Design and Performance of Multipurpose Constructed Wetland and Flow Equalization Basin

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Abstract: Stormwater runoff from a portion of a 273 ha (675 acres) Midwestern rail yard contacts industrial facilities including fuel storage tanks and fueling and servicing operation areas. Stormwater draining from a smaller 64 ha (159 acres) sub-basin containing the industrial facilities previously flowed into a retention pond within the rail yard. The retention pond had a surface area of 607 m^2 (0.15 acre) and a maximum storage capacity of 1.4 million L (370,000 gal). Given the large drainage area of the pond the retention time within the pond was shorter than optimal, limiting its potential effectiveness for improving water quality. To address these issues the pond was redesigned to have a 6.25 million L (1.65 million gal) storage capacity and configured into a constructed wetland to control a 50-year storm event and increase its ability to treat stormwater runoff. A network of riparian plants (5,700) was placed within the stormwater wetland to treat runoff prior to discharge off-site. Evaluating the performance of both the former and current retention basins revealed significant improvements in the retention and treatment ability when comparing the two structures. Mean total suspended solid concentrations and oil and grease concentrations were reduced approximately 45% when comparing pre- and postconstruction flow analysis. This innovative multiuse approach has demonstrated effectiveness in controlling storm flows and treating runoff from the rail yard.

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Introduction and Problem Overview

With the onset of stricter regulations and more stringent enforcement from local, state, and federal governments, many industries are turning to innovative treatment approaches to remain in compliance with their various industrial discharge permits. Five years ago, a Class I Railroad Company was faced with a permit revision, which caused them to reevaluate their approach to retaining and treating stormwater from a Midwestern railyard. The yard in question was constructed in 1955 and consists of 273 ha (675 acres) of land with a relatively unvarying topography. Stormwater, which flows across the property, eventually discharges to a nearby river, approximately 1.6 km north of the yard. With an average rainfall in the area of approximately 1 m (39 in.), approximately 2.7 billion L (715 million gal) of stormwater falls onto the rail yard each year. Portions of the stormwater contacts industrial areas of the yard involved with locomotive fueling and servicing operations. This contact has the potential to impact the stormwater with industrial pollutants. State regulations mandate discharge limits for potential pollutants, which in turn require treatment of the stormwater to comply with these standards. These industrial areas of the yard are housed on a 63 ha (159 acres) subarea within the main rail yard facility, and all of the drainage in this area converges to a common point prior to discharging to the previously mentioned river. Formerly located at this convergent point was a 2.13 m (7 ft) deep retention pond with a surface area of approximately 607 m^2 (0.15 acre), yielding a maximum holding volume of approximately 1.4 million L (370,000 gal). The retention pond was lined with shotcrete 0.61 m (2 ft) above and below the normal pool elevation. Three underflow baffles were utilized to skim and retain floatage (i.e., oil) in the pond. Also, a portable rope oil skimmer was placed on the bank of the pond as a backup system to catch any oil that reached the retention basin. In addition, no shutoff mechanism was present at the pond to limit or stop the discharge from the pond. This type of mechanism is desirable in the event of a spill in the yard to contain a catastrophic occurrence from leaving with the effluent from the pond. Finally, when the yard was originally constructed, twin 0.76 m (30 in.) pipes were used to convey water from the pond to a surface drain which flowed to the river. The carrying capacity of these pipes was on the order of 2,800 L/s (100 ft^3/s), which was the outflow from the pond during the 5-year, 24-h storm event. These twin pipes crossed beneath the only access road to the yard and multiple in- and outbound freight lines. Accordingly, it was imperative to attenuate the flow out of the yard on the upstream side of these pipes to prevent disruption of yard operations to replace them to increase the carrying capacity out of the yard. To address these problems, the railway company evaluated different options for tackling the issues regarding the quantity and quality of stormwater flow, and

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Table 1. Input Parameters for Watershed Used in Small-Watershed Hydrograph-Formulation Analysis

