Reviews

Regulatory and Resource Management Practices for Urban Watersheds: The Florida Experience

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SUMMARY. Urban water quality management is becoming an increasingly complex and widespread problem. The long-term viability of aquatic ecosystems draining urban watersheds can be addressed through both regulatory and nutrient and water management initiatives. This review focuses on U.S. regulatory (federal, state, and local) and management (runoff, atmospheric deposition, and wastewater) impacts on urban water quality, specifically emphasizing programs in Florida. Because of rapid population growth in recent decades, and projected increases in the future, appropriate resource management in Florida is essential. Florida enacted stormwater regulations in 1979, before the U.S. Environmental Protection Agency (USEPA) amended the Clean Water Act (CWA) to regulate stormwater discharges. However, in the United States, more research has been conducted on larger structural best management practices (BMPs) (e.g., wet ponds, detention basins, etc.) compared with smaller onsite alternatives (e.g., green roofs, permeable pavements, etc.). For atmospheric deposition, research is needed to investigate processes contributing to enhanced deposition rates. Wastewater (from septic systems, treatment plants, and landfills) management is especially important in urban watersheds. Failing septic systems, elevated nutrient concentrations in discharged effluent, and landfill leachate can all potentially degrade water quality. Proposed numeric nutrient criteria from the USEPA and innovative technologies such as bioreactor landfills are emergent regulatory and management strategies for improved urban water quality.

The majority of people in the world now live in urban areas. Projections indicate that urban residents will account for 60% of the world's population in 2030 and 70% in 2050 (United Nations, 2008). To confront the challenges of an increasingly urbanized world, federal agencies in the United States work in conjunction with states to develop

and implement programs addressing water quality. Local jurisdictions additionally apply different strategies to comply with federal and state water quality regulations (Bamezai et al., 2001; Hartman et al., 2008). Attempts to minimize nitrogen (N) and phosphorus (P) transport from urban areas to streams, rivers, and estuaries depend on the efficacy of

federal, state, and local regulations. The relative impacts of BMPs, the most practical and effective nutrient-control strategies, are also important to protect water quality. Nutrient sources in urban watersheds include stormwater runoff, atmospheric deposition, effluent from wastewater treatment systems, and leachate from solid waste facilities. The regulatory and management framework associated with each of these nutrient sources determines the overall impact of urban areas on adjacent water resources.

Strategies to identify and reduce urban environmental impacts are especially important in areas experiencing rapid population growth. In Florida, the statewide population has increased from 1.9 million in 1940 to 17.4 million in 2005 and is projected to exceed 24 million by 2025 [Marella, 2004; Purdum, 2002; South Florida Water Management District (SFWMD), 2008]. Most new Florida residents live in urban areas (SFWMD, 2008) and the state's population density in 2010, 350.6 people per mile², was among the highest in the United States. (U.S. Census Bureau, 2011). Florida's current population already places great demands on the state's natural resources and with the continued influx of new residents, resource management increasingly becomes more essential (Marella, 2004).

Overall growth rates, along with greater population density in urban areas, create unique conditions whereby laws, regulations, and efficient resource management systems are required to meet human demands for water while protecting environmental functions. This review focuses on the development of U.S. federal, state, and local regulations that guide resource management practices in urban watersheds. Regulatory and management impacts on urban water quality are explored throughout the review, primarily emphasizing historical and ongoing programs in Florida. We also identify opportunities for future research where current information is limited.

Runoff and leaching

The primary regulatory mechanism for stormwater management in the United States is the federal CWA, created through the 1972

amendments to the Federal Water Pollution Control Act (1948). Initial programs under the CWA [such as the National Pollutant Discharge Elimination System (NPDES)] targeted point source discharges from wastewater facilities, but stormwater runoff soon emerged as a pervasive threat to water quality. The USEPA developed the NPDES Stormwater Program after further amending the CWA in 1987. Phase I (1990) required NPDES permits for stormwater discharges from industrial operations, large construction sites (2 ha or greater), and municipal separate storm sewer systems (MS4s) serving at least 100,000 people. Phase II (1999) required NPDES permits for smaller MS4s and construction sites. Stormwater systems now dominate the NPDES program, accounting for 80% (greater than 500,000) of all permits [National Research Council (NRC), 2008]. All dischargers are required to have either individual permits with specific requirements (e.g., Phase I MS4s) or general permits that are applicable to a particular category (e.g., construction sites, Phase II MS4s, etc.). To prevent stormwater pollutants from degrading water resources, industrial facilities and construction sites with NPDES permits are required to develop stormwater pollution prevention plans, while MS4s have to implement stormwater management plans.

Several states (e.g., Florida, Washington, and Maryland) enacted programs to reduce the impacts of stormwater runoff before USEPA

federal mandates. Stormwater treatment is required in Florida because of the rapid growth of urban areas, annual average rainfall (137 cm per year), and the 4672 mile² of water covering ≈9% of the state. In addition, Florida's generally low topographic relief, sandy soils, high water tables, and porous karst terrain facilitate extensive ground and surface water interactions [Florida Department of Environmental Protection (FDEP), 2010d]. These factors can combine to potentially deliver significant nutrient loads to lakes, streams, rivers, and estuaries.

