EFFECTIVENESS OF STORMWATER TREATMENT SYSTEMS WITHIN A HIGHLY URBANIZED WATERSHED

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ABSTRACT: The South Central Connecticut Regional Water Authority is a non-profit public utility that provides an average of 55 million gallons of potable water per day to approximately 400,000 consumers in twelve municipalities in the greater New Haven, Connecticut area. One of the Authority's surface water reservoirs, Lake Whitney, has been an inactive water supply since 1991 but will be reactivated by 2005. The area surrounding Lake Whitney is highly developed and over 60 urban stormwater outfalls discharge into the lake and its primary tributary. The CT DEP has identified Lake Whitney as being adversely affected by nonpoint source pollution from urban land use. In 1993, EPA grant funding was used to design and construct a multi-cell system to treat stormwater from a 20-acre watershed. This system provides stormwater treatment via a sediment forebay, created wetland, and wet pond, eliminating a direct discharge to the reservoir. Water quality monitoring indicates the system is successful in removing targeted pollutants. An additional system was recently constructed. Three similar systems are in the planning or construction stage. These projects demonstrate how low technology urban runoff management techniques can be used to mitigate the potential adverse impacts of existing and proposed development on water resources.

KEY TERMS: stormwater treatment systems; urbanized watershed; pollutant removal.

INTRODUCTION

Lake Whitney is a public water supply reservoir owned by the South Central Connecticut Regional Water Authority (Authority). From 1906 to 1991, all water taken from Lake Whitney for water supply was filtered at a slow sand filtration plant. Due to gradual deterioration of the plant structure over its 85 years of operation, the Authority took the plant off-line in August of 1991. The Authority is now constructing a new water treatment plant to help serve the region's water supply needs. Lake Whitney has been identified as a water body adversely affected by nonpoint source pollution from urban land use (CT DEP, 1989). The Authority owns only about five percent of the Lake Whitney watershed, mostly in a narrow strip along the reservoir and the Mill River, the main tributary to the reservoir. Although the upper watershed of Lake Whitney is largely forested, the lower watershed is highly developed with commercial, industrial, and high-density residential land uses. The municipal stormwater infrastructure is generally designed to pipe urban runoff from impervious surfaces to the reservoir or the Mill River. Resulting water quality impacts include high external and internal phosphorus loading, sedimentation in the upper reservoir, and dense blooms of bluegreen algae in late summer. Lake Whitney has a high flow rate relative to its storage capacity with an average hydraulic residence time of approximately ten days. Reservoir water quality and water volume can thus change rapidly in response to storm events.

Lake Whitney, because of its highly developed watershed, requires a multifaceted source protection program. Despite the fact that Lake Whitney was inactive as a water supply for most of the 1990s, the Authority's source water protection programs remained in force throughout this period due to the anticipated reactivation of the reservoir now scheduled for 2005. Periodic water quality sampling is performed to determine the impact of known or suspected contaminant sources, as well as for general monitoring of water quality trends in the reservoir and its tributaries. Watershed inspections are used to monitor the activities of existing businesses and residences. To control impacts from future land use activities, Authority environmental staff review development proposals within the Authority's water supply watersheds and provide recommendations to local land use commissions considering these applications. In addition, the Authority is equipped to respond to hazardous material spills within the watershed 24 hours a day. The Authority also has an active land acquisition program where parcels that may be useful for either protection of critical riparian areas or stormwater quality management are evaluated for possible purchase.

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The Authority has recently accelerated its program for retrofitting stormwater discharges to Lake Whitney. This is due in part to the impending reactivation of the reservoir as a water supply and the recommendations of a recent study that evaluated the causes of sedimentation and shallow depths in the upper portion of the reservoir. Although there is no public access to the reservoir property, the reservoir is a scenic attribute visible from nearby homes and streets. Neighbors were concerned that resuming water withdrawals would result in large areas of exposed bottom sediments in the upper basin of the reservoir. In response the Authority commissioned the Upper Lake Whitney Management Study in 2000 to develop a management strategy that maintains and enhances the beneficial uses and attributes of Lake Whitney. The study involved extensive data collection concerning lake bathymetry, sedimentation rates, biota, water quality and lake level modeling, and stakeholder input. The study concluded that water supply withdrawals in accordance with the Authority's management plan would not significantly affect water levels except in unusually dry or drought years. The biological survey indicated that upper Lake Whitney contains a rich and diverse bird population due in large part to the shallow wading habitat available. Using this information, three broad management alternatives were identified and considered: no action, dredging, and watershed management. It was concluded that watershed management best fits the Authority's goal of protecting Lake Whitney as a valuable water supply resource while preserving the lake's environmental integrity. The chosen alternative is also consistent with the Authority's source water protection objective to control contaminant inputs from existing and future watershed development. The Authority is now in the process of designing and constructing stormwater quality management systems to supplement several existing systems in the Lower Whitney watershed. With the completion of these projects these systems will treat nearly 700 acres of urban watershed surrounding Lake Whitney.

