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Impacts of Rainfall Events on Wastewater Treamtent Processes

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by

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Erin K. McMahan

Abstract

Current research is revealing that stormwater can carry pathogens and that this stormwater is entering wastewater treatment facilities. During periods of intense rainfall, not only can stormwater carry higher amounts of pathogens, but it also increases the flow rate to the wastewater treatment facility. In many instances, the flow rate exceeds the facilities' treatment capacity and can impact treatment performance. The purpose of this study was to identify whether wastewater treatment is impaired during periods of increased rainfall, and to compare current policies that address this issue. The study was conducted using a case study approach to analyze historical precipitation and wastewater treatment data from facilities located in Clearwater and St. Petersburg, Florida. The effluent from the biological nutrient removal system operated at the facilities located in Clearwater was compared to the effluent from the activated sludge treatment system operated by the facility located in St. Petersburg. Statistical analyses were conducted to identify significant differences in either the loading or performance of wastewater treatment facilities under wet and dry flow conditions. In this case, the Clearwater facilities operating below their treatment capacity were better equipped to handle peak wet weather flows and efficiently treat wastewater than the St. Petersburg facility which has a less advanced treatment system and was operating at and above its treatment capacity.

Chapter One
Introduction

Stormwater pollution is considered a point source and regulated by authorized state agencies under the National Pollutant Discharge Elimination System (NPDES) (EPA, 2003; Rosenbaum, 2002). When precipitation falls onto the ground and impervious surfaces, such as a parking lot, rooftop, or street, it drains as stormwater runoff. In an area with a high degree of impervious cover, such as in an urban area, stormwater runoff can accumulate microbial and chemical pollutants. If not managed effectively, stormwater runoff can result in the contamination of surface water and groundwater (Cunningham and Saigo, 2001).

Industrial facilities, municipal separate storm sewer systems (MS4s), and construction activities require permits that control for the discharge of stormwater generated on-site (EPA, 2004c). However, stormwater runoff that enters a publicly-owned treatment works (POTW) becomes the responsibility of the POTW (or municipal wastewater treatment facility) (EPA, 2002b). If the POTW does not have adequate capacity to treat the additional pollutant loading generated by the stormwater contribution to the wastewater flow, there is a short-term risk that the treatment facility will be in non-compliance with the NPDES permit requirements for effluent discharge (EPA, 2002b). Extreme rainfall or wet weather events[1] can generate large quantities of stormwater, which can enter the wastewater collection system via sewer manholes, ground infiltration, faulty connections, and leaky or broken pipes (Droste, 1997). These

[1] The terms “extreme rainfall event” and “peak wet weather event” refer to storm events that exceed the average precipitation rates for a particular region, and will be used interchangeably for the purpose of this paper

increases in stormwater inflow to the collection system can increase the flow rate to the POTW and potentially exceed the treatment capacity at which a POTW is designed to operate (Droste, 1997). High flow rates can potentially impair the performance of the treatment facility if they exceed the facility's design capacity (Grady, Daigger, and Lim, 1999; Tchobanoglous, Burton, and Stensel, 2003).

The degree to which stormwater impacts discharges by POTWs depends on the intensity and duration of the storm event, the type of sewer collection system, and the treatment facility characteristics. Issues associated with the management of stormwater are complicated by several factors, including the frequency and intensity of extreme weather events, the impacts of increasing urbanization on land use patterns, and the ratio of pervious to impervious surfaces.

Since 1941, the majority of the United States has experienced a positive rate of precipitation change as shown in Figure 1 (Climate Prediction Center, 2005). Increases in the quantity and frequency of precipitation have led to global increases in the amount of stream and river runoff following these storm events (McCarthy, Canziani, Leary, Dokken, and White, 2001). Global climate modeling has been used to estimate that 61.3-73.3% of global land area is increasing in its amount of stream and river runoff (Döll, Kaspar, and Alcamo, 1999). This increased runoff translates into a higher frequency of extreme storm events. As POTWs reach their design capacity due to population growth, the impacts of stormwater on treatment effectiveness may become more significant.

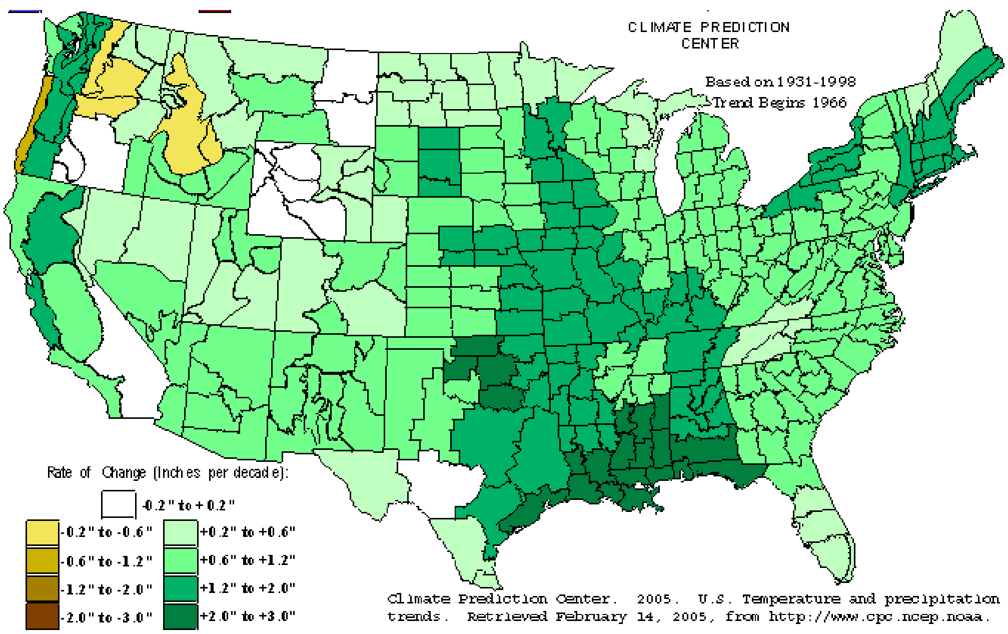

Figure 1. Rate of Long-Term Precipitation Change, 1941-1998 (Climate Prediction Center, 2005)

Collection systems for wastewater treatment facilities in the United States can be classified as either Combined Sewers or Sanitary/Separate Sewers (CSS or SSS). While SSS consists of separate conduits for stormwater and wastewater, CSS are designed to combine stormwater and wastewater (EPA, 2004a). During extreme rainfall events, a CSS may contain short-term flow rates that exceed the facility's design capacity (EPA, 2004b).

Where Combined Sewer Overflows (CSO) during wet weather events are regulated under NPDES (59 Federal Regulation 18688), Sanitary or Separate Sewer Overflows (SSO) are not permitted by NPDES (EPA, 2004b). SSOs can be caused by extreme weather events or poor operation and maintenance of the system (EPA, 2004b). These overflows are less frequent than CSOs, but can pose a bigger health threat when the overflow is coming from the wastewater pipe, which can carry higher concentrations of pathogens (EPA, 2004b).

It is critical to assess the performance of wastewater treatment plants during extreme rainfall events to develop the appropriate policies for stormwater management.

An important issue is to evaluate the relative effectiveness of national versus loacalized policies associated with the stormwater management. Typical national policies are designed based on uniform standards that are unable to account for local conditions, such as average regional rainfall (Rosenbaum, 2002). By imposing uniform standards, the protection of public health and environmental risk is consistant throughout the United States. Conversely, localized approaches are site-specific, thus creating the potential for environmental degradation. In either case, resources are needed to implement and enforce stormwater management programs.

Chapter Two
Objectives

This research project is based on analysis of stormwater policies dealing with extreme weather events. The overall goal of the research is to identify key variables that influence the appropriateness of national (command and control) policies with the use of localized (site-specific) measures. The research hypothesis is: it is not possible to used a national policy to manage stormwater without the use of localized measures.

The specific objectives are to:

1. Define criteria that can be used for evaluating the ability of stormwater policies to mitigate the impacts from wet weather flows on the effectiveness of wastewater treatment facilities.

2. Identify and evaluate differences between national and local policy approaches that address the impact of wet weather flows on wastewater treatment facilities.

3. Assess the susceptibility of wastewater treatment performance to wet weather events using a case study approach to analyze historical precipitation and wastewater treatment data.

Chapter Three
Background

To be able to evaluate stormwater policies in the context of wastewater treatment background information on stormwater policies is needed. Stormwater policy issues relevant to the research hypothesis are presented in this section. Differences between national and localized strategies are summarized and alternative policy approaches are examined. Factors that influence the impacts of stormwater flows on the effectiveness of pathogen removal through wastewater treatment are also identified.

Stormwater Policy

The Clean Water Act (CWA) was an important and complex piece of legislation that was passed by Congress in 1972 (Clean Water Act §101; Cunningham and Saigo, 2001). The CWA established a National Pollutant Discharge Elimination System (NPDES) to aid in accomplishing its goal of making all waters of the United States "fishable and swimmable" (Clean Water Act §101; Cunningham and Saigo, 2001; Rosenbaum, 2002). Stormwater was considered a nonpoint source of pollution under the CWA until the 1987 reauthorization, when its classification was changed to a point source (Rosenbaum, 2002). Because of this reauthorization in 1987, stormwater dischargers are now subject to NPDES regulations (Rosenbaum, 2002).

Issues related to stormwater management are growing in complexity with the escalating severity and frequency of storm events, increases in urbanization necessitating improved stormwater control, and the aging of wastewater treatment facilities. As these issues become more of a priority nationwide, local efforts to manage stormwater will be initiated to supplement the current stormwater policies established on the national level and regulated through NPDES.

Inflow and infiltration (I/I) are two ways that stormwater can enter the collection system carrying wastewater to a treatment facility (WEF, 1999; Dr. Levine Personal Communication, 2005). Inflow and infiltration can occur during heavy rainfall events when large amounts of stormwater flows through manholes, cracked and/or leaking pipes, and improper connections (WEF, 1999; Dr. Levine Personal Communication, 2005).

The majority of wastewater collection systems in the United States were constructed in the early 20th century, and through maintenance and retrofitting, now consist of a combination of older and more recent technologies (Tafuri and Selvakumar, 2002). Almost 75% of the 600,000-800,000 miles of sewer pipelines in the United States function at 50% of their ability or less (Tafuri and Selvakumar, 2002; ASCE, 1994). The Urban Institute (1981) concluded that close to 30,000 major main breaks and 300,000 pipeline stoppages/clogs occur annually, and will continue to increase at a rate of approximately 3% annually (Tafuri and Selvakumar, 2002). Over 50% of these stoppages are caused by tree roots that perforate the sewer pipelines (Tafuri and Selvakumar, 2002).

The Combined Sewer Overflow (CSO), Blending, and Peak Wet Weather policies are the current and recently proposed stormwater policies related to the impacts of wet weather events on wastewater treatment performance. The policy which regulates a POTW depends on whether the facility is served by CSS or SSS. The CSO policy addresses facilities with CSS, while the Blending and Peak Wet Weather policies regulate POTWs with SSS.

The facilities subject to these policies are regulated by the NPDES, which sets uniform effluent limits for dischargers of toxic pollutants, wastewater, and other substances that potentially threaten water quality (Adler, Landman, and Cameron, 1993; Rosenbaum, 2002), and permits discharges for point sources based on the best available technology (BAT) (Rosenbaum, 2002; Smith, 2004). The United States Environmental Protection Agency (US EPA) has given authorized states approval to permit their own point sources in accordance with the NPDES (Cunningham and Saigo, 2001; EPA, 2003;

Rosenbaum, 2002). Currently, 35 states have partial to full authorization to permit POTWs in accordance with the CSO, Blending, and Peak Wet Weather policies (EPA 2003).

Industrial and municipal facilities that discharge either wastewater or stormwater runoffdirectly into a waterbody are considered point sources and are required to obtain a permit through NPDES (EPA, 2003). Any discharge into a waterbody that cannot be precisely defined, such as runoff is deemed a nonpoint source (Rosenbaum, 2002). Nonpoint sources are not regulated under the NPDES (Rosenbaum, 2002).

<u>The Combined Sewer Overflow (CSO) Policy</u>

Due to the concentrations of pathogenic and toxic wastes that can be present in CSOs and the higher frequency with which these events occur, the EPA passed the CSO policy in 1994 to define conditions under which CSOs would be permitted by the NPDES (40 CFR 122; EPA, 1999). Under this policy, those facilities served by CSS were given until 1997 to implement the policy's nine minimum technology-based controls, which encourage facilities to minimize the necessity of CSOs (40 CFR 122; EPA, 1999). The nine minimum controls are:

1. Proper operation and regular maintenance programs for the sewer system and the CSOs
2. Maximum use of the collection system for storage
3. Review and modification of pretreatment requirements to assure CSO impacts are minimized
4. Maximization of flow to the publicly owned treatment works for treatment
5. Prohibition of CSOs during dry weather
6. Control of solid and floatable materials in CSOs
7. Pollution prevention
8. Public notification to ensure that the public receives adequate notification of CSO occurrences and CSO impacts

9. Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls (40 CFR 122)

Facilites regulated by the CSO policy are also required to develop a long-term plan, which is devised to aid the POTW in meeting state water quality standards (40 CFR 122; EPA, 1999). Important elements of the long-term plan include characterization and monitoring (pre and post permit issuance) of the CSS, public participation, consideration of cost versus performance options, and the development of an implementation schedule which is used for assessment during permit renewal (40 CFR 122).

<u>The Proposed "Blending" Policy</u>

The EPA proposed a blending policy in 2003 to combat the problems associated with increased stormwater runoff, including the potential for more waterborne-disease outbreaks due to inadequate wastewater treatment (40 CFR pt. 133) (Federal Register, 2003). The proposed EPA policy provided a rationale for diverting stormwater runoff around biological treatment units and mixing (or "blending") it with treated wastewater before discharge (EPA, 2003).

The major concepts delineated in the Federal Register of the Blending policy are modeled after some of the concepts embodied by the Nine Minimum Controls aspect of the Combined Sewer Overflow (CSO) policy (40 CFR 122). The most obvious difference between the Blending Policy and the CSO policy is that wastewater treatment facilities served by a Sanitary Sewer System (SSS) are to be regulated under the Blending Policy, while Combined Sewer Overflow Policy regulates facilities operating under a CSO. However, this is not explicitly stated by the Blending policy.