Florida adopted its first stormwater rule in 1979, which required stormwater treatment for all new development and redevelopment projects by 1982 (Livingston, 1995). Significant revisions to the Florida stormwater rule in 1989 and 1990 included greater emphasis on watershed-based stormwater management and improved partnerships among statewide authorities, regional water management districts [WMDs (there are five in Florida)], and local governments. The Stormwater Management Program in Florida now enables the FDEP, as the lead statewide agency, to delegate administration of the program to the WMDs. Local governments, therefore, develop stormwater design criteria that comply with overall objectives outlined by respective WMDs. Statewide stormwater criteria in Florida include BMPs to treat the first flush (pollutant loading during initial stormwater runoff) and to achieve pollutant removal of at least 80% of annual average loads. For stormwater discharges to Outstanding Florida Waters (specially protected water bodies in the state, for example, the Suwannee River), both

the design and performance criteria for BMPs increase to a 95% reduction in pollutant load.

Some states and counties have chosen the local ordinance approach to reduce the nutrient content of urban stormwater runoff. Minnesota was the first state (2002) to enact regulations on P in urban fertilizers. The Minnesota Phosphorus Lawn Fertilizer Law prohibited the application of fertilizers containing P because of the prevalence of soils high in P content [Bray P1 test > 25 mg·kg⁻¹ (Rosen and Horgan, 2005)]. The law did not apply under certain conditions, such as the establishment of new lawns or if soil tests revealed insufficient P levels. However, in a report to the Minnesota Legislature, the Minnesota Department of Agriculture did not document direct water quality changes during the first years of the law (Minnesota Department of Agriculture, 2007).

Ann Arbor, MI, enacted a fertilizer ordinance controlling P fertilization of turfgrass on all nonagricultural land, including residential, recreational, educational, commercial, and government grounds (Ann Arbor, 2011). Under this ordinance, P fertilizers cannot be applied before 1 Apr. or after 15 Nov., coinciding with the part of the year when the turf is not growing. Water quality sampling stations were established in the Huron River watershed in southeastern Michigan (Lehman et al., 2009) in conjunction with the Ann Arbor ordinance. Stations were located in the city and a geographic area not under the ordinance. Phosphorus concentrations in river water were lower in 2008 compared with the period before the ordinance and lower for the Ann Arbor sampling sites compared

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.0283	ft ³	m ³	35.3147
0.0283	million ft ³	Mm ³	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
48.8243	lb/1000 ft ²	kg·ha ⁻¹	0.0205
1.1209	lb/acre	kg·ha ⁻¹	0.8922
2.5900	mile ²	km ²	0.3861
1	ppb	nL·L ⁻¹	1
1	ppm	mg·kg ⁻¹	1
1	ppm	mg·L ⁻¹	1
0.9072	ton(s)	Mg	1.1023

with upstream sites. The study showed a positive relationship between P concentration reduction in the water with the implementation of mandated fertilizer management practices. The authors acknowledged that P reduction in the river was likely due to both the ordinance and to the accompanying fertilizer management education program.

The Ann Arbor ordinance and the Minnesota law are similar in their suggested practices to the Florida Green Industries BMPs (FDEP, 2008a) and the Florida-Friendly Landscaping approaches (FDEP, 2009). These best-management approaches control fertilizer applications through research-based turfgrass fertilization management decisions. In 2007, the Florida Department of Agriculture and Consumer Services (FDACS) created the Urban Turf Fertilizer Rule (FDACS, 2007) to help protect the state's water quality by restricting N and P fertilizer applications to urban turf and lawns. The rule requires that fertilizer packages less than 50 lb sold for urban use are labeled with only the applied rates of N and P needed to sustain healthy turfgrass. In addition, the rule limits the amount of N and P that can be applied in a single application [0.7 to 1 lb/1000 ft² N, 0.25 lb/1000 ft² phosphate (P₂O₅)] and the total amount per year (0.50 lb/1000 ft² P₂O₅). Acceptable annual application rates for N vary depending on turfgrass species and designated Florida regions (FDACS, 2007; Trenholm, 2009).

Although Florida uses statewide fertilizer guidelines to reduce pollution associated with urban areas, many counties and municipalities in Florida have opted for more stringent regulations. These local municipalities have chosen the ordinance as a means to

control fertilizer use (FDACS, 2007; Hartman et al., 2008). Severe Florida red tide blooms in 2005 and 2006 precipitated local governmental action in Florida (Hartman et al., 2008). Ordinances in several counties and municipalities in Florida include a fertilizer ban during the summer active growing season from 1 June to 30 Sept. Although the summer months are the active growing period for warm-season turfgrass (when nutrient requirements are the highest), summer is also the time of year when heavy rainfall is most frequent. The justification for the summer ban is the proposed increase in runoff potential during this part of the year. The ban was part of a recommendation by a workgroup for a model ordinance from the Tampa Bay Estuary Program (TBEP, 2008a, 2008b).

Planning and regulatory initiatives are examples of nonstructural BMPs that do not rely on facilities specifically constructed to control pollutant loading from stormwater runoff. Additional examples of nonstructural BMPs include public education and outreach programs, riparian buffers, and street sweeping. Nonstructural BMPs are frequently implemented in municipalities, but studies evaluating their effectiveness for nutrient control are limited (NRC, 2000; Pennington et al., 2003; Taylor and Fletcher, 2007). Taylor and Fletcher (2007) surveyed stormwater managers in the United States, Australia, and New Zealand. The authors reported an increasing trend in the use of nonstructural stormwater BMPs despite the lack of extensive information on performance and cost analysis of these measures. Several studies have evaluated the impact of street sweeping (Selbig and Bannerman, 2007; Tobin and Brinkmann, 2002). In Tampa, FL, Tobin and Brinkmann

(2002) reported that rotary brush sweepers were more effective than vacuum sweepers in removing nutrients associated with coarse sediments (medium to fine sands) from streets. Vacuum sweepers were more effective on fine sediments, suggesting street sweeper requirements for areas with predominantly coarse sediments (e.g., Florida) contrast with areas characterized by fine sediments (Tobin and Brinkmann, 2002). However, three types of street sweepers in Madison, WI, had little differential impact on stormwater quality, possibly because of the extreme variability in pollutant loads (Selbig and Bannerman, 2007).