	Design storm return period				
Parameter	2-year	10-year	25-year	50-year	100-year
Regression coefficient, g=	108	172	204	243	272
Regression coefficient, h=	22	21	24	28	23
6 hour precipitation depth, $Pn6$ (cm)=	5.31	7.62	9.35	10.80	12.70
Watershed area, A (ha)=	64.3	64.3	64.3	64.3	64.3
Elevation difference, H (m)=	6.1	6.1	6.1	6.1	6.1
Flow distance, L (m)=	1,280	1,280	1,280	1,280	1,280
Runoff C (Rational), Ca=	0.31	0.31	0.31	0.31	0.31
SCS curve number, CN=	63	63	63	63	63
Ultimate soil storage, S (cm)=	14.9	14.9	14.9	14.9	14.9
Runoff depth, Q^*=	3.5	12.3	21.2	29.9	42.7
K=	1	1	1	1	1
Time of conc., T_c (min)=	37.74	37.74	37.74	37.74	37.74
Rainfall intensity, i (cm/h)=	4.59	7.44	8.39	9.39	11.38
Estimated peak inflow into pond, Qp (L/s)=	2,492	4,021	4,559	5,097	6,173
Time to peak, T_p (min)=	10	21	32	41	48

Note: Values were obtained from the Midwest Climate Center, Applied Hydrology (Chow et al. 1988), or calculated using the small-watershed hydrograph-formulation method (Malcolm 1989).

the need to capture and contain any catastrophic releases of pollutants in the yard.

Considered Options

For decades industrial users and small domestic waste treatment systems have been faced with problems similar to those confronting the railroad company at this particular yard. The two major issues posed at this facility were how to attenuate and regulate the contributing flow, and how to effectively treat a large volume of minimally impacted stormwater. At this facility, the potential stormwater contact pollutants included volatile organic compounds and metals. Many researchers have focused on work removing metals from stormwater (Dunbabain and Bowmer 1992; Karpiscak et al. 2001; Scholes et al. 1998; Scholz 2004; Vymazal and Krasa 2003; Walker and Hurl 2002; Weis and Weis 2004) or treatment of volatile organic compounds (Keefe et al. 2004; Mastin et al. 2001). The problems facing this facility also integrated aspects of urban hydrology, which has been extensively studied (Berezowsky 1995; Carleton et al. 2000; Helfield and Diamond, 1997; Koob et al. 1999; Scholes et al. 1999; Shutes et al. 1997). In examining potential treatment strategies, the goal was to maintain long-term performance (Carleton et al. 2001; Farrell and Scheckenberger 2003; Griffin 2003) and compliance with the regulatory goals of the project. Many options for treating the stormwater were considered, some of which included: an in-line constructed treatment plant, wet detention structure, biofiltration cells, and mechanical aeration of the existing pond. In the final analysis, combining a stormwater attenuation basin with a specially designed constructed wetland and an underflow emergency detention structure appeared to be an innovative and effective approach for addressing the issues posed at this site.

Flow Control and Storm Routing

In order for the stormwater attenuation and treatment approach to be effective, the designed basin needed to be adequately sized to handle the storm flows draining to the retention structure. The first step in this process was to determine the expected inflow through the system and correlate the volume of flow with specific recurrence intervals of storms of known duration. The flow recorder on the former basin was a chart recorder interfaced with an ultrasonic level transducer used to record the water level behind a V-notch weir. Unfortunately, there was not a rain gauge on site to be able to develop a relationship between rainfall and runoff through the former basin. However, data tabulated by the Midwestern Climate Center and housed in a website maintained by the Applied Meteorology Group of the Plant and Soils Laboratory in the Department of Agronomy at Purdue University provided extremely detailed records of rainfall for nine geographic regions in Indiana.