It has been reported that stormwater can transport pathogens, and may be linked to waterborne disease outbreaks (Curriero, Patz, Rose & Lele, 2001; Kistemann, Claben, Koch, Dangendorf, Fischeder, Gebel, Vacata & Exner, 2002; Gaffield, Goo, Richards & Jackson, 2003; Auld, MacIver & Klaasen, 2004; Wade, Sandhu, Levy, Lee, LeChevallier, Katz & Colford, 2004). Blending untreated stormwater with treated wastewater could pose a potential public health threat. The EPA received over 98,000 public comments challenging the proposed policy, and decided in 2005 not to finalize the policy and instead to review other alternatives (EPA, 2005).

The main issues in the debate about this proposed Blending policy concern public health, the policy's inconsistency with current rules, and expensive infrastructure renovations. If the Blending policy is passed, there is concern that these practices will become routine and pose a greater public health threat as stormwater containing pathogens is not treated but instead recombined with treated wastewater and released into the environment (Curriero et al., 2001; Kistemann et al., 2002; Gaffield et al., 2003; Auld et al., 2004; Wade et al., 2004).

There are also claims that the policy will allow intentional bypasses at a wastewater treatment facility, contradicting existing rules that state such bypasses are illegal (40 CFR §122.41 (m)) (Copeland, 2005). However, the other side of the debate argues that if blending practices are subsequently banned following the defeat of the proposal, the necessary infrastructure renovations will be too costly and result in substantial increases in customer fees (Copeland, 2005).

Existing alternative practices include measures to reduce inflow and infiltration within the CSS or SSS, along with designing storage tanks aimed at equalizing the inflow into the wastewater treatment facility during wet weather events (Payne, 2005). Although these alternative measures have proven effective from a long-term perspective, a facility must make a significant initial investment (Payne, 2005). The capital costs can be substantial due to the fact that these alternative methods only need to be used for some extreme wet weather events that normally occur during a certain season of the year (Payne, 2005).

The Proposed "Peak Wet Weather" Policy

The public comment period for the most current "Peak Wet Weather" policy ended on January 23, 2006 (EPA 2006). This new policy reconciles many of the issues associated with the proposed and defeated "Blending" policy.

The “Peak Wet Weather” policy specifically regulates peak wet weather flow diversion around secondary treatment units at wastewater treatment facilities served by a sanitary sewer system (EPA 2006). Where the “Blending” policy was ambiguous as to whether its purpose was to regulate a CSS, SSS, or both, the “Peak Wet Weather” policy explicitly states its distinction from policies related to combined sewer systems and CSOs (Federal Register, 2005). The “Peak Wet Weather” policy exclusively sets regulations for facilities served by a sanitary sewer system (Federal Register, 2005).

As with the Blending policy, this newly proposed regulation is also modeled after the CSO policy. The Peak Wet Weather policy alleviated many of the issues present with the Blending policy by factoring in the components of the CSO policy that the Blending policy neglected to define in terms of SSS.

In addition to the public comment period that is routine for any proposed federal regulation, the Peak Wet Weather policy provides for public participation in many ways. The policy encourages public planning meetings to minimize the necessity of diversion events and to maximize flow management along with treatment (40 CFR 122 and 123) (Federal Register, 2005). This policy also requires the regulating authority to include a permit provision that any diversion event be made known to the public within 24 hours of the event, and a follow-up notification be submitted for public perusal within 48 hours identifying the duration and volume of the diversion event (40 CFR 122 and 123) (Federal Register, 2005). A permit provision is also required by the EPA to invite public review of the POTW operator’s diversion practices (40 CFR 122 and 123) (Federal Register, 2005).

Any diversion discharge into a sensitive area must be minimized by the POTW through cautionary restrictions placed on the permit by the regulating authority (40 CFR 122 and 123) (Federal Register, 2005). These permit limitations are intended to reduce the impact of any discharge entering a sensitive area.

The policy also requires the POTW to conduct a “No Feasible Alternatives Analysis” before a diversion permit is granted (40 CFR 122 and 123). The responsibilities of the POTW, regulating authority, and EPA are outlined in the regulation to ensure that wet weather diversions are only resorted to under the specific conditions set forth by the policy (40 CFR 122 and 123) (Federal Register, 2005).

The "No Feasible Alternatives Analysis" requires the POTW to define its design capacity and maximum flow, evaluated existing storage and other alternatives for expansion, while also evaluating the cost of increasing the capacity to minimize the necessity for diversions (40 CFR 122 and 123) (Federal Register, 2005). It also requests information on the frequency, duration, and volume of the current diversions along with the use of climate prediction analyses to assess the need for future diversions (40 CFR 122 and 123) (Federal Register, 2005).

The POTW is required by the feasibility analysis to assess the costs of additional technologies for use on treated diverted influent and whether the service community would be able to fund any possible improvements to the POTW (40 CFR 122 and 123) (Federal Register, 2005). Even in the event that new technologies are affordable for the POTW, the facility is expected to develop a protocol for monitoring the diverted and recombined flow for all parameters for which NPDES has set effluent limitations for that POTW (40 CFR 122 and 123) (Federal Register, 2005).

Combined Sewer and Sanitary Sewer Systems

The effect of stormwater on the performance of wastewater treatment facilities depends on whether the stormwater enters through a Combined Sewer System (CSS) or a Sanitary Sewer System (SSS). A CSS transports sanitary wastewater and stormwater to a treatment plant, while a SSS provides a separate system for the conveyance of wastewaters and stormwater (EPA, 2004a). A CSS is therefore designed to accommodate larger amounts of stormwater due to extreme wet weather events, while a SSS does not account for storm events.

An estimated 40 million people in 772 cities within 31 states are served by Combined Sewer Systems (CSS) (EPA 2004d). These can overflow during peak wet weather events and discharge approximately 850 billion gallons of untreated stormwater and wastewater annually (EPA 2004d). There are close to 19,000 Separate/Sanitary

Sewer Systems (SSS) serving 160 million people in the United States (EPA 2004d). These SSS have been estimated to overflow between 23,000 and 75,000 times per year, discharging 3 to 10 billion gallons of untreated wastewater annually (EPA 2004d). Due to the pathogenic microorganisms carried in varying concentrations by wastewater and stormwater, the occurrence of CSOs and SSOs can impact human health (EPA, 2004b). A CSS conveys wastewater along with stormwater, and therefore overflows may occur more frequently depending on the system design and infrastructure integrity, resulting in the potential for CSOs to pose a greater health threat (EPA, 2004b). In fact, the locations of CSSs across the United States represented by Figure 2 can be compared to the locations of waterborne disease outbreaks found in Figure 3.

During heavy rainfall events, combined systems are likely to experience a large increase of inflow and decrease in performance of wastewater treatment facilities because a CSS collects both stormwater and wastewater together. However, a sanitary sewer system will also see increases of inflow and decreases in performance of wastewater treatment facilities (WEF, 1999; Dr. Levine Personal Communication, 2005). This is due to what is termed "inflow and infiltration" or "I/I" (WEF, 1999).

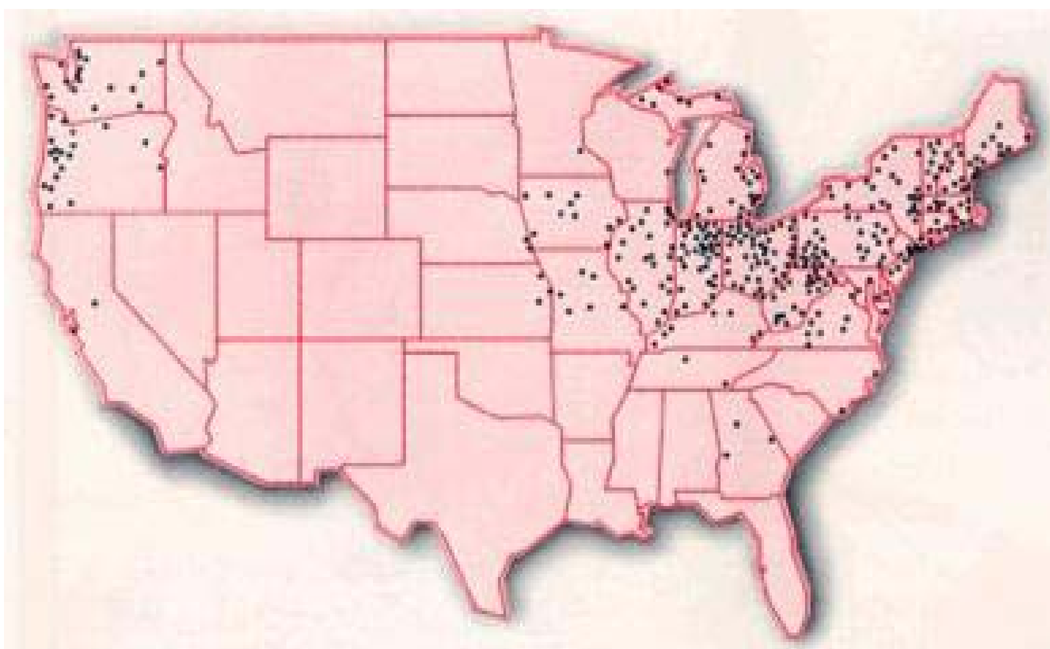

Figure 2. The Geographic Locations of Combined Sewer Systems (CSS) in the Contiguous United States (EPA 2002a)

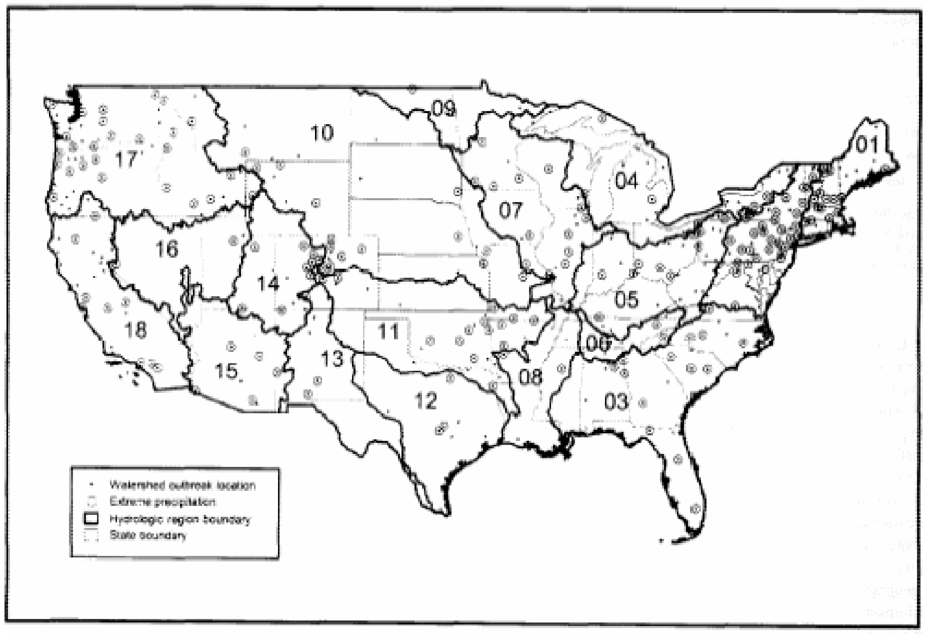

Figure 3. The Locations of Waterborne Disease Outbreaks and the Associated Precipitation Levels in the Contiguous United States, 1948-1994 (Curriero et al., 2001)

Impact of Stormwater on Wastewater Treatment

During intense rainfall, stormwater runoff from residential, urban, and agricultural areas can be contaminated with chemicals and pathogenic microorganisms (Curriero et al., 2001; Kistemann et al., 2002; Reeves et al., 2004). A comparison of the characteristics of stormwater and wastewater is given in Table 3. Stormwater is either collected by a SSS or it drains into a CSS (EPA 2004a). It can also enter a wastewater treatment facility through infiltration and inflow (I/I) (WEF 1999). As with BOD, COD, fecal coliform bacteria, and nitrogen, the differences between the ranges of stormwater and wastewater constituent concentrations can be significant (Tchobanoglous et al., 2003). The wastewater concentrations of TKN and fecal coliforms can be 50-700 and 100-1000 times greater, respectively than the concentrations of the same parameters in stormwater (Tchobanoglous et al., 2003). On the other hand, the difference between stormwater and wastewater concentrations of nitrate and phosphorous range from .approximately 5-1 and 3-10, respectively with the nitrate concentration being higher in stormwater than wastewater (Tchobanoglous et al., 2003).

Table 1. Comparison of Consituent Concentrations in Stormwater Runoff and Untreated Municipal Wastewater (Tchobanoglous et al., 2003)

Parameter	Unit	Stormwater Runoff	Municipal Wastewater
Total Suspended Solids (TSS)	mg/L	67-101	120-370
Biochemical Oxygen Demand (BOD)	mg/L	8-10	120-380
Chemical Oxygen Demand (COD)	mg/L	40-73	260-900
Fecal Coliform Bacteria	MPN/100mL	10^3-10^4	10^5-10^7
Nitrogen:			
Total Kjeldahl Nitrogen (TKN)	mg/L	0.43-1.00	20-705
Nitrate	mg/L	0.48-0.91	0
Phosphorous	mg/L	0.67-1.66	4-12

Effluent Standards and Testing Parameters

Indicator organisms, such as coliform bacteria, fecal streptococci, and *Clostridium perfringens* are intestinal organisms used to indicate fecal contamination in wastewater

(Maier et al., 2000; Rose et al. 2004). Pathogenic microorganisms are often associated with fecal contamination, and are assumed to be present when an indicator organism is detected (Maier et al., 2000; Tortora, Funke, and Case, 2001).

Other parameters are also used to evaluate the quality of the effluent being produced at wastewater treatment facilities. These parameters include BOD, TSS, and nutrients if the POTW is equipped with a nutrient removal system.

The NPDES has set minimum secondary treatment standards for domestic wastewater treatment facilities, which are found in Table 9. These standards must be followed by every state, but states are capable of going beyond the minimum standards and can set their own requirements to include other parameters or to make the standards more stringent (Adler et al., 1993; Rosenbaum, 2002).

A coliform effluent limitation is not included in the NPDES minimum requirements; however, testing for coliform presence in effluent wastewater has been adopted as a standard in many states, including Florida. The NPDES effluent limits for fecal coliforms stipulated in the Clearwater facilities' permits are included in Table 9.