Additional stormwater treatment options, categorized as structural BMPs, include retention, detention, and infiltration systems. Structural BMPs are common in urban areas, but nutrient removal efficiencies vary (Table 1) because of incoming pollutant concentrations, site characteristics, and hydraulic conditions (NRC, 2000). More research has been conducted on larger structural BMPs (e.g., wet ponds, detention basins, etc.) compared with smaller onsite alternatives (e.g., green roofs, permeable pavements, etc.) (NRC, 2008; Sample et al., 2003; Weiss et al., 2007) (Table 2). For example, installing green roofs in the United States can add more than \$40/ft² to roof costs, and the benefits of these structures are not widely accepted (Berghage et al., 2009).

Treatment systems that reduce some types of pollutants [e.g., metals and total suspended solids (TSS)] may be ineffective for dissolved nutrients. Teague and Rushton (2005) investigated stormwater treatment (wet detention with a filtration system) in Tampa Bay, FL, and reported a significant reduction in metals and

Table 1. Median nutrient removal efficiencies for different types of structural best management practices used for stormwater treatment.

Treatment type	Total nitrogen		Nitrate/Nitrite-nitrogen		Total phosphorus		Soluble phosphorus	
	(% Removal)	<i>n</i> ^a	(% Removal)	<i>n</i>	(% Removal)	<i>n</i>	(% Removal)	<i>n</i>
Dry pond	24	7	9	7	20	10	-3	6
Wet pond	31	22	45	29	52	45	64	28
Constructed wetland	24	24	67	33	48	37	25	26
Filters	32	9	-14	14	59	17	3	7
Bioretention	46	8	43	9	5	10	-9	5
Infiltration	42	7	0	5	65	8	85	4
Open channel	56	9	39	16	24	16	-38	14

^aNumber of studies used to calculate removal efficiencies (Center for Watershed Protection, 2007).

Table 2. Typical construction and maintenance costs for different types of structural best management practices used for stormwater treatment.

Treatment type ^a	Construction costs (\$/ft ³ of storage) ^b	Annual maintenance costs (\$/ft ³ of storage)
Dry retention basin	0.50–1.00	0.02–0.06
Dry detention ponds	0.50–1.00	0.01–0.05
Wet detention pond	0.50–1.00	0.02–0.05
Constructed wetland	0.05–1.00	0.001–0.05
Open channel (swales)	0.60–1.60 (per sq. ft.)	0.03–0.11 (per sq. ft.)

^aPeluso and Marshall (2002).

^b\$1.00/ft³ = \$35.3147/m³.

TSS (79% to 89%) in the system outflow. In contrast, both ammonia (NH₃–N (84%) and orthophosphate (64%) loads increased in the discharged water. In another study comparing typical stormwater systems in Florida, Harper (1999) concluded that filters may degrade the performance of detention systems. Improper maintenance of these systems is a primary factor contributing to reduced hydraulic performance and pollutant removal effectiveness (Harper, 1999; NRC, 1993). Microbial activity within wet detention filtration systems may also lead to the conversion of particulate organic nutrients into soluble inorganic species, thus increasing nutrients in system outflow (Harper and Herr, 1993).

Effective stormwater BMPs for nutrient removal in Florida include wet detention, dry retention, off-line retention/detention (separation and treatment of first flush runoff), and aluminum sulfate (alum) treatment (Fulton et al., 2004; Harper, 1999; Livingston and McCarron, 1992). However, it has been found that these conventional measures have not provided the desired level of treatment (Harper and Baker, 2007). In response, the state of Florida is currently updating its stormwater rule (FDEP, 2010e), which has not yet been approved. Constructed wetlands may be the most cost-effective stormwater treatment option if suitable land is already available, but the process of land acquisition can increase treatment costs relative to other BMPs (Weiss et al., 2007).

Alternative, microscale stormwater BMPs for low-impact development include bioretention systems and green roofs. Hunt et al. (2008) used bioretention cells to achieve significant reductions in total N [TN (32%)], total Kjeldahl N (44.3%), and ammonium–N [NH₄–N (72.3%)]. In

experimental bioretention test columns using simulated runoff, Hsieh and Davis (2005) reported total P (TP) removal efficiencies ranging from 47% to 68%. Collins et al. (2010) discussed several factors influencing the effectiveness of both bioretention systems (e.g., soil and vegetation characteristics) and green roofs (e.g., media composition and fertilization rates). The design and maintenance of green roofs require careful attention because these systems can deliver more nutrients to stormwater compared with nonvegetated roofs (Berghage et al., 2009; Berndtsson et al., 2006). Updated stormwater regulations in Florida will address specific design criteria for green roofs, such as pollutant control media and vegetation (FDEP, 2010e). Advanced research on alternative BMPs such as bioretention systems and green roofs would help to improve overall stormwater nutrient removal efficiencies in urban watersheds (Wanielista et al., 2007, 2008).