Using the small-watershed hydrograph-formulation method (Malcolm 1989) along with the rainfall records from the north central region of Indiana, it was possible to estimate the inflow and outflow from the original pond. The inflow characteristics for the watershed are listed in Table 1 and using the small-watershed hydrograph-formulation method (with a corresponding value of K_s=138.41 and b=1.13 at a depth of 0.3048 m), representations of the inflow and outflow hydrographs for the original pond could be calculated (Fig. 1). The goal of the design effort for the new retention structure was to completely contain all but the most extreme storms (i.e., storms with a recurrence interval of greater than 50 years), and for those storms the design constraint was to attenuate the peak flow such that the maximum outflow would be less then 50% of the inflow (IDEM 1997; USEPA 1993). This constraint was for two reasons, the first, as has already been stated, was that the effluent from the pond was conveyed by the undersized twin 0.76 m (30 in.) pipes under the only access road in the yard and multiple in- and outbound freight lines. The second reason was that a longer retention time would provide more treatment contact time in the constructed wetland.

To maintain constant flow between the inlet and outlet structures, while providing the necessary storage and ensuring maximum contact between the wetland vegetation and the water flowing into the basin, the layout of the basin used a combination of shallow water and "shallow land" to accomplish the retention

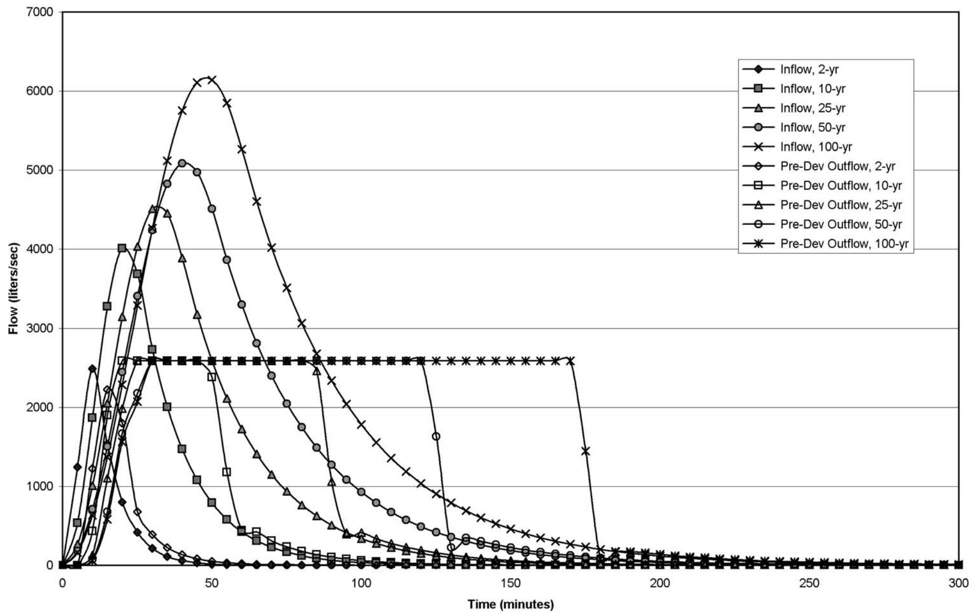

Fig. 1. Predevelopment inflow and outflow hydrographs

and treatment objectives. Using a winding "stream" to convey flow from the inlet structure to the V-notch weir, typical elements of a constructed wetland were designed into the system to assist in the form and function of the treatment strategy. Fig. 2 presents a plan view representation of the proposed design (for comparison purposes, the original pond is shown for reference).

The pond design specified the installation of two riser barrel structures just prior to the existing outlet culvert, and one low flow culvert. In the final renderings, the outlet structures consisted of a 0.3 m (12 in.) diameter (underflow) pipe and two 1.2 m (48 in.) riser barrel structures. The input parameters for the final layout of the proposed basin are listed in Table 1 and Fig. 3 depicts the inflow and outflow hydrographs for the proposed pond using a value of $K_s=218.42$ and a value of $b=2.10$ at a depth of 0.3048 m. As demonstrated by these calculations, with a holding volume of 6.25 million L (1.65 million gal), the pond theoretically contains all but the most extreme storm events and provides the necessary attenuation for even these rare storms. Additionally, a comparison of Figs. 1 and 3 demonstrates that when flooding conditions are encountered, the newly constructed pond remains surcharged for a shorter time period than the previous basin. Table 2 displays a comparison of the calculated storm routing for the