Table 2. US EPA Minimum Secondary Treatment Standards for POTWs (EPA, 2002d; Tchobanoglous et al., 2003)

Parameter	7 Day Average	30 Day Average	75 Percent of Samples
BOD_5 (mg/L)	30	45	
TSS (mg/L)	30	45	
pH	6-9	N/A	
Removal	85 % BOD_5 and TSS	N/A	
Fecal Coliform (#/100mL)	N/A	N/A	<1

Table 3. Types and Range of Microorganisms Commonly Associated with Untreated Domestic Wastewater (Maier et al., 2000)

Microorganism	Concentration (per mL)
Total Coliform	10^5-10^6
Fecal Coliform	10^4-10^5
Fecal Streptococci	10^3-10^4
Enterococci	10^2-10^3
Shigella	Present
Clostridium perfringens	10^1-10^3
Giardia cysts	10^{-1}-10^2
Cryptosporidium cysts	10^{-1}-10^1
Helminth ova	10^{-2}-10^1
Enteric viruses	10^1-10^2
Salmonella	10^0-10^2

Pathogenic Microorganisms

Giardia and *Cryptosporidium*, two of the microorganisms listed in Table 10, have been implicated in approximately one-third of all waterborne disease outbreaks associated with drinking water (Tortora et al., 2001). *Giardia* and *Cryptosporidium* are very prevalent protozoan pathogens that cause gastrointestinal illnesses (Maier et al., 2000; Tortora et al., 2001). The illnesses they cause (Giardiasis and Cryptosporidiosis) can be fatal in immuno-compromised individuals, such as the elderly, young children, and those afflicted with diseases that target the immune system (Mackenzie, Hoxie, Proctor, Gradus, Blair, Peterson, Kazmierczak, Addiss, Fox, Rose, and Davis, 1994). Immuno-compromised individuals represent close to 20% of the United States population (Gerba, Rose, and Haas, 1996), and it is therefore imperative that the public is protected from exposure to waterborne illnesses.

Only 10% of these outbreaks are foodborne, while the other 90% have been attributed to water-related methods of transmission (Guy, Payment, Krull, and Horgen, 2003). This is due mainly to the fact that both *Giardia* and *Cryptosporidium* are capable of forming cysts and oocysts, respectively, when environmental conditions become too harsh (Tortora et al., 2001; Roberts and Janovy, 2000). These cysts and oocysts are very resistant to chlorine disinfection (Tortora et al., 2001; Roberts and Janovy, 2000), which is an important step in the tertiary treatment stage of the wastewater treatment process (Maier et al., 2000). It is imperative to eliminate the transport of these waterborne pathogens to the environment through wastewater discharge to waterbodies.

Therefore, it is necessary to examine any differences in the pathogen removal rates between similar facilities to determine which units are more effective at treating wastewater for pathogen microorganisms. The units deemed the most effective at removing pathogens should be required for stormwater treatment by a potential stormwater policy. However, those that are not very effective could be targeted as those able to be bypassed or unnecessary for stormwater treatment.

Upgrading Wastewater Treatment Facilities to Meet Future Demands

According to the most recent Clean Water Needs Survey (1996), there are 16,024 existing wastewater treatment facilities in the United States, and 28% of those provide greater than secondary treatment (EPA, 1996; EPA, 2002c). Population increases and growing service areas will increase the amount of wastewater entering the treatment facility, and will subsequently increase the probability for the occurrence of CSOs (Daigger and Buttz, 1998' EPA, 1996). The design capacity of existing treatment facilities will have to be upgraded in the future to meet more stringent discharge requirements and manage for wet weather events when the flow rate will be higher than the design capacity and threaten treatment performance (Daigger and Buttz, 1998; EPA, 1996; National Research Council, 1993; Tchobanoglous et al., 2003).

The factors influencing the necessity for treatment upgrades at a POTW include population growth within the existing service area, expansion of service area to include a new community, implementation of more stringent effluent limitations, and the use of dated technologies and equipment (Daigger and Buttz, 1998). The ability of a facility to make the changes necessitated by the occurrence of these factors is dependent upon the funds to which the facility has access. A POTW with severely limited resources will be less likely to be able to make the required improvements to treat the wastewater efficiently, whereas a POTW with a larger, more affluent service area would have the resources able to make these changes.

Suspended Growth Processes: Activated Sludge

As the quality of stormwater entering the wastewater treatment facility increases, it adds to the amount of wastewater influent (Q_{WW}) and increases the total influent flow rate (Q_T) (Tchobanoglous et al., 2003). Wastewater treatment operations with shorter solids retention (SRT) and hydraulic retention times (HRT) and lower mixed liquor suspended solids (MLSS) concentration are more vulnerable to wet weather flows (Tchobanoglous et al., 2003; Rose et al., 2004). However, the impact of wet weather flows can be mitigated if the treatment capacity encompasses the range of the expected wet weather flows (Grady, Daigger, and Lim, 1999; Tchobanoglous et al., 2003). Most treatment facilities are designed for a finite planning horizon. As POTWs near their design life, their ability to efficiently treat the increasing concentrations and quantity in the influent are reduced, and treatment improvements become necessary.

If increased flows are significant enough that the hydraulic retention time (HRT) represented by “t” is decreased, the solids retention time (SRT), otherwise known as the mean cell residence time (MCRT), in wastewater treatment units could be reduced (Tchobanoglous et al. 2003; Bertrand-Krajewski, Lefebvre, Lefai, and Audic, 1995; Mihelcic et al., 1999). The MCRT can be controlled using short-term adjustments to the waste sludge flow rate (Q_W) and by minimizing the impacts the biomass concentration of the reactor (X) (Tchobanoglous et al. 2003; Bertrand-Krajewski, Lefebvre, Lefai, and Audic, 1995; Mihelcic et al., 1999). The SRT or MCRT is the total mass of cells in the tank divided by the rate of cell wastage in the tank (Tchobanoglous et al., 2003; Mihelcic et al., 1999). If not controlled, SRTs in the range of 1 to 3 days can cause substantial loss of MLSS (Grady et al., 1999).

MLSS concentrations can range from 500 to 5000mg/L depending on the design and operating characteristics of the wastewater treatment facility (Grady et al., 1999). If the MLSS concentration falls below the minimum level during operations, the ability of the process to develop an adequate settling sludge floc will decrease and result in a lower quality effluent (Grady et al., 1999).

Wastewater treatment processes with a shorter SRT and HRT and a lower MLSS concentration are more susceptible to being disrupted by wet weather flows (Tchobanoglous et al., 2003; Rose et al., 2004). However, those treatment processes which are better equipped to manage a higher design flow rate are more capable of performing well under these conditions of increased influent flow rate (Grady et al., 1999; Tchobanoglous et al., 2003). Typical SRT, HRT, and MLSS of suspended growth processes are listed in ascending order by Table 4, beginning with the processes exhibiting lower SRT, MLSS, and HRT and moving down to those processes less susceptible to disruption by wet weather flows. Some of the mechanisms by which each process is capable of dealing with higher flow rates are also listed.

Table 4. Typical Design Parameters for Commonly Used Suspended Growth Processes: Activated Sludge (Grady et al., 1999; Tchobanoglous et al., 2003)

Process	SRT (d)	MLSS (mg/L)	HRT (h)	Mechanisms Influencing Process Ability to Manage High Flow
High-rate Aeration	0.5-2	200-1000	1.5-3	Less stable; Can be disrupted by peak flows that wash out the MLSS
Conventional Plug Flow	3-15	1000-3000	3-5	
Complete Mix	3-15	1500-4000	3-5	
Step Feed	3-15	1500-4000	3-5	Numerous inputs at different points split the influent flows to the system and reduce the amount of purged solids
Contact Stabilization	5-10	1000-3000[a] 6000-10000[b]	0.5-1[a] 2-4[b]	Separate compartments enable it to handle peak flows without loss of MLSS
Sequencing Batch	10-30	2000-5000	15-40	Use of separate reactors; Peak flows may disrupt operation if not accounted for in designing the cycling of the system
Batch Decant	12-25	2000-5000	20-40	Use of a baffled or prereact chamber to prevent disruption of the MLSS in the main chamber
Oxidation Ditch	15-30	3000-5000	15-30	Use of numerous baffled chambers/zones to prevent disruption of the MLSS in the main chamber; MLSS recycle operation
Extended Aeration	20-40	2000-5000	20-30	Larger reactors and longer hydraulic loading rate that enable accommodation of a large variation in flow rates

[a] MLSS concentration and HRT in contact basin
[b] MLSS concentration and HRT in stabilization basin

Nutrient Removal

The amount of nitrogen removal is influenced by the concentration of ammonia and nitrogen (NH_4-N) in the influent wastewater and the type of treatment (Randall et al., 1992; Tchobanoglous et al., 2003). Nitrogen can be removed biologically through sequential nitrification and denitrification (Grady et al., 1999; Tchobanoglous et al., 2003). Nitrification is an aerobic process completed by chemoautotrophic bacteria, which have a lower specific growth rate than the heterotrophic bacteria used for denitrification (Grady et al., 1999). These bacteria require a longer SRT to ensure adequate microbial growth necessary for sufficient ammonia and nitrite oxidation (Grady et al., 1999; Tchobanoglous et al., 2003).

On the other hand, the anoxic process of denitrification is carried out by heterotrophic bacteria, which can grow and survive at very short SRTs due to their higher specific growth rates (Grady et al., 1999).

Biological phosphorous removal (BPR) systems operate with shorter SRTs in the range of 2 to 10 days (Randall et al., 1992; Tchobanoglous et al., 1992). Longer SRTs can induce nitrification (Randall et al., 1992) and produce less phosphorous biomass, which allows less phosphorous to be removed (Tchobanoglous et al., 2003). However, the SRT must also be long enough to grow phosphate accumulating organisms (PAOs) that are required for BPR (Grady et al., 1999; Randall et al., 1992). Grady et al. (1999) suggests that SRTs should be chosen based solely on meeting treatment requirements and not increased or decreased beyond that specified limit. Typical nutrient removal processes and the corresponding SRT, HRT, and MLSS values are compared in Tables 5 and 6.

Facilities with nutrient removal systems provide an extra stage for treatment, and therefore are more capable of efficiently treating wastewater with increased flow rate. Those nutrient removal processes considered to be more resilient to peak wet weather events are those that have longer SRTs and higher MLSS concentrations and a larger range for these values as well. The larger range of SRT and MLSS values indicates that the process is capable of handling varying flow rates.

The BNR facilities in Table 5 have fairly similar levels of MLSS and SRT, which makes it difficult to predict resiliency solely from the data presented in the table. However, it is clear from the lower SRT and smaller range for SRT and MLSS of the Modified Ludzack-Ettinger (MLE) process, that this system is most likely to be the least resilient to peak wet weather conditions out of all the processes presented in Table 5. The BPR processes shown in Table 6 are normally those that remove both nitrogen and phosphorous. It is clear from the data exhibited in the table that these processes have more variability in their design parameters than those for BNR. Compared to the rest of the processes in Table 6, the Phoredox (A/O) process appears to be the least able to cope with peak wet weather flows due to his very low SRT and smaller range of SRT and MLSS values. On the other hand, the UCT, Bardenpho (five-stage), and Sequencing Batch Reactor (SBR) all have longer SRTs and higher MLSS concentrations than the other processes in Table 6, and could be considered to be more resilient to peak wet weather flows.

Table 5. Typical Design Parameters for Commonly Used Nutrient Removal Processes: Nitrogen (Tchobanoglous et al., 2003)

Process	SRT (d)	MLSS (mg/L)	HRT (h)			Mechanisms Influencing Performance
			Total	Anoxic	Aerobic	
Modified Ludzack-Ettinger (MLE)	7-20	3000-4000	5-15	1-3	4-12	Amount of denitrification is limited by the nitrate recycling rate, which is dependent upon the influent flow rate
Sequencing Batch Reactor (SBR)	10-30	3000-5000	20-30	Flexible	Flexible	Flow equalization minimizes MLSS washout from hydraulic surges
Bio-denitro™	20-40	3000-4000	20-30	Flexible	Flexible	Resistant to shock loading if operated with large reactor volume
Bardenpho (4-stage)	10-20	3000-4000	8-20	1-3[c] 2-4[e]	4-12[d] 0.5-1[f]	Resistant to shock loading if operated with large reactor volume
Oxidation Ditch	20-30	2000-4000	18-30	Flexible	Flexible	Recycle rate to the influent is very high, reducing the effluent total nitrogen concentration
Orbal	10-30	2000-4000	10-20	6-10	3-6[c] 2-3[d]	

[c] First stage
[e] Third stage
[d] Second stage
[f] Fourth stage

Table 6. Typical Design Parameters for Commonly Used Nutrient Removal Processes: Phosphorous (Crites and Tchobanoglous, 1998; Tchobanoglous et al., 2003)

Process	SRT (d)	MLSS (mg/L)	HRT (h)			Mechanisms Influencing
			Anaerobic	Anoxic	Aerobic	Performance
Phoredox (A/O)	2-5	3000-4000	0.5-1.5	N/A	1-3	High-rate operation optimizes phosphorous removal by minimizing nitrification
A^2/O	5-25	3000-4000	0.5-1.5	0.5-1	4-8	Efficiency reduced by combined nutrient removal effort.
University of Cape Town (UCT)	10-25	3000-4000	1-2	2-4	4-12	Lower MLSS concentration in the anaerobic zone, which necessitates a longer anaerobic HRT and SRT
Virginia Initiative Plant (VIP)	5-10	2000-4000	1-2	1-2	4-6	High-rate operation optimizes phosphorous removal by minimizing nitrification
Bardenpho (5-stage)	10-20	3000-4000	0.5-1.5	1-3[g] 2-4[h]	4-12[g] 0.5-1[h]	
PhoStrip	5-20	1000-3000	8-12	N/A	4-10	
Sequencing Batch Reactor (SBR)	20-40	3000-4000	1.5-3	1-3	2-4	Flow equalization minimizes MLSS washout from hydraulic surges

[g] First stage
[h] Second stage

Nutrient removal can be influenced by factors other than the SRT, including temperature and pH (Grady et al., 1999; Randall et al., 1992; Tchobanoglous et al., 2003). The temperature is directly proportional to the specific growth rates of nitrifying bacteria as exhibited in Figure 3 (Grady et al., 1999; Randall et al., 1992). As higher temperatures increases the specific growth rate of the bacteria, a shorter SRT is necessary to increase the amount of ammonia-nitrogen entering the reactor for oxidation (Grady et al., Randall et al., 1992; Tchobanoglous et al., 2003). Conversely, if the temperature drops below the optimal value, a longer SRT will be necessary to decrease the amount of ammonia-nitrogen entering the reactor as the specific growth rate of the nitrifying bacteria decreases (Grady et al., Randall et al., 1992; Tchobanoglous et al., 2003). The relationship of temperature and SRT for nitrogen removal and phosphate removal is compared in Figure 4. Nitrifying bacteria appear to be more susceptible to temperature fluctuations than phosphate accumulating organisms (PAOs) (Grady et al., Randall et al., 1992; Tchobanoglous et al., 2003).