Atmospheric deposition

Atmospheric pollutants are commonly associated with acid deposition (USEPA, 2007a), but the atmosphere can also be a significant source of N to both inland and coastal waters. Human activities doubled atmospheric deposition rates of N in the tropics during the 20th century while the northern temperate zone experienced a 6-fold increase (Holland et al., 1999). For the last two decades in Florida, the volume-weighted mean concentration of NO₃–N in rainfall has increased 5-fold and wet atmospheric deposition rates have increased 8-fold (Grimshaw and Dolske, 2002). Fossil fuel combustion (e.g., from automobiles, power plants, industrial facilities, etc.) increases atmospheric N in urban watersheds, but other sources include soil emissions, lightning, and

biomass (plant and animal) burning. Per capita fossil fuel combustion and N emission rates are greatest in the United States (Howarth et al., 2002), where N deposition generally increases from the west to the east because of the spatial distribution of atmospheric N sources, precipitation patterns, and prevailing westerly winds (Ruddy et al., 2006). In the mid-Atlantic and northeast regions of the United States, atmospheric deposition can contribute greater than 40% of TN inputs to streams; western streams receive less than 10% of TN inputs from the atmosphere (Smith and Alexander, 2000). In coastal systems, direct deposition of N can account for up to 40% of TN inputs (Howarth, 2008) and is an important source of new N in areas such as Tampa Bay, FL. From 1999 to 2003, atmospheric deposition contributed 21% of N loads to Tampa Bay (Anderson, 2006). Chesapeake Bay and other northeastern U.S. estuaries receive relatively more atmospheric N inputs than southeastern estuaries (Meyers et al., 2001). The airshed size for Chesapeake Bay (108 million ha) compared with Tampa Bay (26 million ha) is an important factor contributing to regional differences in atmospheric N inputs.

Options to control N deposition rates involve regulations targeting emission sources, but the USEPA does not have federal authority to regulate air emissions under the CWA. The 1970 amendments to the Clean Air Act (CAA) enabled the USEPA to develop National Ambient Air Quality Standards (NAAQS) to address pollutants from stationary (e.g., industrial facilities) and mobile (e.g., motor vehicles) sources. Federal NAAQS currently exist for six pollutants, including three pollutants associated with N emissions: N dioxide [NO₂, used as an indicator for all N oxides (NO_x)], ozone (produced from reactions between NO_x and volatile organic compounds), and fine particulate matter [nitrate (NO₃[–]) and NH₄⁺ aerosols]. First established in 1971, both the primary (protecting human health) and secondary (public welfare) NO₂ standards have an annual average of 53 ppb (USEPA, 2010). Annual NO₂ averages at nationwide monitoring sites (required in urban areas with at least 1 million people) currently range from 10 to 20 ppb and have declined

by greater than 40% since 1980 (USEPA, 2010). Several factors have contributed to reduced NO₂ emissions, including the 1990 amendments to the CAA that expanded the range of civil and criminal penalties available to the USEPA (e.g., limiting federal highway funds to states) (USEPA, 2007a, 2009a). Since 1990, the USEPA has formally notified states of impending sanctions 855 times, but sanctions have only been imposed 14 times because of the required 18-month window between formal notification and enforcement (USEPA, 2009a).

Development and implementation of advanced technologies have additionally contributed to declines in NO_x emissions throughout the United States and Europe although global NO_x emissions are projected to increase as energy consumption becomes greater in developing countries (Bradley and Jones, 2002). Environmental concerns such as ground-level ozone and acid rain have been the primary impetus for both NO_x emission reduction policies and technologies. These initiatives also limit nutrient loading associated with atmospheric deposition. For example, the USEPA has limited summer NO_x emissions for several northeastern states and the District of Columbia based on recommendations of the Ozone Transport Assessment Group (NRC, 2000). Various emission reduction technologies have been developed for different pollutant sources, including power plants [e.g., selective catalytic reduction that converts NO_x emissions to gaseous N (N₂) and water] and the transportation sector (e.g., NO_x adsorber technology and three-way catalytic converters) (Bradley and Jones, 2002).

Under the CAA, states develop and submit State Implementation Plans to the USEPA that outline regulations and procedures aimed at ensuring compliance with NAAQS. These plans are revised as necessary to reflect new or updated federal and state requirements, improved modeling techniques, or the failure of polluted areas to comply with established standards (USEPA, 2009a). Based on air quality data collected in a 3-year period by the 216 monitors in Florida's statewide network, the USEPA in 2006 designated the state as an attainment area for all criteria pollutants, indicating air quality surpassed

the primary NAAQS (FDEP, 2006). In 2006, there were 14 monitoring stations in Florida's statewide network measuring NO₂ in 10 counties. Annual average concentrations were less than 25% of NAAQS (FDEP, 2006).

Another program established in response to the 1990 CAA amendments was the Clean Air Status and Trends Network (CASTNet), designed to assess temporal trends in air quality. Monitoring stations from both CASTNet and the National Atmospheric Deposition Program (NADP) provide data that can be used to investigate relationships among atmospheric emissions, air quality, and deposition rates. Poor et al. (2001) estimated atmospheric N deposition to Tampa Bay during a 3-year period (1996–99). This study showed the dominance of both dry-deposited NH₃-N and wet-deposited NO₃-N, which was consistent with CASTNet and NADP data revealing lower N fluxes in Florida compared with the northeastern United States.

Reducing atmospheric N deposition rates requires regulatory policies and standards that can effectively control emissions from stationary and mobile sources. To develop these regulations, research is needed to investigate atmospheric processes contributing to enhanced deposition rates. For example, the origin and movement of air masses are important factors contributing to nutrient loads in Florida. Strayer et al. (2007) conducted an 8-year study (1996–2004) comparing rainfall concentrations from different air mass trajectories. They reported overland trajectories had significantly higher NH₃-N and NO₃-N concentrations, with local sources contributing ≈25% (1 kg·ha⁻¹ N per year) of the total inorganic N deposited to Tampa Bay.