STORMWATER TREATMENT SYSTEMS

Lake Whitney has been identified as a water body adversely affected by nonpoint source pollution from urban land use (CT DEP, 1989). According to the EPA, stormwater runoff from urban and agricultural areas is the leading cause of water quality degradation in the nation's water bodies. Sediment is often the most widespread pollutant within an urbanized area and is of particular concern since it can carry with it other pollutants (Whipple et al., 1983). Stormwater treatment systems have been utilized to provide pollutant removal within urbanized watersheds. These treatment systems are generally comprised of one or more basins in series and are targeted to remove specific pollutants from a predetermined storm event. Some common components of stormwater treatment systems are forebays, sediment basins, infiltration basins, created marshes, and wet ponds.

Forebays are generally the first basin in a stormwater treatment system. They serve to dissipate incoming flow velocities and to trap trash and course sediment such as road sand. Periodic maintenance of forebays is necessary to remove accumulated sediments. Sediment basins provide a detention area for runoff to settle and trap sediments that were not removed in the forebay. The primary pollutant removal mechanism for these basins is sedimentation. While they are effective in reducing sediments, they do not have much impact on nutrient loading beyond what is adsorbed to the particles that settle out (Scholze et al., 1993, Schueler, 1987, Claytor and Schueler, 1996). The outlet structures of these basins may be equipped with skimmers to assist in trapping floatable contaminants such as oil sheens and trash.

Infiltration basins are designed to allow water to infiltrate into the soil, thereby removing pollutants in a manner similar to that of a sand filter. The soil type on the basin bottom controls infiltration rates. A properly functioning infiltration basin should have very high removal efficiency for typical urban runoff pollutants loads. The primary function of marshes and wet ponds is to provide an environment conductive to the removal of dissolved pollutants by biological and chemical processes, as well as physical trapping and settling of particulates and attached pollutants. These removal processes include adsorption, chemical precipitation, vegetative uptake, bacterial degradation, and volatilization (RI DEM, 1989).

Stormwater treatment systems are often designed to treat the "first-flush" from a storm event. This design goal calls for the system to provide a storage volume adequate to accommodate the first one-half or inch of runoff from the impervious areas within the watershed during a rainfall (Schueler, 1987). The rationale for this design criterion is that this first flush carries a disproportionately large pollutant load.

TREATMENT SYSTEMS WITHIN LAKE WHITNEY WATERSHED

The Upper Lake Whitney Management Study, completed in 2002, concluded that the greatest threat to the water quality of the reservoir is impacts from the surrounding urban areas and highways. A number of urban runoff control structures have been put in place over the years to limit sediment and contaminant inputs to the reservoir from stormwater discharges. These treatment systems were designed with the goal of improving stormwater quality prior to their discharge to the Lake. A gabion detention structure located within the reservoir, at the outlet of a municipal stormwater pipe, provides a site for sediment control and nutrient uptake by plants. Another sediment basin, located on Authority land, controls stormwater from a nearby state roadway and is maintained by the Connecticut Department of Transportation. Clarks Pond, a small impoundment several miles upstream of Lake Whitney, was restored in 1986 by dredging the pond and replacing the previously breached dam. This provides opportunity for part of the sediment load carried by the upper Mill River to settle out before reaching the reservoir. In addition to these systems, several other stormwater management facilities have been constructed in recent years as a result of cooperative efforts among the Authority and developers.

In an effort to target those outfalls to the reservoir that are known to provide a significant sediment load, several larger treatment systems have been, or will be, constructed in the ten-year period beginning in 1993. Table 1 summarizes these systems. Pictures of Treatment System Number 1 are shown in Figures 1 through 3.

Table 1. Treatment Systems within Lake Whitney Watershed.

Treatment System	System Configuration	Watershed Characteristics
Number 1	Constructed by RWA 1993. Demonstration project funded in part by an EPA 319 grant. Sedimentation basin with forebay, marsh and wet pond	20 acre high density residential, 45 percent impervious
Number 2	Constructed by RWA 2001. Sedimentation basin with forebay, infiltration basin, created marsh and wet pond	Highly developed 280 acres, 20 percent impervious
Number 3	Constructed by retail developer 1994. Infiltration basin discharging to off-site sediment basin and forested buffer strip.	30-acre shopping center and 12 acre industrial park.
Number 4	To be constructed by RWA 2003. Forebay, created wetland marsh, & infiltration basin	32 acre residential, 23 percent impervious
Number 5	To be constructed by RWA 2003. Forebay, created wetland marsh, & infiltration basin	27 acre high density residential, 36 percent impervious
Number 6	To be constructed by RWA 2004. Two forebays, sedimentation basin & created wetland marsh	209 acre residential, 17 percent impervious

Treatment System No. 1

Treatment System Number 1 was constructed in 1993 as a demonstration project funded in part by the EPA's Clean Water Act 319 program (EPA, 1997). The 20-acre drainage area to the treatment system consists primarily of small residential lots along with a few commercial uses. This area is estimated to be approximately 45 percent impervious, with grass lawns making up the pervious portion of the watershed. Stormwater runoff is conveyed to the treatment system by a pre-existing interconnected network of roadway catch basins and pipes. Overland flow contributions to the system are minimal.

The system components include a sedimentation basin with sediment forebay, a created wetland marsh, and a wet pond. The system design is such that the structures contain removable weir boards to adjust flows to system components. Also included in the design of this treatment system is a high flow bypass. This system was designed to treat the first one half inch of runoff from the contributing watershed. The overall system size is approximately 0.2 acres with a treatment volume of 12,400 cubic feet. The system has been on line since 1993 and has well established wetland vegetation. Design, permitting, and construction costs were approximately $50,000.