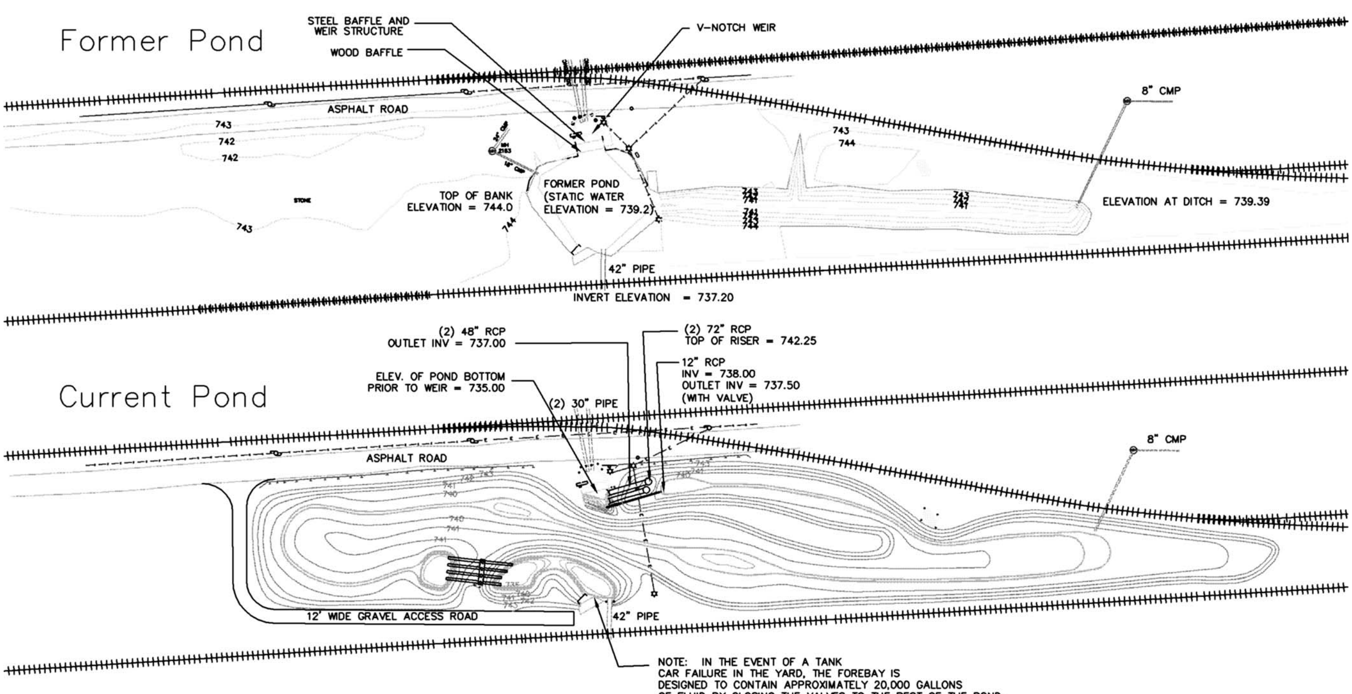

Fig. 2. Layout of former and current pond

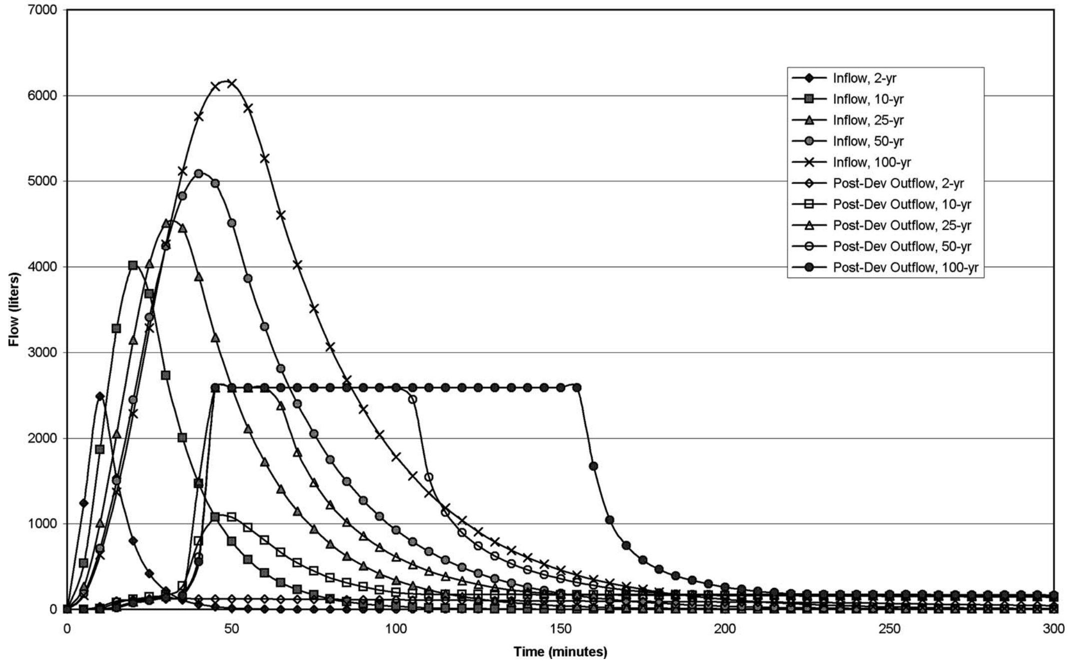

Fig. 3. Postdevelopment inflow and outflow hydrographs

original and proposed retention basins. With the hydraulic performance estimated to be sufficient for the retention requirements associated with the railyard, the design also focused on controlling the effluent from the facility and the quality of the discharge.

Forebay Construction and Underflow Control

While the function of a forebay in removing sediment is typical of constructed wetlands, the railroad company wanted to have the ability of containing a catastrophic rail car release which might deposit as much as 75,700 L (20,000 gal) of potentially regulated or hazardous materials during a failure event. To accommodate this constraint, the forebay was equipped with four, parallel, individually valved, 0.6 m (24 in.) diameter culverts, which could be closed to isolate the forebay and shutoff flow into the rest of the basin. These submerged pipes were not sized to restrict flow in any way during storm events; but, if a catastrophic event were to occur, then these underflow structures could be closed containing the spill with the available 1.2 m (4 ft) of freeboard in the forebay. By concentrating the spill it would make the removal more efficient and expedite cleanup.

Stormwater Treatment