At the facilities examined in the case studies, the increasing flow rate is associated with the higher temperatures of the summer rainy seasons. These higher flow rates complicate the nutrient removal process by making it more difficult to attain the lower SRT needed to accomplish successful nitrification.

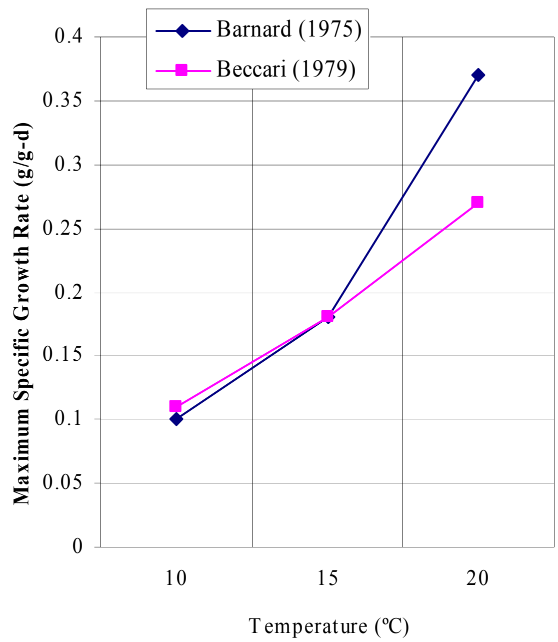

Figure 4. Effect of Temperature on the Maximum Specific Growth Rates of Nitrifying Bacteria (Barnard, 1975; Beccari, Marani, and Ramadori, 1979; Randall et al., 1992)

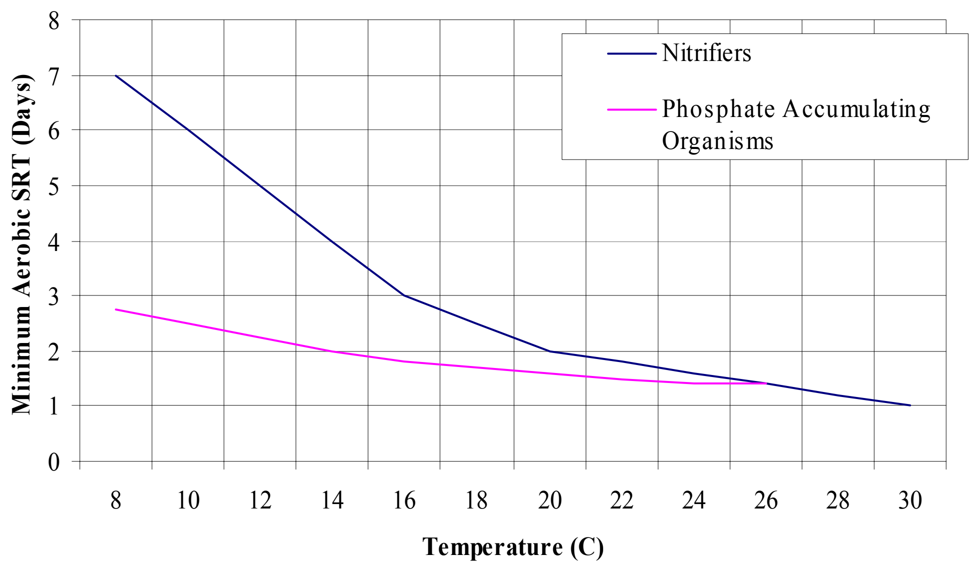

Figure 5. Effect of Temperature on the Minimum Aerobic SRT Required to Grow Nitrifiers and Phosphate Accumulating Organisms (PAOs) (Grady et al., 1999)

Nitrifying bacteria are particularly vulnerable to changes in pH in comparison to the sensitivity of denitrifying bacteria and PAOs to varying pH values (Grady et al., 1999; Princic, Mahne, Megusar, Paul, and Tiedje, 1998; Randall et al., 1992; Tchobanoglous et al., 2003). The process of nitrification can be severely altered by the reduction in microbial activity resultant of pH fluctuating outside of its optimal range, which varies slightly with the particular nitrogen removal process (Grady et al., 1999; Princic et al., 1998; Randall et al., 1992; Tchobanoglous et al., 2003). The effect of pH on the specific growth rate of nitrifying bacteria is exhibited in Figure 5, which shows an optimal pH range at or around a value of 7 (Grady et al., 1999; Princic et al., 1998; Randall et al., 1992; Tchobanoglous et al., 2003).

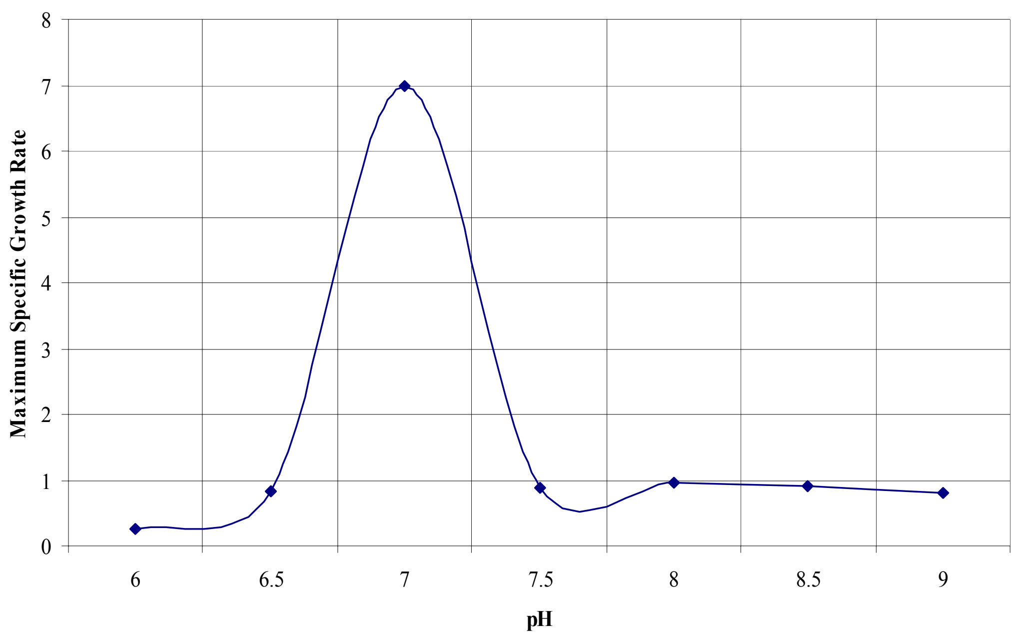

Figure 6. Effect of pH on Maximum Specific Growth Rates of Nitrifying Bacteria (Grady et al., 1999; Quinlin, 1984)

The pH value of influent stormwater and wastewater can vary considerably depending on certain characteristics of the surrounding area, such as air quality and the chemical constituent of the wastewater. As stormwater enters the POTW at elevated flow rates, the ability of the operator to adequately adjust the pH level is reduced and the process of nitrification becomes compromised due to the variable pH.

Attached Growth Processes: Trickling Filters

The treatment performance of trickling filter systems cannot be characterized by one design parameter (i.e. SRT) as in activated sludge and nutrient removal systems, because the biomass in a trickling filter is not uniformly distributed and is not easily calculated (Grady et al., 1999; Tchobanoglous et al., 2003). The hydraulic loading rate (q) is directly proportional to the flow rate (Q), and the organic (BOD) loading rate has been positively correlated with the percent BOD removal as can be seen in Figure 7 (Bruce and Merkens, 1973; Grady et al., 1999; Tchobanoglous et al., 2003). Therefore, these parameters can be used to assess the treatment performance of a trickling filter under high inflow conditions.

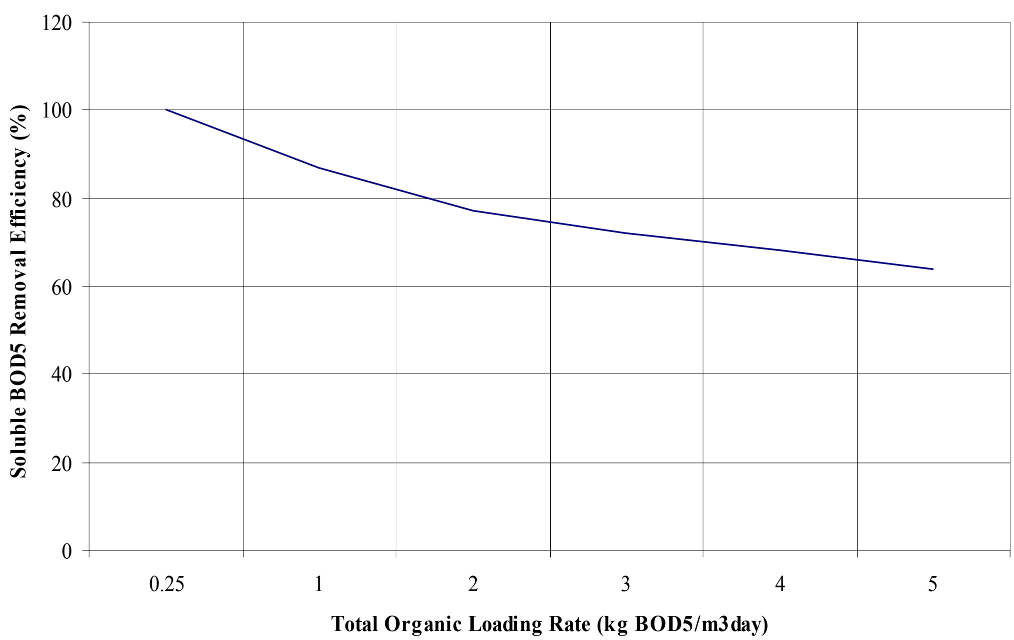

Figure 7. Relationship Between Total Organic Loading (TOL) and BOD_5 Removal Efficiency for a High-Rate Trickling Filter (Grady et al, 1999)

Typical hydraulic and organic loading rates, along with BOD removal efficiency for different types of attached growth systems are presented in Table 7. Trickling filters can also be combined with activated sludge processes to optimize performance of both systems and result in higher percentage of BOD removal (Crites and Tchobanoglous 1998). Typical organic loading rates of trickling filter component and the typical SRT, HRT, and MLSS values for the activated sludge component of four common combined systems: trickling filter/solids contact (TF/SC), roughing filter/activated sludge (RF/AS), activated biofilter (ABF), and biofilter/activated sludge (BF/AS) are compared in Table 8

Table 7. Typical Design Parameters for Commonly Used Attached Growth Processes: Trickling Filters (Grady et al., 1999; Tchobanoglous et al., 2003)

Process	Packing Medium	Hydraulic Loading Rate (m^3/m^2d)	Organic Loading Rate (kg BOD/m^3d)	% BOD Removal
Low/Standard Rate	Rock	1-4	0.07-0.22	80-90
Intermediate Rate	Rock	4-10	0.24-0.48	50-80
High Rate	Rock	10-40	0.4-2.4	50-90
High Rate	Plastic	10-75	0.6-3.2	60-90
Roughing	Rock/plastic	40-200	>1.5	40-70

Table 8. Typical Design Parameters for Commonly Used Attached Growth Processes: Combined Trickling Filter Systems (Grady et al., 1999; Tchobanoglous et al., 2003)

Process	Trickling Filter Organic Loading Rate (kg BOD/m^3d)	Activated Sludge			Mechanisms Influencing Performance
		SRT (d)	MLSS (mg/L)	HRT (h)	
TF/SC	0.3-1.2	0.3-2.0	1000-3000	10-60	
RF/AS	1.2-4.8	2.0-7.0	2500-4000	10-60	
ABF	0.36-1.2	0.5-2.20	1500-4000	N/A	High loading rates result in performance variability
BF/AS	1.2-4.8	2.0-7.0	1500-4000	2-4	

As with activated sludge and nitrogen removal systems, combined systems most resilient to peak wet weather flows will be those with the longest SRT and highest level of MLSS, along with a larger range of SRT and MLSS. There has been less research performed on trickling filters, but it can be speculated that processes with higher and/or larger range of hydraulic loading rate be more resilient to extreme weather events. With less resilient processes, increases of the influent flow rate could result in a reduction of the time available for attachment to the trickling filter media. Organic materials harboring microbial organisms, along with larger microbes will, as a result, not be filtered out and will still remain in the effluent from the trickling filter.

Chapter Four
Methodology

The purpose of this study is to identify whether wastewater treatment is impaired during periods of increased rainfall, and to compare current policies that address this issue. The goal of the research is to provide tools for assessing management scenarios for peak flow events and to offer suggestions for improvements in the stormwater policies related to peak flows and wastewater treatment.

Stormwater Policy Framework

The CSO, Blending, and Peak Wet Weather policies were examined to develop a framework of concepts that could serve as a basis for comparison between the three policies. These components derived from the developed framework were then analyzed to determine the effectiveness in managing peak wet weather flows to wastewater treatment facilities and the applicability of these policies on a national scale.

Case Studies

The impacts of stormwater on wastewater treatment will be evaluated using a case study approach. Two urbanized locations were chosen and the facilities at those locations were assessed using three basic tasks of data acquisition, management, and analysis. The locations included in the study include Clearwater and St. Petersburg, Florida. Site and process descriptions are provided in the next sections followed by a detailed account of the methodology used to analyze each site location.

Clearwater, Florida

The facilities included in the study of Clearwater, Florida are the Marshall Street, East, and Northeast Wastewater Treatment Facilities. Specific facility images and the locations of the facilities are shown in Figures 9 through 12. All three facilities were equipped with a biological nutrient removal system known as the five-stage Bardenpho process in 1991 (Marshall Street SOP, 2005). The study period for this site spanned 2003-2005.

All three facilities are active domestic wastewater treatment facilities permitted under NPDES (FDEP, 2006; Marshall Street SOP, 2005). The effluent limitations for each facility as outlined in their NPDES permit are shown in Table 10, and facility characteristics are listed in Table 11.

Table 9. NPDES Effluent Discharge Limits for the Three Clearwater Facilities (FDEP, 2006; Marshall Street SOP, 2005)

Facility	Flow (MGD)	BOD (mg/L)	TSS (mg/L)	TN (mg/L)	TP (mg/L)	Fecal Coliforms (#/100mL)
Marshall Street	10	5	5	3	1	<1.0[2]
East	5	5	5	3	1	<1.0[i]
Northeast	13.5	5	5	3	1	<1.0[i]

[2] This standard of <1.0 fecal coliforms/100mL must be attained for 75% of samples.