Treatment System No. 2

The second treatment system listed in Table 1 was constructed in 2001. This system treats runoff from a highly developed 280-acre drainage area. Almost 50 percent of this watershed consists of multi-family residential, businesses and commercial development. The area is estimated to be approximately 20 percent impervious, with forested areas and lawns accounting for the majority of the pervious portion. Stormwater runoff is conveyed to the treatment system by a pre-existing interconnected network of roadway catch basins and pipes. Overland flow contributions to the system are minimal.

The system components include a sedimentation basin with sediment forebay, infiltration basin, created wetland marsh, and wet pond. As with Treatment System Number 1, this system has a high flow bypass and was designed with removable weir boards within the structures so flows to the system components can be adjusted. The design for this system was such as to accommodate the existing base flow from the influent piping along with the initial flow from any rain events. The overall system size is 1.3 acres with a treatment volume of 171,000 cubic feet. The system has been online since fall 2001. Wetland vegetation is poorly established and additional seeding and plantings are planned for Spring 2003. Design, permitting, and construction costs were approximately $200,000.

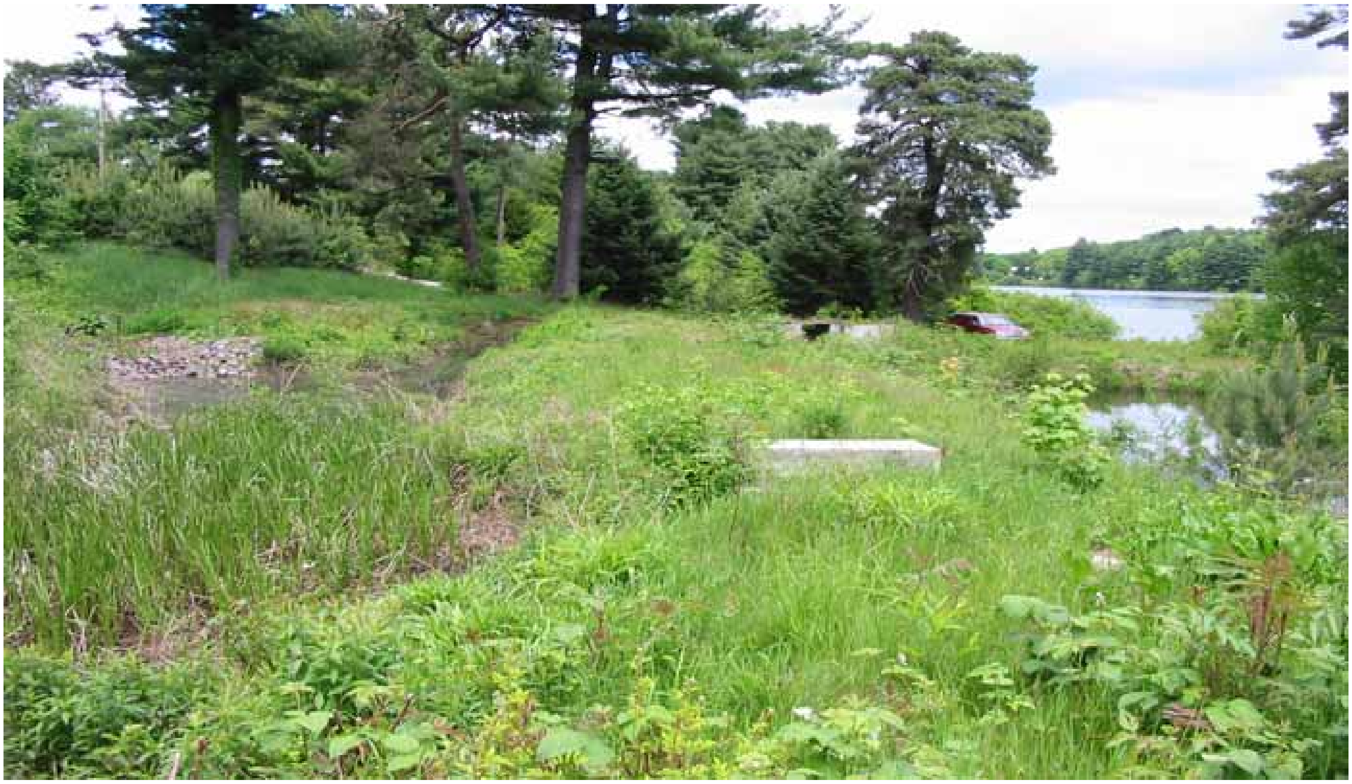

Figure 1. Treatment System Number 1.