To remove the trace anthropogenic constituents from the stormwater it was first necessary to determine which industrial chemicals needed to be targeted for treatment. As previously discussed, the major potential pollutants of interest at this facility were volatile organic compounds and metals. Specifically, the constituents and their corresponding discharge limits for the National Pollution Discharge Elimination System (NPDES) permit are listed in Table 3. While bulk separation and attenuation are effective for gross removal, for this facility, the trace constituents needed to be addressed with alternative methods, in this case, a constructed wetland. Using continually cyclical contact with "shallow land" planted with specific native wetland species, the volatile organic

Table 2. Results of Discharge Calculations from Small-Watershed Hydrograph-Formulation Method

	Design storm return period				
Parameter	2-year	10-year	25-year	50-year	100-year
Peak inflow (L/s)=	2,490	4,011	4,507	5,084	6,173
Former basin characteristics					
Peak outflow (L/s)=	2,237	2,577	2,577	2,577	2,577
Maximum surface area (h)=	0.053	0.085	0.121	0.121	0.121
Rise (m)=	1.2		Flood stage (1.5 m of rise)		
Storage (m^3)=	752	1,801	1,981	2,179	2,397
New constructed wetland—basin characteristics					
Peak outflow (L/s)=	125	1,076	2,577	2,577	2,577
Maximum surface area (ha)=	0.30	0.88	1.05	1.25	1.75
Rise (m)=	0.57	1.12	Flood stage (1.2 m of rise)		
Storage (m^3)=	1,867	5,397	6,561	7,217	7,938