Wastewater

SEPTIC SYSTEMS. Onsite sewage treatment and disposal systems, which include septic systems, serve ≈20% of U.S. homes, including 22% of households less than 4 years old (USEPA, 2008b). State, tribal, and local governments are the primary authorities for these systems, but the USEPA provides technical guidelines to aid management programs (USEPA, 2002, 2003). The USEPA can also become involved in the regulation of septic

systems through the CWA and Safe Drinking Water Act, particularly under conditions where contamination threatens public wells or wetlands.

The increasingly widespread use of septic systems throughout the United States during the 1940s resulted in new state laws specifically targeting system design and installation practices (USEPA, 2005). Local public health departments previously enforced these regulations based on several incorrect assumptions: 1) the development of adequate system designs required only clean-water percolation tests, 2) proper location of systems and construction could be completed by untrained individuals, and 3) environmental protection could be satisfied through compliance with public health requirements (Otis et al., 1993). These assumptions and another assumption, the belief that centralized wastewater treatment would soon be available in areas relying on decentralized systems, ultimately resulted in inconsistent state and local regulations nationwide (USEPA, 2005). Research and development of advanced technology during the 1970s led to code revisions, but these updates largely failed to target system performance considering risk management and site conditions (USEPA, 2002). Septic systems can be cost-effective alternatives to centralized wastewater treatment, but inadequate regulations and improper management and maintenance practices lead to reduced water quality.

The Florida Department of Health (FDOH) began regulating septic tanks during the 1920s in response to public health concerns regarding waterborne diseases such as hepatitis, cholera, and typhoid (Otis et al., 1993). Early regulations were followed by a comprehensive code in the 1970s based on the "Manual of Septic Tank Practice" from the U.S. Public Health Service. Later regulations, such as the Water Quality Assurance Act (1983), included surcharges on construction permits that sponsored research investigating the effects of septic system installations on water resources, considering environmental conditions in Florida (Otis et al., 1993). Revisions of the Florida Administrative Code and Florida Statutes concerning septic systems have continued to reflect advances in

research, such as siting, sizing, and discharge stipulations (Olexa et al., 2005). The current FDOH treatment standard for $\text{NO}_3\text{-N}$ is $10 \text{ mg}\cdot\text{L}^{-1}$.

About 33% of Florida's population relies on the estimated 2.67 million septic systems currently in operation. More than half of these systems were installed at least 30 years ago. Maintenance of septic systems, both old and new, is crucial to protect water resources because ineffective systems promote nutrient transport to groundwater and surface water through percolation and runoff. Less than 1% of septic systems in Florida undergo routine maintenance because the state does not have a mandatory maintenance and management program for most onsite systems (Briggs et al., 2008). Florida Senate Bill 550, requiring mandatory inspections every 5 years, was signed into law in 2010. However, subsequent legislation (Senate Bill 2A) has been recently enacted to delay implementation of required inspections. Some Florida counties (e.g., Charlotte, Escambia, and Santa Rosa) that implemented inspection programs in lieu of mandatory statewide requirements have reported septic system failure rates between 8% and 11% (Briggs et al., 2008; Hall and Clancy, 2009). Age and income of septic system owners may additionally influence failure rates in Florida and throughout the United States. Swann (1999) conducted a survey on nutrient management practices in the Chesapeake Bay watershed and found high-income residents, older than 45 years, were more likely to seek professional advice on septic system maintenance. USEPA (2003) published guidelines to improve septic system performance that included inventory assessments for different types of management models (e.g., homeowner awareness, maintenance contracts, operating permits, etc.). Florida is creating a statewide inventory of all sewage systems as a baseline for planning and growth management (Hall and Clancy, 2009).

Soil characteristics are particularly important to reduce the environmental impact of septic systems. About 74% of Florida soils are unsuitable for conventional onsite system designs based on U.S. Department of Agriculture Soil Conservation Service criteria (Otis et al., 1993). Limiting

conditions include seasonal wetness, high water table, and periodic flooding. Research on the unique soil conditions in Florida has led to mandated separation distances of at least 24 inches between the bottom of drainfields and seasonal high water tables. The likelihood of contamination from older systems is greater because these systems may have been installed with only a 6-inch separation distance (Briggs et al., 2008). Anderson (2006) suggested that establishing operating permits for all onsite systems and requiring upgrades where necessary would bring tens of thousands of existing systems into compliance with current standards and improve overall performance. The Wekiva Study Area in central Florida, which includes sections of Orange, Seminole, and Lake counties that contribute to the Wekiva River system, contains more than 55,000 septic systems. Researchers suggest that upgrades could reduce N loads from older systems by $\approx 40\%$ in the Wekiva Study Area (Ursin and Roeder, 2008).

Alternative onsite wastewater treatment system designs emphasizing passive nutrient removal, such as drainfields with green sorption media or subsurface upflow wetlands, enhance nutrient removal compared with conventional systems (Chang et al., 2010). Smith et al. (2008) explored septic system designs in Florida and identified passive nutrient removal technologies that enhanced N removal compared with conventional designs. These designs were simple to operate and had relatively low life cycle costs. Alternative onsite wastewater treatment systems have also been successfully implemented in Cape Cod, MA. Addition of a biofilter and N filter to a community septic system reduced average effluent TN concentrations from 57 to $3.5 \text{ mg}\cdot\text{L}^{-1}$ (USEPA, 2009a). Implementing regulations that target older systems and developing effective septic system technologies for the future are key aspects of nutrient reduction strategies. Ongoing research in Florida seeks to identify suitable technologies that will provide reliable treatment without additional energy requirements (Chang et al., 2010).