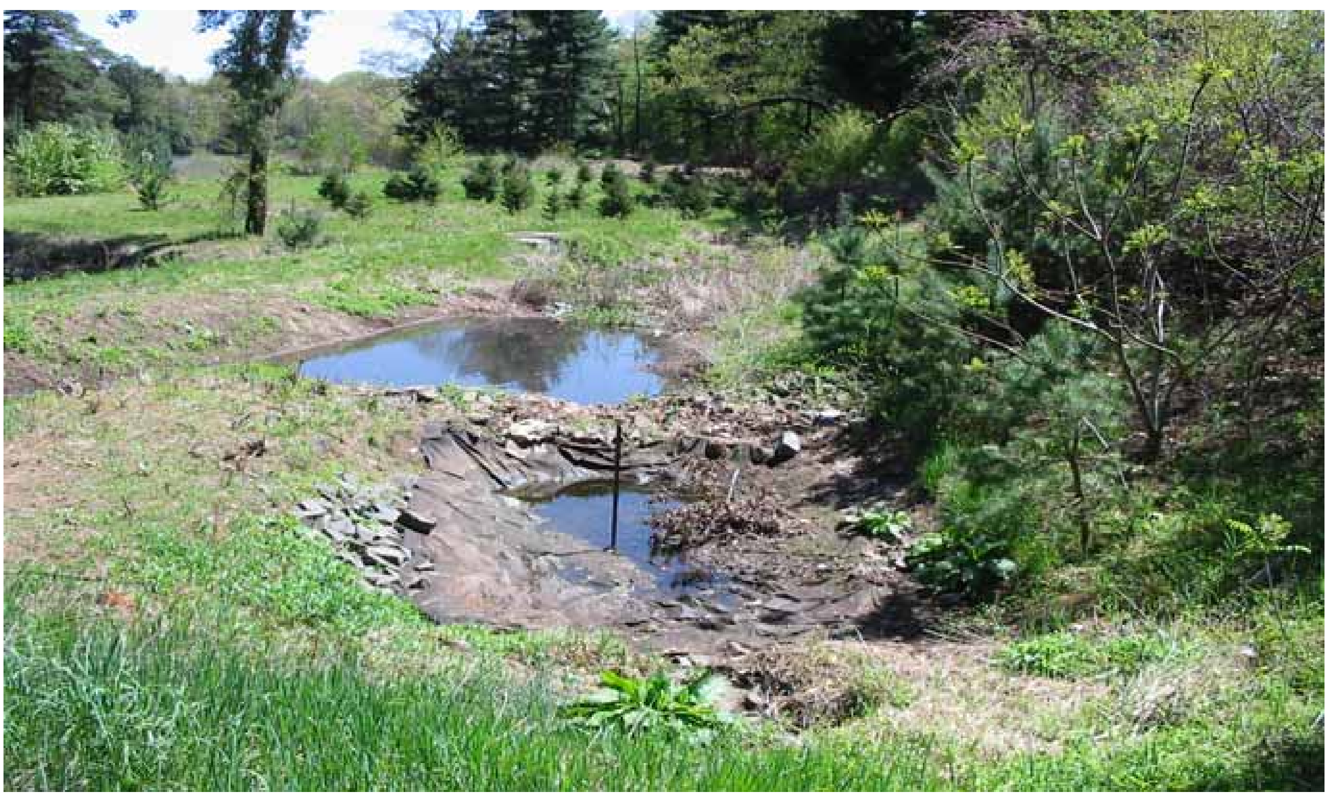

Figure 2. Treatment System No. 1 Forebay and Sedimentation Basin.