Table 10. Characteristics of Facilities from both St. Petersburg and Clearwater, Florida (FDEP, 2002; Marshall Street SOP, 2005)

Facility	Date of Construction	Date of Last Improvement	Type of Treatment	Design Capacity (MGD)	Average Annual Flow (MGD)
Marshall Street	1930	1991	Biological Nutrient Removal	10; 25 maximum	6-10
East	1960	1991	Biological Nutrient Removal	5	2-3
Northeast	1978	1991	Biological Nutrient Removal	13.5	5-6
St. Petersburg			Activated Sludge	20	20-35

Figure 8. Marshall Street Wastewater Treatment Facility, Clearwater, Florida

Figure 9. East Wastewater Treatment Facility, Clearwater, Florida

Figure 10. Northeast Wastewater Treatment Facility, Clearwater, Florida

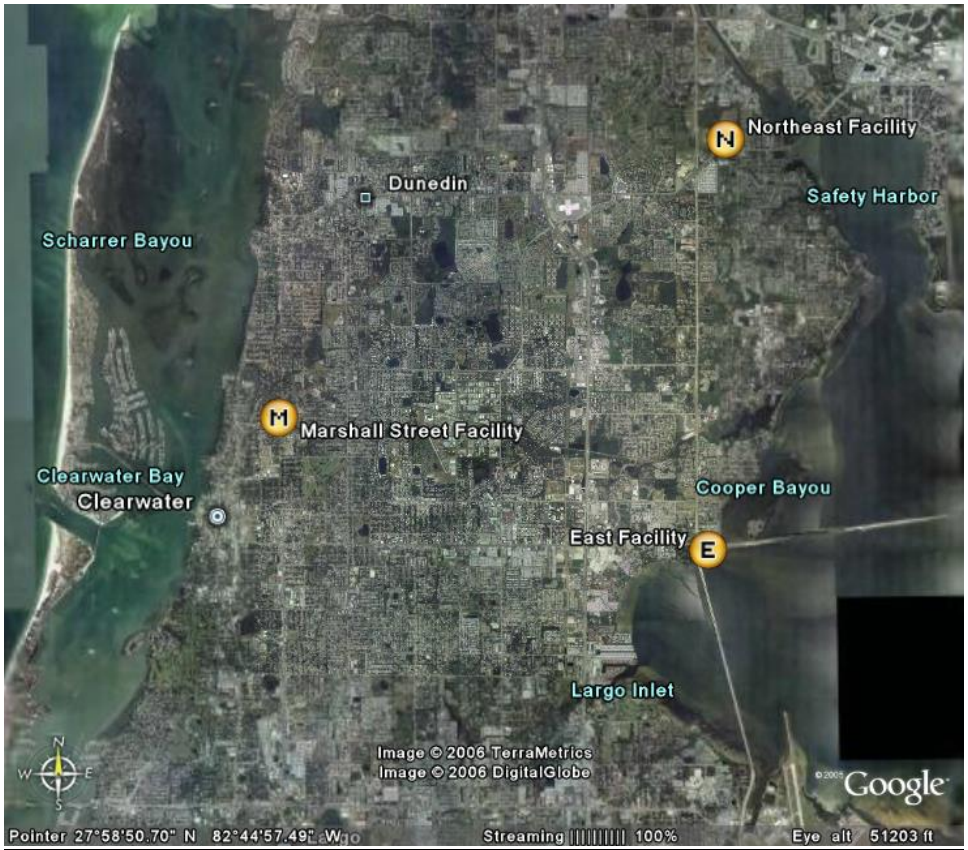

Figure 11. Location of Facilities Included in the Study from Clearwater, Florida

St. Petersburg, Florida

The St. Petersburg facility operates using an activated sludge process with no nutrient removal system, and was studied during the period of 2000-2001. The St. Petersburg plant is an active domestic wastewater treatment facility not regulated under NPDES, but is permitted as a reuse facility with a design capacity of 20 MGD (FDEP 2006). An image of this facility is shown in Figure 13, its specific location exhibited in Figure 14, and facility characteristics can be found in Table 10.

Figure 12. St. Petersburg Northwest Water Reclamation Facility, St. Petersburg, Florida

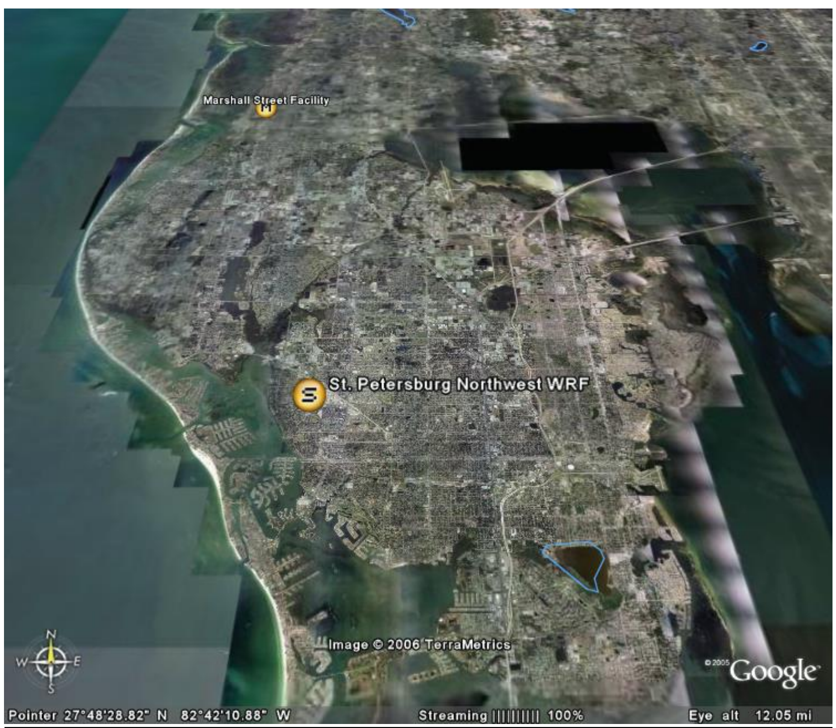

Figure 13. Location of the St. Petersburg Northwest Water Reclamation Facility

Impacts of Stormwater on Wastewater Treatment Systems

Three basic methods of data acquisition, management, and analysis were conducted to examine data from facilities in Los Angeles County, California, and Clearwater and St. Petersburg, Florida. Statistical analyses of influent and effluent data from wastewater treatment facilities in two different locations were evaluated to draw conclusions about the performance of these facilities through comparison with precipitation data obtained for each location.

<u>Data Acquisition</u>

Measurements of water quality monitoring data (i.e. BOD and TSS) taken from the influent and effluent of wastewater treatment plants in Pinellas County, Florida were obtained through other projects for analysis in this study. Daily precipitation data from Pinellas County for the study period (2000-2005) was then obtained from the National Environmental Satellite, Data, and Information Service (NESDIS) available through the National Oceanographic and Atmospheric Administration's (NOAA) Climate Center. There was no available precipitation station through data gateway known as "Summary of the Day" that provided rainfall data for Pinellas County. Therefore, daily precipitation values in Pinellas County were exported from the "Unedited Local Climatological Data (LCD)" gateway, which had the Saint Petersburg/Clearwater International Airport as a station.

<u>Data Management</u>

First the influent and effluent data from the wastewater treatment facilities was evaluated to define which parameters would be useful for the study. The parameters included in the study are shown in Table 12. This task was completed by listing or ranking these parameters in terms of what is most significant to the wastewater treatment process, and what can be used to draw conclusions about the performance of the treatment facility.

Table 11. Parameters Studied at Each Location

Parameter	Clearwater	St. Petersburg
Giardia		
Cryptosporidium		
Influent BOD	X	X
Effluent BOD	X	X
Influent TSS	X	X
Effluent TSS	X	X
Influent NH3	X	
Effluent NH3	X	
Influent TP	X	
Effluent TP	X	
Flow Rate	X	X
BOD Mass Loading	X	X

Rainfall data was exported into Microsoft spreadsheets separate from the wastewater treatment data. Rainfall events were identified and color-coded into two categories based on whether the amount of rainfall was above or below 0.5 inches. Those peak rainfall events resulting in precipitation amounts greater than 0.5 inches were considered to be more likely to influence the wastewater treatment process.

The data obtained from the Clearwater wastewater treatment facilities included influent and effluent concentrations of BOD, NH3, Total Phosphorous (TP), Total Suspended Solids (TSS). Data was also obtained from the St. Petersburg water reclamation facility, which included influent and effluent concentrations of BOD and TSS. The St. Petersburg facility does not operate a nutrient removal process, which is most likely the line of reasoning for not measuring influent nutrient concentrations. Because there were no influent concentrations to serve as a comparison, influent and effluent nutrient concentrations were not included in the study of this facility. The parameters chosen from the Pinellas County data included BOD, TSS, MLSS, nitrogen, and phosphorous. The parameters included in the study are located in Table 12. The data provided by Pinellas County was already in the Microsoft Excel spreadsheet format, and ready for statistical analysis.

Data Analysis

Statistical analyses were conducted to identify significant differences in either the loading or performance of wastewater treatment facilities under wet and dry flow conditions.

Clearwater Wastewater Treatment Facility and St. Petersburg Northwest Water Reclamation Facility

Data Sorting Rules

The data set from Clearwater and St. Petersburg were sorted according to dry and wet conditions for each parameter. The values reported during days where there was no rainfall were deemed dry conditions, while those values reported on days where there was rainfall were identified as wet periods. A period with ‘dry conditions’ was considered all of the daily events that experienced less than 0.5 inches rainfall. It was assumed that any precipitation less than this value would have negligible effects, and therefore were not included as ‘wet conditions’.

Those periods considered ‘wet conditions’ were therefore determined to be any day experiencing greater than 0.5 inches of rainfall. Because it is possible for precipitation events to continue influencing facility operations after the day’s rainfall event has elapsed, any day’s measurements following a ‘wet condition’ (greater than 0.5 inches of rainfall) was excluded from the study. This would aid in ensuring that any measurements influenced by heavy rainfall from the preceding day but experiencing no rainfall for that particular day would not confound the results by being considered a ‘dry condition’.

Normality Tests

The D'Agostino & Pearson and Shapiro-Wilk normality tests were performed using GraphPad Prism version 4 for Windows (Graphpad Software, San Diego California USA, www.graphpad.com) to determine whether the sample populations were normally distributed. The D'Agostino & Pearson normality test quantifies the difference between the distribution of the experimental data set and a Gaussian distribution, which is determined using a P value (GraphPad Prism version 4.00 for Windows, GraphPad Software, San Diego California USA, www.graphpad.com). The P value is calculated by squaring the sums of the differences in skewness and kurtosis between the experimental data set and what would be expected from a Gaussian distribution (GraphPad Prism version 4.00 for Windows, GraphPad Software, San Diego California USA, www.graphpad.com).

The Shapiro-Wilk normality test is a reliable method for determining if a sample is not normally distributed (Conover, 1999). This method tests whether a random sample within the sample set is normally distributed, which is calculated by a W statistic (Conover, 1999).

The results of these test exhibited in Table 17 of the results section found that the majority of the populations were not Gaussian. Although the D'Agostino & Pearson test found that the influent BOD at the St. Petersburg facility was normal, the Shapiro-Wilk test found that it was not and therefore a nonparametric test was used to analyze all sample parameters.

Although nonparametric tests do not have the same degree of power as a parametric test, the sample size was large enough to reconcile this issue. The power of the study was determined once the statistical operations were completed by performing a power analysis for each of the parameters using GraphPad StatMate version 2.00 for Windows (GraphPad Software, San Diego California USA, www.graphpad.com).

Nonparametric Tests

The Mann-Whitney nonparametric test was performed using GraphPad Prism version 4.00 for Windows (GraphPad Software, San Diego California USA, www.graphpad.com) to identify significant difference between the values of each parameter during dry conditions and those values reported for wet conditions. This test was chosen because it was capable of comparing unpaired data from the two groups (wet and dry conditions) of each parameter (i.e. influent BOD, effluent BOD, influent TSS, effluent TSS, etc.).

This test is performed by ranking all parameter values in ascending order regardless of group, attributing the smallest value with the rank of 1 and the largest with the rank of N (GraphPad Prism version 4.00 for Windows, GraphPad Software, San Diego California USA, www.graphpad.com). The sum of each group's rank is calculated and then compared to determine if there is any significant difference, which is represented by the P value (GraphPad Prism version 4.00 for Windows, GraphPad Software, San Diego California USA, www.graphpad.com).

A one-tailed approach was used instead of the commonly used two-tailed test. According to the tutorials and statistics guide provided by the GraphPad Prism software, a one-tailed test should be chosen when testing for directional parameter hypotheses against one another. The groups experiencing wet conditions were expected to have higher average values and be significantly different from the groups experiencing dry conditions. The one-tailed test was more appropriate because it assumed a null hypothesis that the true mean of one sample parameter (wet conditions) would be greater than the true mean of another sample parameter (dry conditions).

Percent Removal

The percent reduction of parameter concentration from influent to effluent was then calculated using Equation 1 to determine the efficiency of the facilities in decreasing the effluent concentrations of each parameter.

$$\text{Percent Removal} = \frac{Influent - Effluent}{Influent} \times 100$$

Equation 1.

Chapter Five

Results

Stormwater Policy Framework

The components identified for comparison between the three stormwater policies relating to the impact of wet weather events on wastewater treatment processes are:

- Treatment requirements (final discharge and bypassed effluent);
- Enforcement procedures for facility noncompliance;
- Specific conditions under which the overflow/bypass is permitted (define whether these conditions are outlined in the policy);
- Monitoring requirements (pre and post permit issuance);
- Characterization and modeling for site-specific determination;
- Operation and Maintenance (O&M) permit provisions;
- Public participation;
- Consideration of sensitive areas;
- Evaluation and use of alternatives;
- Evaluation of costs; and
- Long-term schedule/Long-term plan

The results of the comparison between the three policies based upon these components are available in Tables 13 and 14. Table 13 displays a comparison between the components that serve as a foundation for all three policies. Table 14 identifies the components that are evident in the CSO and Peak Wet Weather policy, but excluded from the Blending Policy. The results exhibited in Table 14 examine how the newly proposed Peak Wet Weather Policy makes up for the flaws in the abandoned Blending Policy.
The CSO policy initially set the framework for the Peak Wet Weather Policy, which redefines each policy element in terms of SSS. The Blending policy managed to embody

a few of the characteristics of the CSO policy, but fell far short in its thoroughness. Although the Blending policy addressed a majority of the aforementioned components, this effort was inadequate and lacked comprehensiveness. The Blending policy also completely neglected to factor into its approach public participation, consideration of sensitive areas, evaluation and use of alternatives, evaluation of costs, long-term schedule, and a long-term plan.