WASTEWATER TREATMENT PLANTS. The total U.S. population served by wastewater treatment plants

(WWTPs) in 1968 was 140 million (71% of all residents); projections indicate an increase to 295 million (88%) by 2025 (USEPA, 2000). The CWA has been integral to the increased accessibility and improved efficiency of WWTPs across the country, influencing processing capacities, treatment methods, and effluent concentrations. In 1972, only 7.8 million people had access to advanced wastewater treatment (AWT), but WWTPs provided this service to 108.5 million people in 2004 (USEPA, 2008a). The initial focus of the CWA was point source pollutants, and programs such as the NPDES targeted WWTPs. Facilities that discharge effluent into surface waters monitor and report pollutant information to comply with specific NPDES permits. Under the CWA, both the USEPA and individual states can issue NPDES permits based on technology or water-quality-based standards, but most WWTPs operate under state permits. All NPDES permits include effluent limits that can be developed from waste load allocations for impaired waters as required by total maximum daily load (TMDL) programs. More than 7000 nutrient TMDLs have been developed in the United States, but few states include numeric nutrient standards in NPDES permits because of the prevalence of alternative narrative nutrient criteria. Numeric nutrient standards define specific N and P concentration limits, while narrative standards describe conditions under which water bodies are considered impaired. Only 4% of the more than 16,000 publicly owned WWTPs in the United States have numeric N limits and $\approx 10\%$ have P limits (USEPA, 2009a).

In Florida, more than 3800 domestic and industrial wastewater facilities operate under the authorization of FDEP. Florida currently calculates NPDES permit limits by determining nutrient concentrations that would "cause an imbalance in natural populations of aquatic flora or fauna." The USEPA has proposed numeric nutrient criteria for Florida (Obreza et al., 2010) that could affect both NPDES permits and TMDL programs by requiring additional nutrient control measures for WWTPs discharging to surface water, groundwater, and deep injection wells. Municipal or domestic WWTPs serve $\approx 66\%$ of Florida's

population and constitute the majority (>60%) of FDEP-permitted facilities. Effluent from domestic WWTPs receives at least secondary treatment before being discharged, but AWT is required where designated, such as discharges to sensitive coastal systems. Legislative directives include the Grizzle-Figg Act (1990), which mandated AWT ($3 \text{ mg}\cdot\text{L}^{-1}$ TN, $1 \text{ mg}\cdot\text{L}^{-1}$ TP) for all domestic WWTPs in the Tampa Bay area, and the Indian River Lagoon System and Basin Act (1990), which required AWT for effluent discharged to the lagoon. Southern Florida (Miami-Dade, Broward, and Palm Beach counties) has six WWTPs discharging effluent through ocean outfalls that only require secondary treatment. The Leah Schad Memorial Ocean Outfall Program (2008) will require AWT for outfall discharges by 2018 and the elimination of these discharges by 2025, except in the case of wet weather flows, from reuse systems (FDEP, 2010c).

Strategies to reduce nutrient loads from WWTPs complement ongoing efforts to increase U.S. water reuse because of increasingly stringent nutrient discharge standards. The USEPA has provided guidelines for reclaimed water and comprehensive reuse systems have been developed in Florida, California, Texas, and Arizona (Koopman et al., 2006; Toor and Rainey, 2009; USEPA, 2004). Florida reclaims 40% of wastewater from WWTPs and plans to increase reuse to 65% by 2020 (Koopman et al., 2006). Reuse programs in Florida began in Tallahassee during the 1960s and have continued to expand statewide, with only three counties (Calhoun, Glades, and Holmes) currently not using reclaimed water from WWTPs (FDEP, 2010b). Upgrades to WWTPs in the Sarasota Bay region, along with reuse projects using $\approx 46\%$ of treated effluent, have resulted in an 81% decline in N loads discharged to the bay from 1988 (569 tons/year) to 1999 (110 tons/year) (Southwest Florida Water Management District, 2002). In Tallahassee, recent AWT and reuse improvements are expected to decrease N in treated effluent by $\approx 75\%$ (Northwest Florida Water Management District, 2009). Florida's reuse capacity continues to increase, but obstacles remain. For example, southern Florida generates

Fig. 1. Total flow in 2008 from wastewater treatment plants in three southern Florida counties ($2.5 \text{ Mm}^3\cdot\text{d}^{-1}$) compared with all other counties ($3.5 \text{ Mm}^3\cdot\text{d}^{-1}$) (Florida Department of Environmental Protection, 2010b); $1 \text{ Mm}^3 = 35.3147$ million ft^3 .

Fig. 2. Total reuse flow in 2008 from wastewater treatment plants in three southern Florida counties ($0.3 \text{ Mm}^3\cdot\text{d}^{-1}$) compared with all other counties ($2.3 \text{ Mm}^3\cdot\text{d}^{-1}$) (Florida Department of Environmental Protection, 2010b); $1 \text{ Mm}^3 = 35.3147$ million ft^3 .

Table 3. Examples of advanced wastewater treatment technologies for nutrient removal.

Location ^a	Nutrient removal technology	Total nitrogen ($\text{mg}\cdot\text{L}^{-1}$) ^y	Total phosphorus ($\text{mg}\cdot\text{L}^{-1}$)
Graceville, FL	Sequencing batch reactor (activated sludge) + filtration	<2.50	<0.50
Daytona Beach, FL	Separate stage denitrification packed bed + chemical addition	1.00	0.19
Reno, NV	Modified Phostrip + trickling filters + filtration + fluidized bed	2.00	0.34
Atlanta, GA	Parallel tertiary granular trimedia filters + membrane filters	N/A ^x	0.08
Durham, OR	Biological nutrient removal (BNR) + chemical addition	N/A	0.05
McMinneville, OR	BNR (oxidation ditch) + chemical addition + multimedia traveling bed filtration	N/A	0.06

^aOleszkiewicz and Barnard (2006), Pagilla et al. (2006), and U.S. Environmental Protection Agency (2007b).