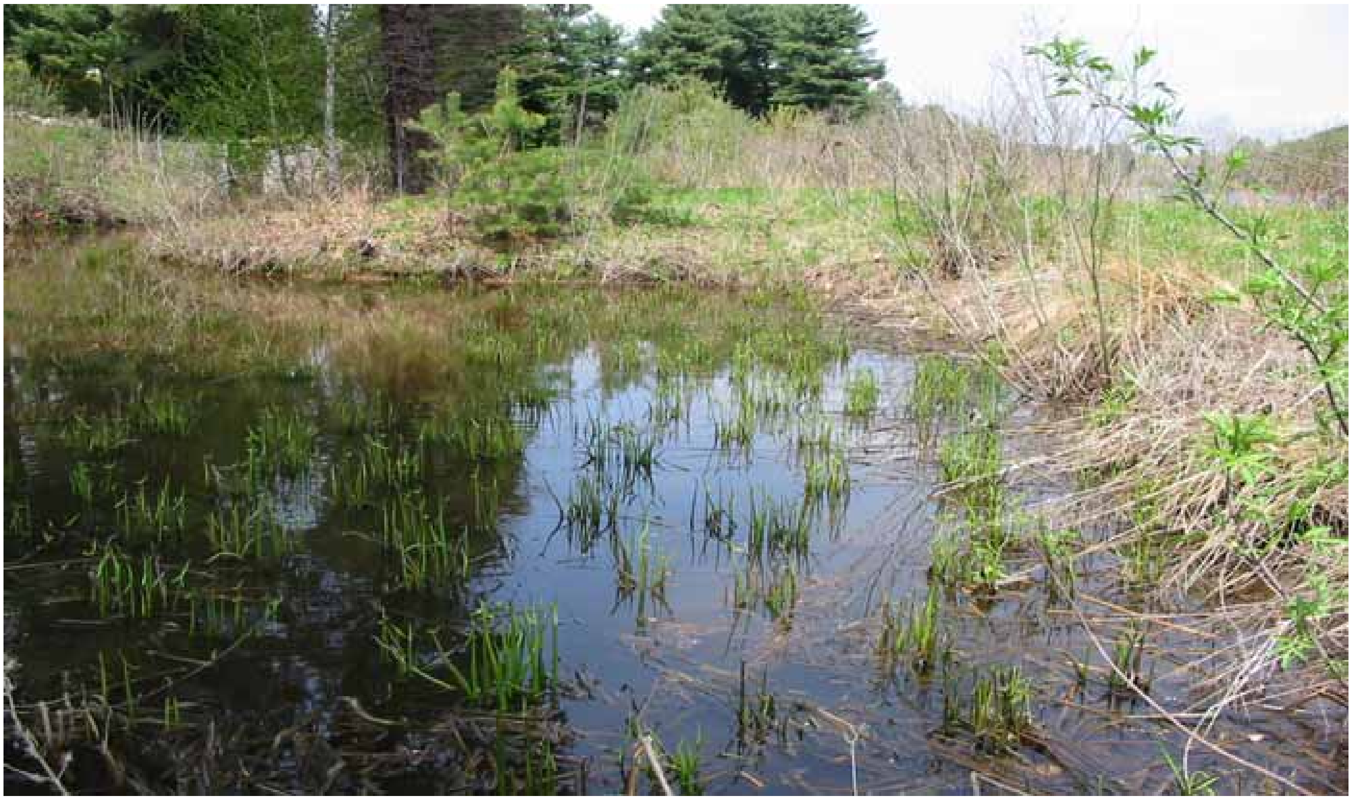

Figure 3. Treatment System No. 1 Wet Pond/ Marsh.

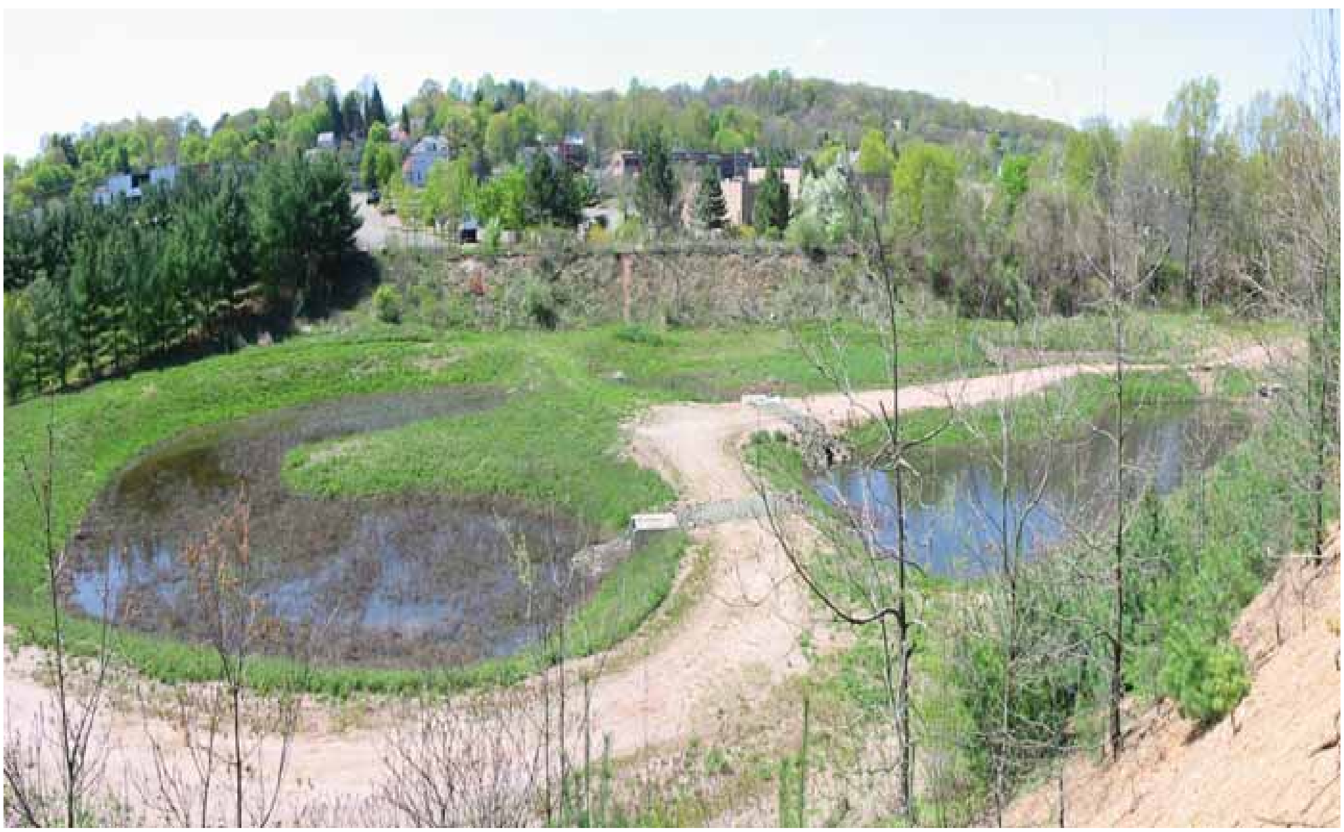

Figure 4. Treatment System Number 2.