Table 3. Effluent Limitations and Monitoring Requirements

Parameter	Quantity or monthly average	Maximum daily loading	Units	Quantity or monthly average	Maximum daily loading	Units	Measurement frequency	Sample type
Flow	Report flow		MGD	—	—	—	Weekly	24 h total
Oil and grease	Report value		lb/day	10	15	mg/L	Weekly	grab
Total suspended solids	Report value		lb/day	—	20	mg/L	Weekly	24 h composite
Hexavalent chromim	0.03	0.08	lb/day	6.8	16.0	ug/L	Monthly	grab
Copper	0.08	0.2	lb/day	16	37	ug/L	Monthly	24 h composite
Zinc	0.6	1.5	lb/day	120	290	ug/L	Monthly	24 h composite
Lead	Report value		lb/day	Report value		mg/L	Monthly	24 h composite
Naphthalene	Report value		lb/day	Report value		mg/L	Monthly	24 h composite
Ammonia	Report value		lb/day	Report value		mg/L	Monthly	24 h composite
Chloride	Report value		lb/day	Report value		mg/L	Monthly	24 h composite
Sulfate	Report value		lb/day	Report value		mg/L	Monthly	24 h composite
E. Coli	Report value		lb/day	Report value		mg/L	Monthly	24 h composite

compounds, and metals were treated through a system of filtration, aeration, uptake, or chelation. Table 4 provides a list (and quantities) of the vegetation planted in the basin, while the restricted, invasive plant species that could not be permitted in the planting included: purple loosetrife (lythrum salicaria), Eurasian water milfoil (myrlophyllum spicata), reed canary grass (phalaris arundinacea), and common reed (phragmites asutralis). Over 5,700 native, noninvasive wetland plants were planted in the basin (in both monospecific and mixed plantings) to treat the constituents present in the stormwater at the facility. To populate the wetland, a listing of native riparian species approved by the state regulatory agency was cross-listed with plants available at a local nursery. These available plants were then selected based on their documented ability to uptake metals based on studies (Carbonell et al. 1998; Lasat 2002; Schafer et al. 1998; Stoltz and Greger 2002). Additionally, the plant selection focused on the viability and persistence of the vegetation, with the ability to assist in the removal of organic nutrients to help the wetland comply with the stated regulatory objective. With the vegetation planted and the mechanisms for treating the constituents installed over 6 years ago, the true test of the effectiveness of the treatment approach would be the empirical performance data to come.

The results of the discharge monitoring reports (DMR) for the past 7 years are displayed in Figs. 4 and 5, which demonstrate the concentration of oil and grease and total suspended solids in the effluent. With all of these samples collected and analyzed following state approved standard testing methods, Table 5 compares numeric values of the concentrations and the performance of the system with respect to the established regulatory levels. As demonstrated in the figures and table, there was a significant reduction of constituents from the original, preconstruction, 607 m^2 (0.15 acre) surface area, shotcrete lined pond to the postconstruction, 6.25 million L (1.65 million gal) storage volume, basin planted with over 5,700 riparian plants. As demonstrated in the figures, for the 4 years immediately preceding and immediately following the construction, the average oil and grease concentration dropped by 47% and the average total suspended solids concentration dropped by 45%. Additionally, prior to the construction, the confidence limit for the total suspended solids concentrations was above the regulatory threshold. Now the confidence interval (2 SD above the mean) is significantly below the limit for both total suspended solids (45% below) and oil and grease (60% below). Quantifiable concentrations of metals in both pre- and postconstruction analysis were for the most part unable to be detected. Therefore, the data do not offer any insight to the effectiveness of the wetland in the treatment of metals. An anecdotal measure of the effectiveness of the treatment process is the growth of algae on the outlet structure and the presence of snails and other wildlife inhabiting the wetland. Additionally, most of the plant species have thrived in the wetland, with the varieties of bullrush and sedge actually expanding their habitat. All told, based on information provided by yard personnel, approximately 50–60% of the plant population still remains. All of these measures demonstrate that the constructed system is functioning in accordance with the design and is effectively treating the constituents flowing off of the railyard.