^y $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

^xNot available.

41% of the total domestic wastewater flow in the state, but reuse programs are limited compared with other regions (Figs. 1 and 2). Nutrient removal technologies can be implemented at southern Florida WWTPs to reduce pollutant loads, increase water reuse, and comply with upcoming ocean outfall restrictions (FDEP, 2010c; Koopman et al., 2006).

Advanced technologies can reduce nutrient loads in discharged effluent significantly (Table 3), but costs associated with these technologies and intended reuse applications determine which treatment processes are implemented (Carey and Migliaccio, 2009; Ko et al., 2004; Muga and Mihelcic, 2008). Construction costs for secondary treatment processes

at U.S. WWTPs range from \$260 to \$2770/m³ per day (Muga and Mihelcic, 2008). Tertiary treatment construction costs at a Louisiana WWTP were calculated to be \$502/m³ per day, not including expenses for primary and secondary treatment (Ko et al., 2004). Strategies to reduce treatment costs include using enhanced biological nutrient removal during secondary treatment, which reduces the need for expensive chemical additions (e.g., lime, alum, etc.) during tertiary treatment (USEPA, 2007b).

Water reclaimed after advanced treatment has many benefits, such as reducing the need for additional fertilizers when used for irrigating landscapes. However, implementing dual distribution systems in developing urban areas is more cost-effective than constructing pipelines in well-developed areas (USEPA, 2004). The amount of reclaimed water used by urban customers is also related to how utilities charge for this resource. Florida residents who were charged a flat rate averaged 1112 gal per day, while other residents, who were charged based on volume of water used (per 1000 gal), averaged 579 gal per day (Andrade, 2000; USEPA, 2004). Incentives to use reclaimed water can, therefore, contribute to increased nutrient loading.

Alternative strategies to reduce wastewater-derived nutrient concentrations in surface and groundwater resources include the use of wetlands and water quality trading programs. Nutrient removal efficiencies for different types of constructed wetlands (e.g., surface or subsurface flow) range from 40% to 50% for TN and 40% to 60% for TP (Vymazal, 2007). Constructed wetlands have low operation and maintenance costs compared with conventional facilities, and these systems can be used with WWTPs to provide advanced treatment to discharged effluent (Sala and Mujeriego, 2001; Sundaravadivel and Vigneswaran, 2005). Water quality trading programs provide additional opportunities to limit overall nutrient loads from WWTPs. Florida, Maryland, Ohio, and Pennsylvania enable point and non-point source polluters to reduce overall nutrient loads through market mechanisms (USEPA, 2009a; Woodward and Kaiser, 2002).

Water demand in urban areas continues to increase because of population growth. Limiting nutrient discharges through water recycling programs and water quality trading programs helps satisfy the demands of urban residents while protecting water resources. Reclaimed water has many benefits, but the nutrient content can vary depending on the treatment technology. Leaching, surface runoff, or both after prolonged irrigation with reclaimed water may pose risks to water resources (Carey and Migliaccio, 2009). In addition, economic incentives derived from wastewater reuse systems may promote increased nutrient runoff if the water is excessively used. Economic controls guiding reclaimed water consumption may vary in specific locations. These factors, along with relative nutrient concentrations, need to be understood to develop more effective watershed management plans.

SOLID WASTES. Landfills are an integral component of municipal solid waste (MSW) management, but improper siting, construction, or maintenance can lead to surface water pollution, groundwater pollution, or both. The annual volume of MSW generated in the United States (Fig. 3) has increased substantially from 1960 (88 million tons) to 2008 (250 million tons) (USEPA, 2009b). However, the percentage of MSW transported to U.S. landfills has decreased from 1980 (89%) to 2008 (54%) because of improved recycling programs (USEPA, 2009b). The Solid Waste Disposal Act (1965) and its amendment, the Resources Recovery Act (1970), were early U.S. legislations targeting recycling programs and waste disposal methods. The Solid Waste Disposal Act focused on the

development of solid waste management at the state level that resulted in a gradual increase in state regulations between 1965 and 1975 (Jenkins et al., 2008; Louis, 2004). Inconsistent state standards for MSW management led to the Resource Conservation and Recovery Act (1976) and the Hazardous and Solid Waste Amendment (1984), creating national regulatory standards for sanitary landfills and procedures for improving open dumps (unsanitary landfills). These standards have resulted in fewer (8000 sites in 1988; 2100 sites in 2008) and larger landfills because of USEPA technological mandates that include requirements for leachate collection and monitoring systems (Jenkins et al., 2008; USEPA, 2009b).

The Resource Conservation and Recovery Act enabled states to either follow federal guidelines or develop more stringent solid waste management standards. In 1980, there were ≈500 open dumps operating in Florida without any measures to abate leaching (FDEP, 1993). The waste management problem associated with Florida's population growth led to the Solid Waste Management Act (1988), which outlined comprehensive solid waste disposal, management, and recycling standards (Bibeau et al., 1993; Preston and DeRose, 1988). The first 10 years of the Solid Waste Management Act improved waste management in Florida and advanced recycling objectives. Improved liner standards reduced the number of permitted landfills to 143 in 1991. The percentage of wastes sent to landfills in 1993 (49%) was less than 1988 (75%), and the recycling rate increased rapidly from 1988 (4%) to 1998 (28%) (FDEP, 1993, 2010a). In 2008, 83 permitted landfills and 75 construction and

Fig. 3. Total municipal solid waste (MSW) generated, recycled, and combusted in the United States from 1960 to 2008 (USEPA, 2009b); 1 ton = 0.9072 Mg.