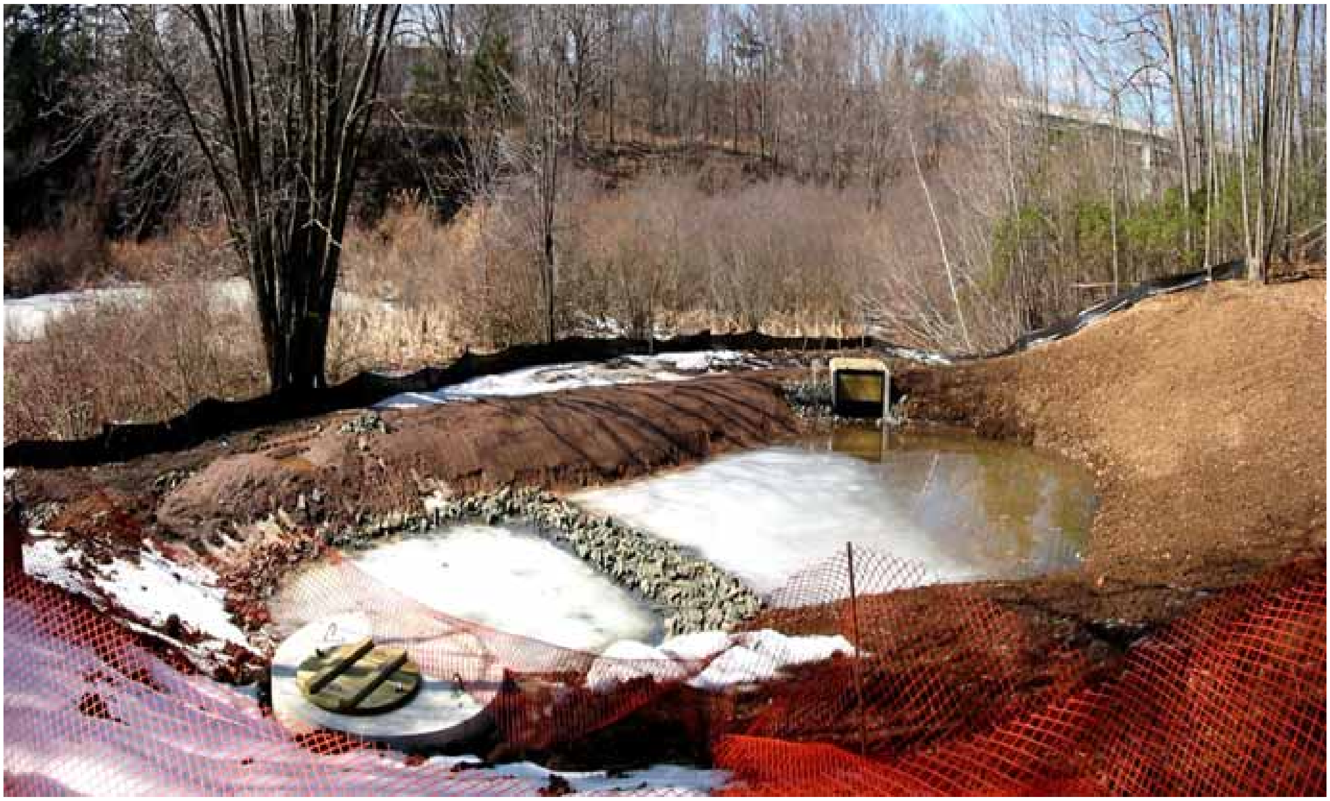

Figure 5. Treatment System No. 5 Under Construction.

Treatment System No. 3

Treatment System Number 3 is located behind a large retail center constructed in 1994. Prior to redevelopment, the site consisted of a SEARS department store and automotive center constructed in the 1950s. Site runoff was directed to the municipal storm sewer system that discharged directly to the Mill River just upstream of Lake Whitney. Through a cooperative effort between the Authority and the developer, a stormwater management system was constructed that substantially improved the stormwater runoff quality leaving the site. Runoff from the 30-acre retail center is now directed to an on-site infiltration basin sized to retain one-inch of runoff from impervious surfaces. Any overflow from the basin is directed to an offsite sediment basin that discharges to an approximately 100 foot wide forested buffer abutting the Mill River. The off-site basin also receives runoff from a 12-acre industrial park unrelated to the shopping center. All design and construction costs for both basins were borne by the developer. This stormwater system received a Source Water Protection Business Award from the US EPA.

Treatment System No. 4

The fourth system noted in Table 1 is slated for construction in 2003 and will treat runoff from two stormwater outfalls whose drainage areas total 32 acres. The drainage areas that this system will treat consist of almost entirely medium density residential lots along with a significant forested area. The area is estimated to be 23 percent impervious, with grass lawns and forested areas making up the pervious portions. Stormwater runoff for this system is conveyed predominantly through existing catch basins and pipes. The forested areas within the drainage area do contribute some overland flow to the system.

The system components include a sediment forebay, followed by a wet meadow and an infiltration basin to intercept and treat runoff from a 24-acre drainage area. As with other systems, there are removable weir boards within the structures so flows to the system components can be adjusted. This system was designed to treat the first one-inch of runoff from the contributing watershed. The overall system size is 0.14 acres with a treatment volume of 16,000 cubic feet. Runoff from an additional eight acres of drainage area will be redirected to a small stilling basin and allowed to sheet flow and infiltrate over a forested area adjacent to the reservoir. Estimated design, permitting, and construction costs are approximately $150,000.