A thorough policy based on this component structure will be more successful than one that does not incorporate these concepts. By comprehensively addressing these components, a policy is better able to manage for peak wet weather events.

Table 12. Comparison of the CSO, Blending, and Peak Wet Weather Policy

Concept	Combined Sewer Overflow Policy (40 CFR 122)	Blending Policy for POTWs (40 CFR 133)	Peak Wet Weather Policy (40 CFR 122 and 123)
Treatment Requirements for Final Discharge	Final discharge must meet the facility's NPDES permit specified effluent limitations	Final discharge must meet secondary treatment requirements[3]	Final discharge must meet the facility's NPDES permit specified effluent limitations
Treatment Requirements for Bypassed Effluent	None; discharge waterbody subject to water quality standards established by the state under NPDES	At least the equivalent of primary treatment[4] will be required for the flow which will be diverted or blended	Requires minimum of primary treatment and any other proven feasible treatment
Enforcement procedure (i.e. if the treatment requirements are not met)	Includes a "reopener" clause for permit modification by NPDES if water quality is not met	N/A	Permit will be revoked by the NPDES authority during the permit renewal process if the facility cannot prove there was no other feasible alternative

[3] Secondary treatment as defined by the EPA (2004a) is the practice of using a combination of chemical and biological processes to remove pollutants in wastewater. Secondary treatment requirements as defined by the US EPA (2004a) are technology-based for POTWs that directly discharge into a waterbody. Standards are expressed as a minimum level of effluent quality in terms of: biochemical oxygen demand (BOD 5), suspended solids (SS), and pH (except as provided for special considerations and treatment equivalent to secondary treatment).

[4] Primary treatment as defined by the EPA (2004a) is the practice of removing some portion of the suspended solids and organic matter in a wastewater through sedimentation.

Table 13. Comparison of the CSO, Blending, and Peak Wet Weather Policy (Continued)

Concept	Combined Sewer Overflow Policy (40 CFR 122)	Blending Policy for POTWs (40 CFR 133)	Peak Wet Weather Policy (40 CFR 122 and 123)
Conditions Under Which Bypassing is Permitted	The plant is only permitted to bypass during wet weather flows when the capacity of the storage or equalization units will be exceeded and the capacity of the facility exceeded[5]; refers specifically to CSS	The plant is only permitted to blend stormwater during wet weather flows when the capacity of the storage or equalization units will be exceeded and the capacity of the facility exceeded	The plant is only permitted to blend stormwater during wet weather flows when the capacity of the storage or equalization units will be exceeded and the capacity of the facility exceeded; refers specifically to SSS
Pre-Permit Monitoring[6]	Yes; completed prior to permit issuance and before the long term control plan is finalized	Yes; completed in an effort to characterize the treatment scenario used for peak flow management	Yes; completed by the facility in an effort to prove that there are no feasible alternatives to overflow

[5] Each permittee will be responsible for an initial characterization study that would define the facility's design parameters and to what degree those parameters can be altered without compromising the structural integrity of the facility.
[6] Monitoring efforts should include, but are not restricted to the mapping of CSO drainage area (actual locations of CSO's and receiving waters); determination of the designated and existing uses of the receiving waterbody, the water quality standards, and whether they are being met during dry and wet weather periods; development of a record for each CSO (occurrence, frequency, duration, and volume); accumulation of all information relating to water quality impacts of CSO's (beach closings, fish kills, etc.) (EPA, 1999).

Table 13. Comparison of the CSO, Blending, and Peak Wet Weather Policy (Continued)

Concept	Combined Sewer Overflow Policy (40 CFR 122)	Blending Policy for POTWs (40 CFR 133)	Peak Wet Weather Policy (40 CFR 122 and 123)
Post-Permit Monitoring	Yes; establishment of a post-construction compliance monitoring program is required	Yes; water quality impacts, pathogen removal efficacy, and ambient levels must be assessed	Yes; inclusion of a permit provision that requires monitoring of the recombined flow at least once daily during bypass events for parameters included in daily effluent limitations
Characterization and modeling for site-specific permit conditions	Yes; NPDES permit details the treatment scenario used for peak flow management through site-specific determinations	Yes; NPDES permit would detail the treatment scenario used for peak flow management	Yes; NPDES permit will detail the treatment scenario used for peak flow management through site-specific determinations
Operation and Maintenance (O&M)	Constant revision by the facility of the operation and maintenance program to optimally remove pollutants throughout and after the rainfall event by using all available units	Expected proper operation and maintenance within bounds of operator's control (accidental bypasses will not be tolerated)	Evaluation of existing program's ability to reduce bypasses and related costs; and, if no program exists, the evaluation of peak flow reduction and related costs through the development of a O&M program

Table 14. Comparison between Concepts Included In Both the CSO and Peak Wet Weather Flow Policies But Excluded from the Blending Policy

Concept	Combined Sewer Overflow Policy (40 CFR 122)	Peak Wet Weather Policy (40 CFR 122 and 123)
Public Participation	Public participation is included in the development of the long-term CSO plan	Requested public comment on the draft policy documents during December 2005 and January 2006; permit provisions for public notification of diversions; permit provisions for public review of POTW operator's diversion practices; public participation encouraged in developing the site specific determination
Consideration of Sensitive Areas	Yes; attention is given to controlling overflows in sensitive areas	Encourages regulating authorities to ensure minimization of any impact to these areas and exercise cautionary limitations in the permits
Evaluation and Use of Alternatives	Yes; alternatives to overflows are explored i.e. storage, and utilization of a POTW as an alternative treatment strategy	Included in the No Feasible Alternatives Analysis
Evaluation of Costs	Yes;Cost/Performance considerations and benefit/cost analyses are evaluated	Included in the No Feasible Alternatives Analysis

Table 14. Comparison between Concepts Included In Both the CSO and Peak Wet Weather Flow Policies But Excluded from the Blending Policy (Continued)

Concept	Combined Sewer Overflow Policy (40 CFR 122)	Peak Wet Weather Policy (40 CFR 122 and 123)
Long-Term schedule	Yes; required establishment of an implementation schedule based on various site-specific determinants	Implementation of feasible technologies and approaches is included in the NPDES permit; permit renewal is contingent upon meeting deadlines of implementation schedule
Long-Term Plan	Yes; incorporates Nine Minimum Controls[7]	Not explicitly required, but proactive efforts toward planning with the community and regulating authority are recommended and implicitly required by the implementation schedule provision of the permit

[7] The Nine Minimum Controls (NMC) are controls that need to be implemented by each permittee under the CSO policy to reduce the occurrence of CSO's. Specifically, these controls are: 1) Proper operation and regular maintenance programs for the sewer system and the CSOs; 2) Maximum use of the collection system for storage; 3) Review and modification of pretreatment requirements to assure CSO impacts are minimized; 4) Maximization of flow to the publicly owned treatment works for treatment; 5) Prohibition of CSOs during dry weather; 6) Control of solid and floatable materials in CSOs; 7) Pollution prevention; 8) Public notification to ensure that the public receives adequate notification of CSO occurrences and CSO impacts; and 9) Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls (40 CFR 122).

Impacts of Stormwater on Wastewater Treatment Systems

The results are organized according to the treatment type. Secondary treatment includes St. Petersburg, while Biological Nutrient Removal includes results from both Los Angeles County and Clearwater.

<u>Comparison of Secondary Treatment and BNR Parameters</u>

Influent Parameters

The influent characteristics at the Clearwater and St. Petersburg facilities were expected to be similar, and it was assumed that the influent concentrations from the two sites be grouped together for analytical purposes. Both areas have similar hydrological conditions and commercial land use patterns with a tourist season that could influence the influent concentrations, including the BOD mass-loading rate.

Other factors affecting influent characteristics are the age and length of the sewer system. During wet weather events, an ideal SSS would result in no significant increases in flow rate at the wastewater treatment facility it is serving. However, aging sewer infrastructures, especially those with longer pipelines, are more likely to be susceptible to I/I due to the cracks and blockages that can occur as pipes age.

It is possible to assess the degree to which I/I is occurring in a SSS by examining the influent flow during dry and wet conditions. A facility exhibiting no significant differences in flow rates between dry and wet conditions would most likely have low I/I occurring within the collection system. However, a collection system with high I/I would show significant increases in the influent flow entering the treatment facility during wet conditions.

Using a one-tailed Mann-Whitney test to compare parameters concentrations at both the St. Petersburg and the Clearwater facilities, it was found that there were significant differences in influent TSS concentration, flow, and BOD mass loading between wet and dry conditions as shown in Table 15.

The influent BOD concentration at both facilities during wet conditions was approximately the same, suggesting that the influent BOD entering these and possibly other facilities is consistent. The average influent BOD concentrations are increasing during wet conditions at the St. Petersburg facility, while decreasing at the Clearwater facilities. This suggests that there is some other factor influencing influent BOD during dry periods.

Effluent Parameters

The concentrations in the effluent parameters were expected to be different between the Clearwater and St. Petersburg facilities mainly due to the difference in the treatment operations. The influent characteristics and flow rates of both sites were anticipated to be similar, but the Clearwater facilities operate a biological nutrient removal system, which is more efficient at treating influent than the activated sludge system at the St. Petersburg facility.

Statistical analyses found both effluent BOD and TSS to be significantly different between the two sites as shown in Table 15. Average effluent BOD concentrations at the St. Petersburg facility are approximately 40-50% lower than the values at the Clearwater facilities. On the other hand, the average effluent TSS concentrations at the St. Petersburg facility are approximately 40% higher than those at the Clearwater facilities.

Table 15. Significant Differences between Parameters at the St. Petersburg and Clearwater Facilities

Parameter		P Value	Significant Difference?	St. Pete Average	Clearwater Average	St. Pete σ	Clearwater σ	St. Pete N	Clearwater N
Influent BOD									
(mg/L)	Dry	P<0.0001	Yes	149.90	169.30	30.64	55.67	352	1756
	Wet	0.4272	No	154.10	154.00	40.19	60.79	28	296
Influent TSS									
(mg/L)	Dry	P<0.0001	Yes	145.20	234.70	31.94	132.60	397	2079
	Wet	P<0.0001	Yes	154.30	242.60	38.41	132.90	29	318
Flow Rate									
(MGD)	Dry	P<0.0001	Yes	22.16	4.87	6.13	1.87	458	2334
	Wet	P<0.0001	Yes	35.64	5.638	13.19	2.41	34	339
BOD Mass Loading									
(lbs/day)	Dry	P<0.0001	Yes	30530	7225	7476	3404	391	1714
	Wet	P<0.0001	Yes	34840	7636	11740	3722	35	237
Effluent BOD									
(mg/L)	Dry	0.0012	Yes	2.64	4.31	0.81	15.45	373	2169
	Wet	0.0001	Yes	2.93	5.54	0.99	21.27	37	351
Effluent TSS									
(mg/L)	Dry	P<0.0001	Yes	1.29	0.89	0.72	2.51	414	3047
	Wet	P<0.0001	Yes	1.12	0.86	0.50	0.63	32	429

Secondary Treatment: St. Petersburg Northwest Water Reclamation Facility

Normality Tests

The D'Agostino & Pearson and Shapiro-Wilk normality tests were used to determine whether the sample population from the St. Petersburg facility exhibited a normal distribution. The influent BOD was found to be normal for both wet and dry conditions using the D'Agostino & Pearson method, however, the Shapiro-Wilk test found the data from dry conditions to not be normal as exhibited by Table 16. Therefore, nonparametric tests were used to statistically evaluate any difference between wet and dry conditions.

Table 16. Normality Tests of St. Petersburg Data Set

	D'Agostino & Pearson		Shapiro-Wilk	
Parameter	**Dry Conditions**	**Wet Conditions**	**Dry Conditions**	**Wet Conditions**
Influent BOD	Yes	Yes	No	Yes
Effluent BOD	No	No	No	No
Influent TSS	No	No	No	No
Effluent TSS	No	Yes	No	Yes

Influent Parameters

The average influent BOD and TSS parameter concentrations increased in during wet conditions, but the differences were not found to be statistically different as shown in Table 13. The standard deviation of the influent BOD increased during wet conditions, whereas the standard deviation of the influent TSS concentrations slightly decreased as exhibited in Table 13. This information indicates that the range of BOD concentrations entering the facility was more variable and possibly more difficult for operations to adjust, while the influent TSS concentrations were less variable and possibly easier for operations control.

Flow rate and BOD mass loading rate both significantly increased during wet conditions as seen in Table 13 and Figures 14 and 15, indicating that heavy rainfall is increasing the amount of influent entering the facility. Due to the increases in flow rate during wet conditions, it can be assumed that I/I is occurring within the infrastructure of the sewer system.

The standard deviations of these values also increased during wet conditions, indicating that the ranges were more variable and exerting a greater pressure on operations control. The flow rate standard deviation during wet conditions was only slightly higher than during dry conditions, suggesting that flow rate is consistently affected by heavy precipitation events.