Table 4. Vegetation Plan and Plantings

Common name	Plant name	Minimum number of stems	Center spacing	Quantity planted
Softstem bullrush	*Scirpus validus*	6	0.9 m × 0.9 m	725
River bullrush	*Scirpus fluviatilus*	6	0.9 m × 0.9 m	725
Bristly cattail sedge	*Carex fankii*	6	0.9 m × 0.9 m	685
Brown fox sedge	*Carex vulipinoidee*	6	0.9 m × 0.9 m	2,014
Bebb's oval sedge	*Carex bebbii*	6	0.9 m × 0.9 m	1,365
Arrowhead	*Sagittaria* spp.	—	Seeded	765 g
Water plantain	*Alisma* spp.	—	Seeded	680 g

Note: Minimum topsoil depth of 15 cm was required in shallow land areas of wetland; minimum topsoil depth of 7.6 cm was required in shallow land areas of wetland (New 2000).

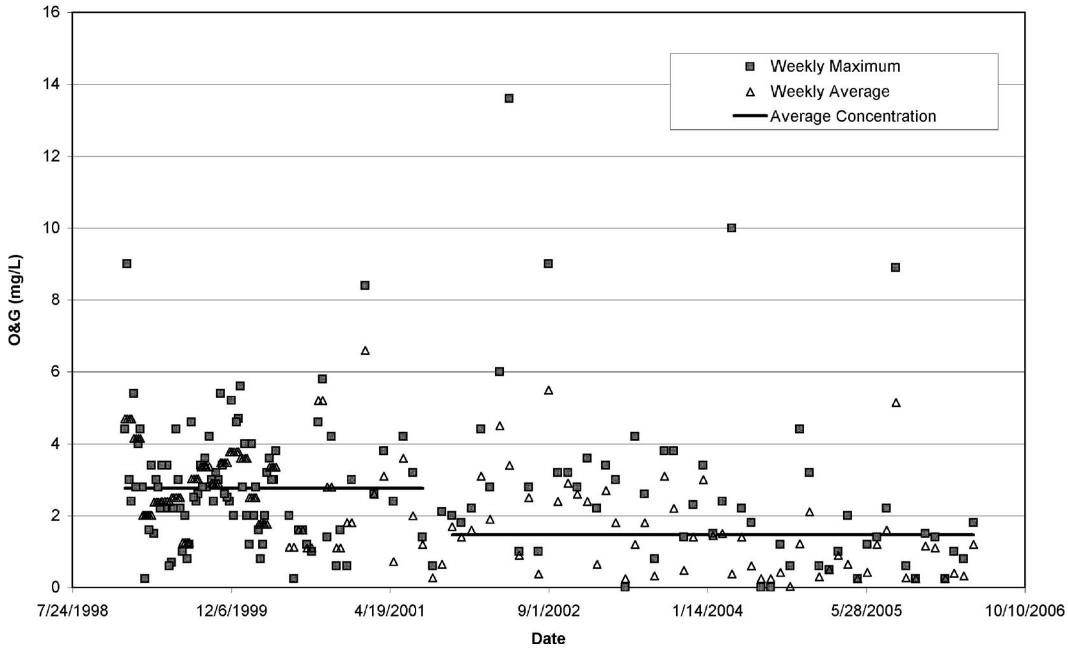

Fig. 4. Oil and grease concentration

Limitations and Areas for Future Study

While this system appears to be effectively treating the storm flow, the long-term measure of the performance of this wetland will be its continued functioning and removal efficiency. While the actual treatment and attenuation appears to match those modeled during the design phase, this is a dynamic system with variable pollutant loadings and seasonal fluctuations in temperature and rainfall. While the design attempted to address many of the foreseeable issues, there are questions left unanswered and issues which could not be fully addressed. Most notably are the temperature extremes this region of the country experiences and how that will affect the performance of the treatment strategy. Also, a sensitivity analysis on the input parameters would help identify which design assumptions affect the modeled results and how variability in specific inputs impacts the actual system performance. Additionally, while currently effective, the long-term monitoring will provide the definitive commentary on the performance of the system. Another aspect left unexamined is the viability of the selected plants and their individual effectiveness in removing target constituents. The final aspect of interest investigated is the effect of continued metals deposition in the wetland