Treatment System No. 5

Treatment System Number 5 is presently under construction. The 27-acre drainage area of this system is comprised entirely of high-density residential land. The area is estimated to be approximately 36 percent impervious, with lawn areas accounting for the majority of the pervious area. As with the other systems, stormwater runoff is conveyed to this basin through a network of existing catch basins and pipes.

This treatment system is a combination sediment forebay and retention basin. This system was designed to treat the first one-inch of runoff from the impervious portion of the contributing watershed. The overall system size of the treatment system is 0.07 acres with a treatment volume of 8,200 cubic feet. The system is not yet online. Design, permitting, and construction costs total approximately $120,000.

Treatment System No. 6

The final treatment system shown in Table 1 is scheduled for construction in 2004. This system will treat runoff from a 209-acre drainage area that is comprised predominantly of low to medium density residential lots along with patches of open space. The area is estimated to be 17 percent impervious, with the pervious portions of the watershed comprised of lawn areas and open space. Existing catch basins and pipes provide the conduit for stormwater runoff to this system.

The proposed system is comprised of two forebays, a sedimentation basin and created wetland marsh. Additionally, an existing cove within Lake Whitney downstream of the proposed system will continue to act as a polishing basin. This cove was dredged in 1976 as a result of high sediment loading from the watershed and has since refilled. The existing streambed through the site will be utilized as a high flow bypass. This system was designed to treat runoff from the two-year storm event. The overall size of the system is 0.8 acres with a treatment volume of 75,000 cubic feet. Estimated design, permitting, and construction cost for the treatment system and dredging of accumulated sediments from the cove is $420,000.

SEDIMENT LOADING

As part of the 2000-2002 Upper Lake Whitney Management Study, radioisotope dating was done on sediment cores collected throughout the Lake. The results of this dating indicate that the average estimated sedimentation rate from 1964 to 2000 was approximately 0.6 centimeter/year (cm/yr) or twice the average rate for the period from 1886 to 1964. Analysis of one cove within the Lake showed a sedimentation rate of two cm/yr since 1976. This increased rate can be at least partially attributed to increased watershed development and the associated increase in runoff.

The amount of sediment that has accumulated within a reservoir can be estimated through the use of Brunes Curve (Vanoni, 1975). Brunes Curve uses the ratio of reservoir volume to the average annual inflow rates. Based on this ratio, the efficiency rating for Lake Whitney is estimated to be 80 percent, meaning that 80 percent of sediment inflow is settled out within the basin. The sediment inflow to Lake Whitney is estimated to be 2,250 cubic yards per year (Milone and MacBroom, 2002). Therefore, the rate of sediment accumulation within the Lake is estimated to be 1,800 cubic yards per year.

Authority staff inspects its stormwater basins on a quarterly basis, prescribing maintenance measures as needed, including trash removal, structural repairs, and removal of accumulated sediments from the basin forebay. From February 15, 2002 to November 13, 2002, ten inches, or approximately 30 cubic yards, of sediment had accumulated in the forebay of Treatment System Number 1. Similarly, from February 22, 2002 to November 13, 2002, 18.5 inches, or approximately 120 cubic yards, of sediment accumulated in the forebay of Treatment System Number 2. As noted previously, since sediment is often the most widespread pollutant within an urbanized area (and is of particular concern since it can carry with it other pollutants), it is assumed that these forebays are both controlling sedimentation and improving the overall water quality of the reservoir.

WATER QUALITY TESTING

The 2000-2002 Upper Lake Whitney Management Study identified the principal pollutants in the Upper Basin to include sediments, metals (cadmium, chromium, iron, lead, manganese, nickel and zinc), nutrients (nitrogen and phosphorus) and polyaromatic hydrocarbons (PAH’s). It is anticipated that the various stormwater treatment systems installed in the Lake Whitney watershed will reduce the pollutant loading to the lake. The Authority conducted a detailed pollutant removal efficiency study of Treatment System Number 1 in 1994 and 1995 (Hudak, 1996). Water quality testing of this system indicated that the basins are achieving a median pollutant removal efficiency of 60 to 90 percent. Preliminary observations from Treatment System Number 2 has been inconclusive, but it is expected that once wetland vegetation becomes better established, future controlled studies of removal efficiencies will yield results similar to those found in System Number 1. Future studies are also anticipated to measure the pollutant removal efficiencies of systems now being designed or constructed.

For Treatment System Number 1, water quality studies were conducted in association with six rain events from May 1994 through November 1995 ranging from 0.4 to 0.9 inches. Incoming runoff quality was comparable to other suburban and moderately developed commercial areas (EPA, 1983; Schueler, 1987), as well as historical data from the project outfall (Van de Mark, 1986). This runoff quality is summarized in Table 2.