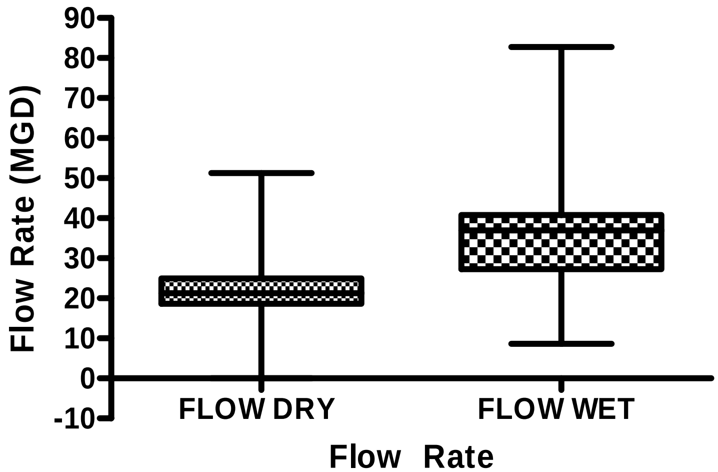

Figure 14. Comparison of Flow Rate during Wet and Dry Conditions

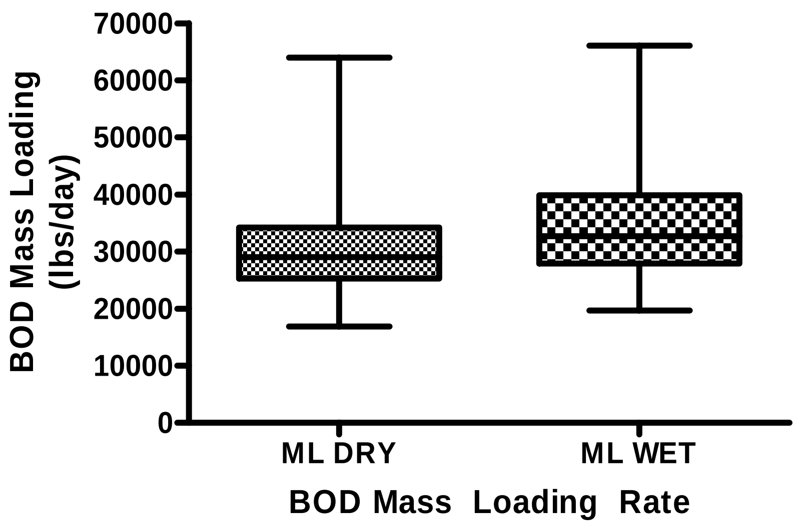

Figure 15. Comparison of BOD Mass Loading Rate during Wet and Dry Conditions

Table 13. Significant Differences between Wet and Dry Conditions for Influent Parameters from the St. Petersburg Northwest Water Reclamation Facility

Parameter	P Value	Significant Difference?	Dry Conditions Average	Wet Conditions Average	Dry Conditions σ	Wet Conditions σ	Dry Conditions N	Wet Conditions N
Flow Rate Total	P<0.0001	Yes	22	36	6.13	13.19	458	34
BOD	0.4566	No	150	154	30.64	40.19	352	28
BOD Mass Loading	0.0124	Yes	30530	34840	7476	11740	391	35
TSS	0.0752	No	145	154	1.10	1.01	406	37

Effluent Parameters

As displayed in Table 14 and Figure 16, the mean effluent BOD was found to be significantly different during wet and dry conditions. The effluent TSS concentrations were neither found to be significantly different nor increase on average. The effluent BOD significantly increased during wet conditions, and exhibited a slight increase in standard deviation during wet conditions. This data suggest that the effluent BOD was affected by an increase in wet weather conditions possibly by reducing the efficiency of operational controls.

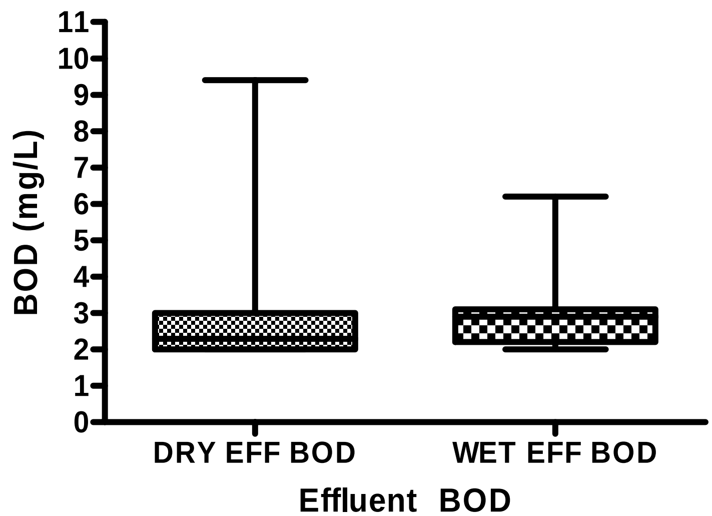

Figure 16. Comparison of Effluent BOD Concentrations during Wet and Dry Conditions

Table 14. Significant Differences between Wet and Dry Conditions for Effluent Parameters from the St. Petersburg Northwest Water Reclamation Facility

Parameter	P Value	Significant Difference?	Dry Conditions Average	Wet Conditions Average	Dry Conditions σ	Wet Conditions σ	Dry Conditions N	Wet Conditions N
TSS	0.1776	No	1.29	1.12	0.72	0.50	414	32
BOD	0.0162	Yes	2.64	2.93	0.81	0.99	373	37

Percent Removal

The data reported by the St. Petersburg facility included less information about influent and effluent concentrations, and percent removal could be calculated only for BOD and TSS. These values appear to be fairly similar during both dry and wet conditions, indicating that both BOD and TSS are removed to the same degree during wet and dry conditions despite the observed significant increase in effluent BOD concentrations during wet periods.

Table 15. Percent Removal of Parameter Concentrtions at the St. Petersburg Northwest Water Reclamation Facility

Parameter	Dry Conditions	Wet Conditions
BOD	98.37	98.17
TSS	99.11	99.28

<u>Biological Nutrient Removal: Clearwater Facilities</u>

The facilities included in this study were located in Clearwater, Florida and all operate biological nutrient removal systems. These facilities are equipped with a system that removes both nitrogen and phosphorous.

Normality Tests

The D'Agostino & Pearson and Shapiro-Wilk normality tests found that no parameter during either dry or wet conditions was normally distributed Therefore, a nonparametric test was used to analyze statistical significance between the influent and effluent parameters.

Influent Parameters

Marshall Street Facility

As displayed in Table 19, all influent parameters were found to be significantly different between wet and dry conditions. It appears that these influent parameters are decreasing in concentration during wet conditions when the averages from Table 19 are compared with the exception of flow, BOD mass loading rate, and TP. Flow rate, BOD mass loading rate, and TP all significantly increased during wet conditions as seen in Table 19 and Figures 20 and 21, indicating that heavy rainfall is increasing the amount of influent entering the Marshall Street Facility. Due to the increases in flow rate during wet conditions, it can be assumed that I/I is occurring within the infrastructure of the sewer system.

The standard deviations of these values also increased during wet conditions, indicating that the ranges were more variable and exerting a greater pressure on operations control at the Marshall Street Facility.

East Facility

All influent parameters from the East facility were found to be significantly different during dry and wet conditions with the exception of TSS and BOD mass loading rate as shown in Table 16 and Figure 20. Of those, only the flow rate significantly increases, while the other influent parameters appear to be subject to dilution during wet conditions.

Northeast Facility

All influent parameters from the Northeast Facility were found to be significantly different during dry and wet conditions with the exception of TSS and TP as shown in Table 16. Of those, only BOD and NH3 appear to be subject to dilution during wet conditions, while the flow rate and BOD mass-loading rate significantly increase during wet conditions.

Comparison

The individual BOD mass loading and flow rates were compared between facilities at the Clearwater location. The results of these comparisons are shown in Table 19 and in Figures 20 and 21. The BOD mass loading and flow rates all significantly increase during wet conditions with the exception of the East facility. The BOD mass loading rate is not significantly affected by increases in precipitation and flow rate at the East treatment facility. However, this could be influenced by its overall low BOD mass-loading rate, suggesting that the Northeast and Marshall Street facilities treat a lower quality influent wastewater than the East facility.

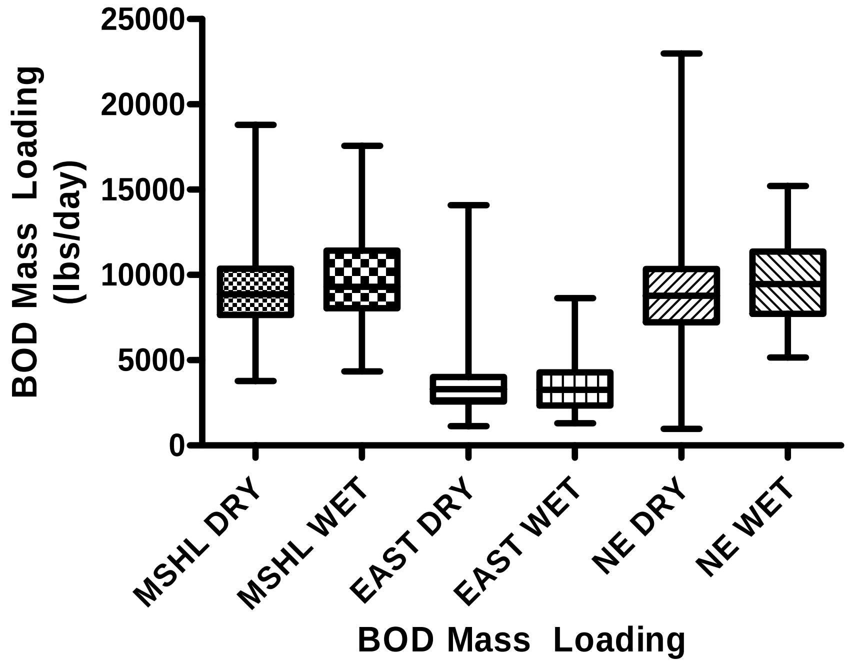

Figure 17. Comparison of BOD Mass Loading Rates during Wet and Dry Conditions between the Marshall Stree, East, and Northeast Facilities

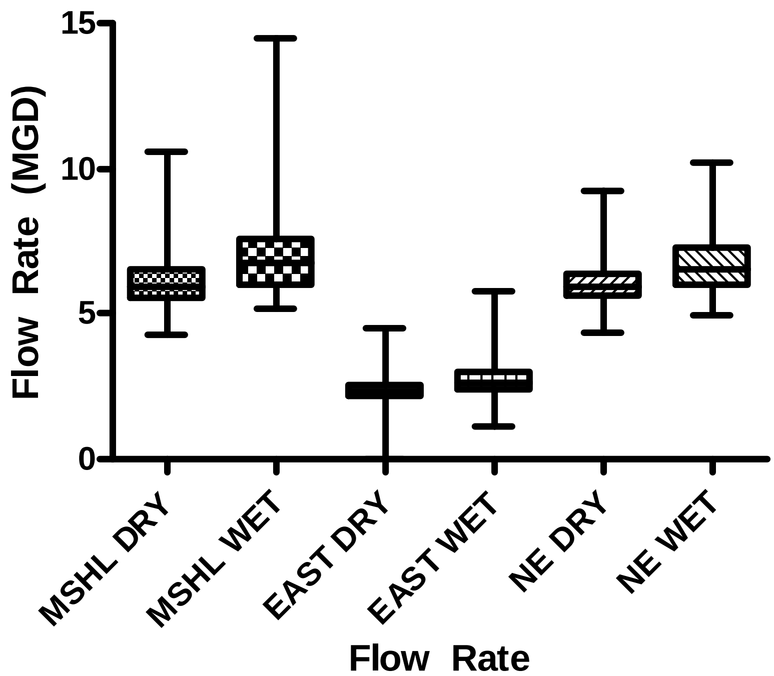

Figure 18. Comparison between Flow Rate (MGD) during Wet and Dry Conditions at the Marshall Street, East, and Northeast Facilities

Table 16. Significant Differences between Wet and Dry Conditions for Influent Parameters from the Marshall Street, East, and Northeast Facilities

Parameter	P Value	Significant Difference?	Dry Conditions Average	Wet Conditions Average	Dry Conditions σ	Wet Conditions σ	Dry Conditions N	Wet Conditions N
Marshall Street								
Flow Rate	P<0.0001	Yes	6	7	0.85	1.88	804	116
TSS	0.0146	Yes	179	166	88.63	94.82	622	320
BOD	0.0009	Yes	159	150	47.77	49.82	854	440
BOD Mass Loading	0.0102	Yes	9148	9873	2251	2612	572	79
NH3	P<0.0001	Yes	27	24	4.22	5.43	509	270
TP	P<0.0001	Yes	9	12	34.13	40.59	509	270
East								
Flow Rate	P<0.0001	Yes	2	3	2.31	0.88	805	116
TSS	0.4207	No	221	225	141.90	145.10	507	270
BOD	P<0.0001	Yes	172	158	58.45	61.37	508	271
BOD Mass Loading	0.3277	No	3551	3462	1602	1498	572	79
NH3	P<0.0001	Yes	30	27	6.25	7.61	508	270
TP	P<0.0001	Yes	5	4	1.15	1.34	507	270
Northeast								
Flow Rate	P<0.0001	Yes	6	7	0.63	1.11	805	116
TSS	0.4223	No	204	210	143.70	153.60	1282	679
BOD	0.0004	Yes	160	152	50.15	48.56	1014	540
BOD Mass Loading	0.0182	Yes	9014	9572	2652	2519	570	79
NH3	P<0.0001	Yes	25	24	3.88	4.42	508	270
TP	0.074	No	5	5	2.28	2.30	508	270

Effluent Parameters

Marshall Street Facility

The concentration of effluent TP was discovered to significantly increase from dry to wet conditions as exhibited in Table 20. Although there was no significant difference between the wet and dry periods, effluent TSS was found to increase in average concentration during wet conditions.

The significant increase in effluent TP is corroborated with its lowered percent removal as shown in Table 22. This data suggest that the treatment process at the Marshall Street Facility is compromised during heavy rainfall periods and its ability to effectively remove phosphorous is reduced.

Due to the discovered increases in effluent TP, the overflow rate from the secondary clarifier was calculated to assess whether the settleability of the wastewater was inhibited during wet conditions.

Increases in flow rates are attributed with increases in the overflow rate over the secondary clarifiers, which could inhibit the settleability of the influent during the nutrient removal process. Settleability is related to the particle size and settling velocity of the influent. As the flow over the secondary clarifier is increased, there is less of an opportunity for the finer suspended particulate matter to settle out. Instead these particles, which include insoluble phosphorous, are present in the flow out of the secondary clarifiers, and can be found in the final discharge.

The schematics for the Marshall Street facility secondary clarifiers were readily available for calculating the overflow rate of the secondary clarifiers using Equation 2. The same statistical operations and rationale as for the facility parameters were used to analyze the overflow rate for the Marshall Street facility secondary clarifiers and the filters. Both overflow rates were found to significantly increase from dry to wet conditions as exhibited in Table 17.

Table 17. Comparison of Overflow Rates from the Secondary Clarifiers and Filters between Dry and Wet Conditions at the Marshall Street Facility

Parameter	P Value	Dry Conditions Average	Wet Conditions Average	Dry Conditions σ	Wet Conditions σ	Dry Conditions N	Wet Conditions N
Secondary Clarifier (GPD/ft2)	P<0.0001	195.20	230.90	27.11	59.92	804	116
Filters (GPM/ft2)	P<0.0001	0.01	0.01	0.02	0.00	804	116

East Facility

No effluent parameters at the East facility were found to be significantly different between dry and wet conditions.

Northeast Facility

The concentration of effluent BOD was found to significantly decrease during wet conditions at the Northeast Facility. This treatment facility is designed to operate at 13.5 MGD but only operated at 5-6 MGD for the study period. The Northeast Facility was more capable of handling peak flows because its average annual flow was much less than its treatment capacity.