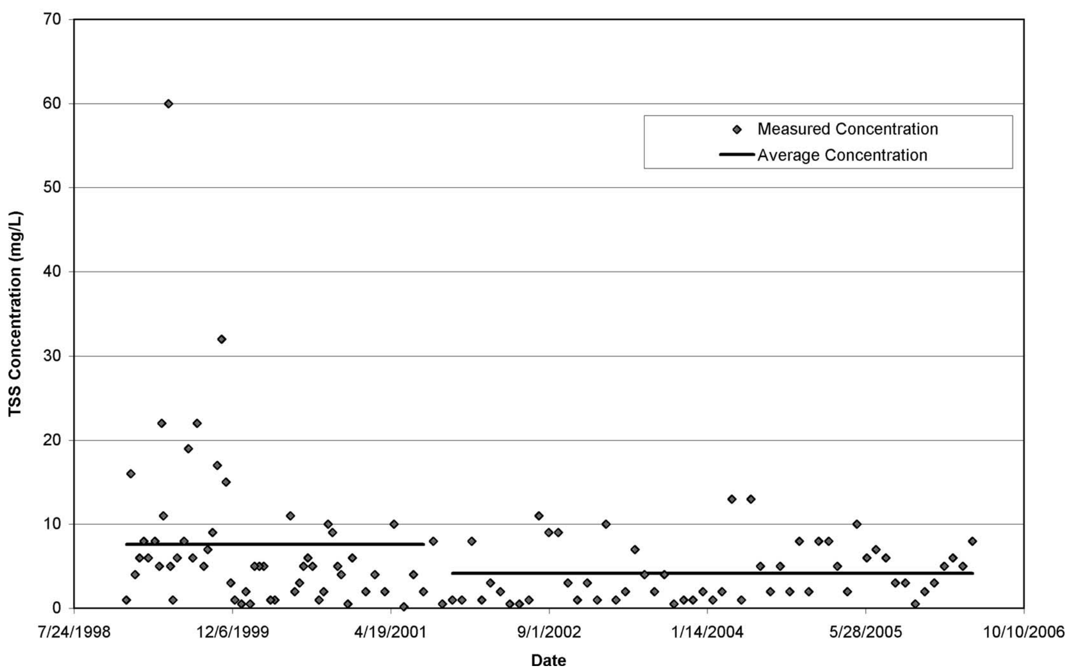

Fig. 5. Total suspended solids concentration

Table 5. Mean and Maximum Concentration of Reported Constituents

Parameter	Total suspended solids (mg/L)	Oil and grease (mg/L)
Maximum value prior to construction	60	9
Maximum value following construction	13	13.6
Percent reduction/increase (%)	−78	51
Mean value prior to construction	7.6	2.8
Mean value following construction	4.1	1.5
Percent reduction/increase (%)	−45	−47
Standard deviation of mean value prior to construction	9.5	1.1
Standard deviation of mean value following construction	3.4	1.3
Regulatory limit (maximum)	20	15
Regulatory limit (average)		10
Percent below/above reg. limit. (Max) with 2 SD above mean—prior to construction (%)	33	−66
Percent below/above reg. limit. (Max) with 2 SD above mean—following construction (%)	−45	−73
Percent below/above reg. limit. (Ave) with 2 SD above mean—prior to construction (%)	—	−50
Percent below/above reg. limit. (Ave) with 2 SD above mean—following construction (%)	—	−60

and how this affects both the viability of the riparian species and the removal efficiency of the system.

Conclusions

With a 6.25 million L (1.65 million gal) storage capacity, the new basin can control a 50-year storm event, attenuates the peak flow, and was constructed with submerged, individually valved pipes to convey flow from the forebay to the rest of the wetland structure. This created an emergency spill storage area within the wetland in the event an entire fuel car inadvertently discharged a full load (75,700 L or 20,000 gal) into the stormwater system. A network of riparian plants (5,700) was placed within the stormwater wetland to further treat runoff prior to discharge off-site. Comparing the performance of both the former and current retention basins indicates significant improvements in the retention and treatment ability when comparing the two structures. This innovative multiuse approach has demonstrated effectiveness in controlling storm flows and treating runoff from the rail yard.

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