Table 2. Treatment System Number 1 Influent Runoff Water Quality [1]

Pollutant	Range	Median	NURP Median [2]
Total Suspended Solids (mg/l)	8.6 - 125.7	32.2	100
Total Phosphorus (mg/l)	0.10 - 0.85	0.22	0.33
Nitrate + Nitrite (mg/l)	0.13 - 3.1	0.96	0.68
TKN (mg/l)	0.74 - 3.9	1.30	1.5
BOD (mg/l)	6.4 - 77.7	12.8	9.0
Lead (mg/l)	0.004 - 0.013	0.01	0.14
Zinc (mg/l)	0.02 - 0.14	0.05	0.16
pH (SU)	5.8 - 7.2	6.6	Not available

1. n=10.
2. Median values from the Nationwide Urban Runoff Program study (EPA, 1983) are shown for comparison.

This system was designed to treat the "first flush" of runoff from the drainage area, which is typically of the poorest quality during a storm event. A time series study of incoming runoff was conducted during the initial stages of a rain event to verify this. The sampling took place within the first 0.3 inches of rainfall during an approximately one-inch storm. Biochemical oxygen demand (BOD), nitrate plus nitrite, sodium, total suspended solids, and zinc were all at elevated concentrations in the first sample of runoff collected. Total phosphorus and total kjeldahl nitrogen (TKN, organic nitrogen plus ammonia) exhibited a brief lag in concentration before reaching maximum levels within 20 to 40 minutes after runoff began. Despite small differences in the time of maximum concentration for different pollutants the "first flush" effect was very evident in this particular drainage area.

Monitoring results have demonstrated the ability of this system to effectively treat for a number of pollutants typically found in urban runoff. A summary of pollutant removal efficiencies as determined by water quality monitoring of system performance is shown in Table 3.

Table 3. Treatment System Number 1 Pollutant Removal Efficiency Summary.

Pollutant	% Removal Sediment Basin		% Removal Sediment Basin & Wet Pond	
	Range	Median	Range	Median
Total Suspended Solids (mg/l)	-80 to 68	23	60 to 91	68
Total Phosphorus (mg/l)	9 to 67	43	24 to 90	73
Nitrate + Nitrite (mg/l)	-16 to 96	42	22 to 87	66
TKN (mg/l)	-30 to 67	23	30 to 89	62
BOD (mg/l)	-85 to 85	-7.1	38 to 90	82
Lead (mg/l)	-178 to 38	-45	67 to 85	78
Zinc (mg/l)	-33 to 86	66	71 to 80	84

Although removal efficiency of individual system components was variable, the system as a whole performed well with overall median removal efficiencies ranging from about 60 to 80 percent. Since the initial monitoring, wetland vegetation density has increased markedly, which should increase its ability to trap sediment and absorb nutrients. In addition to providing water quality benefits, the created wetland environment has been a visual and wildlife enhancement for fish, frogs, invertebrates, turtles, muskrats, and waterfowl. These are important attributes with respect to encouraging the future use of similar systems, whether for new development, or retrofits of existing stormwater outfalls. The relative simplicity of the structures in the system and the multicell design has resulted in a stormwater management facility that has functioned effectively with minimal maintenance effort.

CONCLUSIONS

Conveying stormwater runoff via curbs, catch basins and piped outlets to nearby watercourses was standard engineering practice at the time many existing urban stormwater systems were constructed. These systems have been shown to be counterproductive to achieving and maintaining high water quality in receiving waters. Site design techniques for new development are now readily available to reduce impervious surfaces and minimize impacts to water quality (Center for Watershed Protection, 1998). Reducing water quality impacts from existing urban drainage systems may be difficult given the presence of established infrastructure and land uses. However, improved stormwater runoff quality can be achieved through educating watershed property owners on Best Management Practices (BMP's), redevelopment of commercial and industrial sites, and retrofits of existing stormwater discharges.

Multiple cell basin designs that function to restore natural pollutant removal mechanisms such as particle settling and trapping, biological process promoting nutrient and pollutant transformation and degradation, and infiltration have been shown to be effective herein and elsewhere (Center for Watershed Protection, 2000). Key aspects to ensuring the success of these systems include adequate design capacity to treat the first flush of runoff, establishment of vegetation, and routine inspection and maintenance. Monitoring of system condition in the first several years after construction is particularly important, especially with regards to the establishment of wetland vegetation. The range of water levels in the basin should be monitored after construction to determine appropriate wetland plant selections. Repeated seeding or planting with native species may be necessary in the first several years of operation to establish a dense, sustainable, and diverse wetland plant assemblage. Designing adjustable inflow and outflow structures, e.g., with removable weirboards, allowing for flexibility to adjust system operations based on post-construction observations, and providing for easily accessible maintenance locations are critical design components in establishing a successful treatment system.

The Regional Water Authority has used all of these various approaches to improve stormwater discharge quality to a water supply reservoir set in an urban environment. The most visible BMP utilized by the Authority is the construction of stormwater treatment systems to intercept and treat urban runoff that previously discharged directly to the water supply. Initial water quality monitoring and sediment removal indicate that the treatment systems are functioning as designed. Benefits that have been achieved from redevelopment or retrofitting of these urban stormwater systems include:

- Reduction in pollutant loadings.
- Reduced sediment inputs to shallow portions of the reservoir.
- Containment areas for transportation related hazardous material spills.
- Serving as models and educational tools for urban stormwater management that can be applied to other watersheds and new development projects.
- Creation of wetland habitat for fish and wildlife and improved aesthetics.

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