Table 20. Significant Differences between Wet and Dry Conditions for Parameters from the Clearwater Wastewater Treatment Facility

Parameter	P Value	Significant Difference?	Dry Conditions Average	Wet Conditions Average	Dry Conditions σ	Wet Conditions σ	Dry Conditions N	Wet Conditions N
Marshall Street								
TSS	0.269	No	2.73	4.28	15.13	22.36	761	371
BOD	0.441	No	2.11	2.12	1.36	1.27	1017	542
NH3	0.4355	No	0.04	0.04	0.04	0.02	512	270
TP	0.0003	Yes	0.14	0.18	0.13	0.17	534	274
East								
TSS	0.4008	No	0.88	0.94	0.89	2.39	877	462
BOD	0.3116	No	2.60	2.54	1.32	1.29	508	270
NH3	0.4884	No	0.05	0.04	0.12	0.09	526	273
Northeast								
TSS	0.4227	No	0.92	0.75	4.55	0.49	881	463
BOD	0.0245	Yes	4.46	3.17	8.37	2.51	508	271
NH3	0.2571	No	0.04	0.04	0.04	0.02	545	271

Percent Removal

Comparison

The percent removal of each parameter seems to be fairly similar during both dry and wet conditions as shown in Table 22. Effluent TP measurements were not taken at the East and Northeast facilities, so percent removal of this parameter could not be calculated. The Marshall Street Facility exhibited a reduced percent removal of TP during wet conditions, which supports the significant increase in effluent TP concentration from this facility between dry and wet conditions.

Table 22. Percent Removal of Parameter Concentrations at the Marshall Street, East, and Northeast Facilities

Parameter	Dry Conditions	Wet Conditions
Marshall Street		
BOD	98.67	98.59
TSS	98.47	97.41
NH3	99.85	99.84
TP	96.70	94.88
East		
BOD	98.47	98.33
TSS	99.60	99.62
NH3	99.85	99.84
Northeast		
BOD	97.20	97.89
TSS	99.63	99.64
NH3	99.85	99.84

Chapter Six
Discussion

Stormwater Policy Framework

The CSO, Blending, and Peak Wet Weather policy are all inherently related because they each attempt to address the issues extreme weather events present to POTWs. The CSO and Peak Wet Weather policy are both structured with similar components. However, the Blending policy was not as comprehensive as the two other policies, and did not operate with all of the same component structures.

The Blending policy was defeated possibly due to its lack of a defined regulatory structure. Although an attempt to alleviate the issues concerning extreme weather events, the Blending policy did not define “peak wet weather event” and was not organized according to the structure set forth by the already passed CSO policy. The Peak Wet Weather policy resurrected the ideas of the Blending policy and redefined them in a more thorough framework first set forth by the CSO policy.

The proposed Peak Wet Weather policy is significantly more comprehensive than its predecessor, the Blending policy. Although inherently flawed and incomplete, the defeated Blending policy served purposefully as a stepping stone to a more inclusive and useful policy option for managing SSSs and the stormwater they convey during peak wet weather events. The Blending policy appeared more of an effort to find a way to regulate the frequently occurring and unpermitted SSOs. By imposing a regulatory framework onto these practices, the policy would seemingly be taking control of the situation. However, the regulations were ambiguous, incomplete, and would have clearly been ineffective if instituted.

Comprehensive National and Localized Policy Approach

The Peak Wet Weather policy is a refinement of the initial attempt of the Blending policy to begin regulating SSOs. The two most important concepts delineated in the Peak Wet Weather policy the feasibility analysis and the requirement that site-specific determinations be conducted to define "peak wet weather event". These two aspects of the policy illustrate how it will function on both a national and local level, which is the most effective approach for managing stormwater entering wastewater treatment facilities during peak flows.

For a facility to be permitted, it needs to prove that there are no feasible alternatives to diverting the stormwater stream around treatment units. The entire analysis and responsibilities of each the facility, NPDES permitting authority, and EPA is outlined in the Federal Register notice so as to ensure clarity. The analysis represents how this policy will function on a national level. All facilities and NPDES permitting authorities will be required to prove diversion is the only feasible alternative using a standard, comprehensive analytical rubric.

The policy requires that the term "peak wet weather event" be defined for each facility through a cooperative effort by the NPDES authority, the facility in question, and the community. This site-specific determination process will occur at the local level and will constitute the conditions under which a permitted POTW operator may divert flows. Poor collection system maintenance or lack of investment in treatment upgrades will not be a factor that influences the site-specific determination.

Economic Efficiency

The Peak Wet Weather policy promotes economic efficiency through encouragement of research and development. This is a useful tactic employed by national policy strategies, such as the NPDES, which sets uniform national effluent limits but not the specific technology necessary for compliance. The Peak Wet Weather policy provides for economic efficiency in two ways related to its dualistic national and localized approach. It does so from the national standpoint by setting uniform effluent limitations through NPDES that the policy stipulates the diverted flow must meet. From a local perspective, the Peak Wet Weather policy promotes economic efficiency through research and development by devising the site-specific implementation schedule

The feasibility analysis outlined in the Peak Wet Weather policy requires the regulating authority to include a permit provision for the POTW to develop a schedule for implementing treatment upgrades. The policy also states that the regulating authority consider the POTWs adherence to its devised schedule during the permit renewal process. A POTW not meeting scheduled deadlines for treatment improvements could be reprimanded for such shortcomings by being denied a diversion permit. Therefore, it is in the best economical interest of the POTW to phase in treatment upgrades and improving the collection system to prevent against inflow and infiltration.

This policy component of encouraging economic efficiency is a vast improvement in the evolution from the Blending to Peak Wet Weather policy. The Blending policy offers absolutely no incentive to POTWs for upgrading treatment technologies and improving the collection system infrastructure. This, coupled with the ambiguous terminology present in the policy would eventually allow bypasses to become routine and not just restricted to wet weather events. Inevitably, the costs of treating wet weather flows would be deferred to drinking water treatment facilities, and these costs would be shifted onto the consumer.

Impacts of Stormwater on Wastewater Treatment

Although the two sites are subject to similar land use patterns, the treatment systems are very different. These differences in the treatment processes at the Clearwater and St. Petersburg facilities influence the degree to which the influent and effluent parameter concentrations are altered by increasing precipitation. The more efficient and resistant the treatment process, the less peak wet weather events can affect the concentrations of the parameters entering and leaving the facility.

The site-specificity of the Peak Wet Weather policy combined with the feasibility analysis required by the policy take these factors into account when determining what constitutes a “peak wet weather event” for each facility. This is a critical element of the currently proposed policy that was neglected by the Blending policy. By factoring in the differences at each facility, the site-specific determination and feasibility analysis are geared toward minimizing the necessity of SSOs, optimizing alternative strategies, and implementing a schedule for treatment upgrades to further reduce the frequency of future SSOs.

St. Petersburg Facility

Influent Parameters

The flow and BOD mass loading rate both significantly increased during wet conditions at the St. Petersburg facility, whereas the influent BOD and TSS were not found to be significantly different between dry and wet conditions.

Effluent Parameters

The effluent BOD concentrations from the St. Petersburg facility were found to significantly increase during periods of elevated precipitation, indicating treatment impairment during such wet conditions. The St. Petersburg facility does not operate a nutrient removal process, which could account for these increases. The ability of the facility to remove BOD could have been complicated by the amount of wastewater the St. Petersburg plant was treating per day. This facility is permitted to treat 20MGD, but for the study period, the facility treated between 20 and 40MGD with the largest amounts of influent occurring during wet conditions. It is possible that the St. Petersburg facility was at its design capacity during wet conditions, and its ability to remove BOD using an activated sludge system during wet conditions was even further reduced.

The site-specific determination under the Peak Wet Weather policy would define the conditions under which diversions are necessary for the St. Petersburg facility to efficiently remove BOD from its treated influent stream. The feasibility analysis would then investigate whether any supplemental treatment process to the required primary treatment would be feasible for the adequate removal of BOD from the diverted flow. Since it is clear that the facility experiences significant I/I, the site-specific nature of the Peak Wet Weather policy makes it possible for permit provisions to be made requiring an explicit schedule for infrastructure improvements. The renewal of a permit to divert during peak wet weather flows would then be based on the implementation of this schedule to ensure that improvements are made.

<u>Clearwater Facilities</u>

Influent Parameters

The influent BOD measurements taken at the Clearwater facilities indicate that the increases in rainfall dilute the influent wastewater with the exception of the influent TSS. The increase in average TSS concentration at the Clearwater facilities is expected as increases in stormwater entering a treatment facility commonly accommodate larger amounts of environmental debris associated with storm events.

The Peak Wet Weather policy requires that the diverted flows be subject to at least primary treatment and any other treatment determined feasible by the feasibility analysis. For these facilities, the feasibility analysis would investigate whether applying alternative treatment measures would ensure that TSS is adequately treated in the diverted flow during peak wet weather events.

Effluent Parameters

The effluent concentrations of the parameters measured at the Clearwater facilities do not appear to be significantly influenced by increased precipitation with the exception of effluent TP from the Marshall Street Facility, which is significantly higher during wet conditions. The lack of precipitation influence on the treatment performance of the Northeast and East facilities when compared to the St. Petersburg Facility could possibly be due to the differences in treatment capacity and average annual flow or to the difference in treatment system.

Both the Northeast and East facilities operate at a much lower average annual flow than their designed treatment capacity, whereas the St. Petersburg Facility is operating at and above its treatment capacity especially during wet conditions. Combined with the more advanced treatment system used at the Clearwater sites, the Northeast and East facilities are more capable of handling and adequately treating wastewater during peak wet weather events than the St. Petersburg Facility.

The Clearwater facilities are much newer and more technologically advanced when compared to the Pinellas County Reclamation Facility. The three facilities from Clearwater are each equipped with a five-stage Bardenpho nitrogen and phosphorous removal process that follows its activated sludge stage. This process includes both primary and secondary anoxic and aeration reactors with clarification (Clearwater Summary Report 2006).

It is clear that the average effluent phosphorous concentrations from the Marshall Street facility are increasing during wet conditions and are not being efficiently removed as shown by the reduced percent removal of phosphorous during wet conditions. This indicates that the removal process might be compromised during peak wet weather events. The Bardenpho process is noted for its efficiency in removal nitrogen, but has sometimes been criticized for its lower removal of phosphorous (Grady et al., 1999; Randall et al., 1992; Tchobanoglous et al., 2003). This could be partially due to the process' use of a longer SRT, which has been found to produce less PAOs (phosphate accumulating organisms) and subsequently result in decreased phosphorous removal (Randall et al., 1992; Tchobanoglous et al., 2003).

The increase in overflow rate from the secondary clarifiers at the Marshall Street Facility from 195 GPD/ft2 to 230 GPD/ft2 indicate that the settleability of the wastewater was inhibited during wet conditions. Therefore, less phosphorous particles were able to settle out of the treated wastewater and were present in the effluent.

Both the Peak Wet Weather and Blending policy require that the diverted flow meet the NPDES specified effluent limitations, including an 85% removal requirement unless it is demonstrated that there is significant I/I in the system. All parameters were removed by more than 85% efficiency, and the effluent concentrations at the Clearwater facilities met the NPDES effluent limitations. However, the NPDES permit specifications were met using a biological nutrient removal system, which would most likely not be required by the Peak Wet Weather policy unless it was demonstrated that the effluent limitations for phosphorous and/or other parameters would not be met by the minimum policy requirement of primary treatment. In this event, the Peak Wet Weather policy through the feasibility analysis would investigate any other feasible alternative treatment methods, which would result in the diverted flow meeting the NPDES effluent limitations set for the Clearwater facilities.

Chapter Seven

Conclusions

Objective 1

Define criteria that can be used for evaluating the ability of stormwater policies to mitigate the impacts of peak wet weather flows on the effectiveness of wastewater treatment facilities.

- A consistent approach composed of a standardized framework of specific criteria for policies related to wastewater and stormwater should be developed to ensure that all policies be uniformly thorough in their approach to controlling discharges into receiving waters.
- The criteria should include, as a minimum:
    - Treatment requirements (final discharge and bypassed effluent);
    - Enforcement procedures for facility noncompliance;
    - Specific conditions under which the overflow/bypass is permitted (define whether these conditions are outlined in the policy);
    - Monitoring requirements (pre and post permit issuance);
    - Characterization and modeling for site-specific determination;
    - Operation and Maintenance (O&M) permit provisions;
    - Public participation;
    - Consideration of sensitive areas;
    - Evaluation and use of alternatives;
    - Evaluation of costs; and
    - Long-term schedule/Long-term plan

- It is possible for environmental policies regulating related areas be devised according to a particular set of necessary components as those used for analysis in this paper. Utilizing a pre-created list of components would ensure that all policies be equally comprehensive, and could enable regulatory authorities to effectively implement and enforce the policy.

Objective 2

Identify and evaluate differences between national and local policy approaches that address the impact of wet weather flows on wastewater treatment facilities.

- The focus of the CSO and Peak Wet Weather policy is to establish a framework upon which supplemental local efforts can define the strategies for mitigating the impacts of stormwater on wastewater treatment facilities.
- Supplemental localized policies are crucial to the success of nationally-based policies, such as the CSO and Peak Wet Weather policies. However, localized efforts are often subject to resource limitations that inhibit their effectiveness.
- For policies subject to hydrological boundaries it is important that they be established on the national level (through NPDES) and require permit provisions to include localized efforts for determination of the specified regulatory limit using information from site-specific analyses.

Objective 3

Assess the susceptibility of wastewater treatment performance to wet weather events using a case study approach to analyze historical precipitation and wastewater treatment data.

- Secondary treatment systems are more susceptible to influence from peak wet weather events than biological nutrient removal systems.
- Aging sewer infrastructure, land use patterns, and design capacity are all factors that influence the susceptibility of a wastewater treatment facility to peak wet weather events.

- Increases in flow rate to the wastewater treatment facility can be used to determine the occurrence of I/I in a SSS.
- Alternative measures, such as increasing storage unit capacity should be taken to minimize the necessity of diversion.

Chapter Eight
Suggestions for Future Research

This study examined how the concentrations of various parameters were influenced by increased precipitation entering a SSS. The parameter investigated in this study are all those for which measurements are required by the facilities' NPDES permits. However, the concentration of pathogens, such as *Giardia* and *Cryptosporidium* are not typically measured at POTWs.

Future studies would link parameter concentrations to daily measurements of pathogen levels. This would expand the scope of the data set, and provide a more detailed assessment of how treatment processes are influenced by increased rainfall. The treatment processes evaluated should include a range of different systems so that a thorough comparison of the susceptibility of each system is evaluated and compared. This might eventually lead to a process design that combines all of the optimum components.

Such a study should focus on facilities served by CSS to determine the impacts of stormwater on combined systems. This could then be compared to studies investigating peak wet weather flows entering treatment facilities from SSS to assess the differences between how influent from the two types of collection systems can influence treatment processes.

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