Fig. 4. Distribution of municipal solid waste in Florida for 2008 (Florida Department of Environmental Protection, 2008).

demolition disposal sites received 57% (17 million tons) of Florida's MSW; however, the recycling rate was still below the original 30% goal in the Solid Waste Management Act (Fig. 4) (FDEP, 2008b, 2010a).

The ongoing accumulation of solid wastes requires adequate strategies to minimize nutrient exports from MSW facilities. Landfills undergo different decomposition phases, but $\text{NH}_3\text{-N}$ concentrations in leachate (500 to 2000 $\text{mg}\cdot\text{L}^{-1}$) from conventional landfills remain relatively constant and pose a long-term threat to water quality, even decades after these facilities close (Berge et al., 2005; Kjeldsen et al., 2002; Price et al., 2003). Leachate collection systems attenuate the risks to groundwater by removing leachate from landfills, but design considerations influence system efficiency. Reinhart and Chopra (2000) reviewed designs for leachate collection systems and identified structural (e.g., damaged pipes) and clogging (chemical, biological, or particulate) problems that can lead to system failure. Recommendations to improve leachate collection systems include using flexible joints to connect collection pipes and using gravel trenches to reduce potential clogging. Treating the leachate after collection is also important to mitigate environmental impacts. Renou et al. (2008) reviewed currently available options for landfill leachate treatment, including combining leachate with municipal wastewater for processing at WWTPs. Options to reduce $\text{NH}_3\text{-N}$ leachate concentrations involve ex situ processes such as attached growth biomass systems (85% to 90% reduction), chemical precipitation (86%), air stripping (76% to 99%), and nanofiltration (50%) (Renou et al., 2008).

Bioreactor technology, using moisture additions, air additions, or both to enhance microbial degradation, is an emerging trend for landfill and leachate management. Comprehensive studies such as the Florida Bioreactor Landfill Demonstration Project (Hinkley Center For Solid and Hazardous Waste Management, 2008) have evaluated the design, construction, and operation of these facilities. For example, anaerobic bioreactor landfills use leachate recirculation, water, or other nonhazardous liquids to promote in situ treatment. However, this process increases ammonification rates and leads to greater $\text{NH}_3\text{-N}$ concentrations in leachate from bioreactor landfills compared with conventional landfills (Berge et al., 2005; Onay and Pohland, 1998; Price et al., 2003).

Several laboratory and field-scale experiments have investigated N removal from bioreactor landfills. Onay and Pohland (1998) simulated leachate recirculation among an anoxic denitrification zone, an aerobic zone, and an anaerobic nitrification zone, and achieved 95% N removal. Berge et al. (2007) conducted laboratory-scale experiments using varying temperatures and oxygen concentrations. Results indicated that greater oxygen concentrations increased nitrification, but warmer temperatures reduced denitrification. However, field-scale treatment options for $\text{NH}_3\text{-N}$ in leachate at bioreactor landfills can include simultaneous nitrification and denitrification processes (Berge et al., 2006). The emergence of bioreactor landfills using leachate recirculation represents an intriguing alternative for urban nutrient management. Continued research focused on the problem of increased ammonification

rates within these landfills would contribute to the development of improved system designs.

Conclusions

The U.S. regulatory framework addressing nutrient sources in urban watersheds affects management practices at multiple scales, ultimately affecting surface and groundwater quality. In several instances, state regulations were enacted before federal legislation to protect local water resources. For example, Florida began implementing stormwater treatment standards in 1979 before amendments to the CWA in 1987 expanded the NPDES to include stormwater runoff from multiple sources (e.g., construction sites and MS4s). For atmospheric and wastewater-derived nutrient loads, federal and state policies have fostered innovative technological advances needed to comply with increasingly stringent standards. Evolving emission reduction technologies for stationary (e.g., industrial facilities) and mobile (e.g., motor vehicles) sources affect atmospheric deposition rates that can be a significant component of nutrient loads to receiving waters. Similarly, alternative septic system designs using passive nutrient removal technology can potentially increase wastewater treatment efficiency compared with conventional systems. Advanced nutrient removal technologies at WWTPs can also produce effluent with very low N and P concentrations. Effluent containing low nutrient concentrations reduces pollutant loads to receiving waters and increases the scope of potential applications for reclaimed water.

Federal and state authorities are continuously evaluating the utility of new regulations and technologies to address environmental concerns. Numeric nutrient criteria from the USEPA for effluent discharges and water bodies may potentially reduce pollutant losses from watersheds. Establishing maximum acceptable nutrient concentrations (for water bodies to meet designated uses) will also accelerate the processes of identifying threatened resources and implementing necessary remediation programs. Proposed Florida legislation that includes mandatory inspection and maintenance schedules for septic systems is an example of statewide debates on practicable solutions to nutrient management problems.

Relatively new technologies, such as bioreactor landfills, have been developed to address specific aspects of urban water quality management, but key relationships are often overlooked. For example, educational programs would be critical to minimize solid waste, but only if there are easily accessible options for recycling. Continued population growth in Florida, and in other areas experiencing increased development, places a greater emphasis on resource management. Identifying, understanding, and reducing environmental impacts directly related to urban settings will therefore help to advance sustainability goals.

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