other aspects must also be addressed. For example, the methods utilized to control and treat stormwater discharges and CSOs are not perfect. How can these practices be better applied to newly urbanizing areas to enhance the development? How can the integration of these practices be improved to utilize the different techniques in a cost effective manner? These and other questions must be addressed.

Recently, a large number of papers and reports have been published related to the subject of sewer rehabilitation. It is no secret that the worlds', especially the United States' infrastructure is sorely in need of attention. As the historical portion of the literature review has noted, many of the wet weather systems in this country were developed in the early part of this century. Maintenance, retrofits, and rehabilitation since then have resulted in patchwork systems consisting of parts from different eras. The time is now and in the near future to develop cost effective methods to properly rehabilitate the wet weather flow systems to carry them far into the next century.

In the same vein as the rehabilitation concept, planners, designers, and constructors must provide infrastructure, specifically wet weather flow systems that will sustain themselves into the next century. The topic of sustainable development has been popular in the 1990s and will continue to be in the future. With the ever increasing population of the planet, it is becoming more difficult to provide infrastructure that meets the needs of humanity while concomitantly fusing harmoniously with the natural environment. To date, only a handful of case studies can boast of attaining short-term sustainable development. Developers must now start facing the reality that sustainable development must be a priority, otherwise in the future the engineering community will be faced with the problem of developing sustainable rehabilitation programs in which the systems that do not co-habitat with natural ecosystems will have to be retrofitted for that purpose most likely at a much greater expense.

Specific ideas being set forth recently concerning sustainable infrastructure approaches include the idea of integration (Zimmerman and Sparrow 1997). Integration is a term that can take on many different meanings depending on who is using it. One type of integration amounts to managing the entire urban water resources cycle comprehensively. In this type of arrangement wastewater, water supply, stormwater, and other water resources in an urban setting would be developed and managed comprehensively in a sustainable fashion. Another, broader perspective for integration involves the integration of infrastructure in general. This would amount to developing regions while considering infrastructure systems such as power, water, wastewater, stormwater, solid waste, transportation, communication, and others in an integrated manner. Possible ways to accomplish this would be to develop the infrastructure system comprehensively promoting cooperation in operation and management for the betterment of the community. Of course the ideas surrounding integration are in their infancy and therefore difficulty arises in locating examples and defining procedures of implementation.

Overall, wet weather management in newly urbanizing areas will be important in the future as water resources become more and more scarce. The planets population is growing at an incredible rate and the developing countries' urbanized areas require infrastructure to be constructed. Also the urbanized areas of the developed countries are continuing to expand. Some of the above topics mentioned relating to the future of wet weather management will need to be and possibly will be required to be incorporated into the development of newly urbanizing areas. This will promote the ideas of sustainability, cost effectiveness, comprehensive management that are being shown to be important aspects of wet weather management. The next section further reviews current wet weather flow design methods and also discusses future directions.

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