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COMPARISON OF SOIL AND OTHER ENVIRONMENTAL CONDITIONS IN CONSTRUCTED AND ADJACENT PALUSTRINE REFERENCE WETLANDS

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Abstract: Wetlands are created to compensate for the loss of natural wetlands as a result of human land-use activities. How well these constructed wetlands mimic natural wetlands is in debate. The goal of this study was to compare soil and other environmental conditions within constructed and adjacent reference wetlands to assess the progress of the constructed wetlands towards a functional wetland. Three constructed wetlands in Virginia, USA, 4 to 7 years old, were paired with adjacent palustrine forested and scrub-shrub reference wetlands to examine differences in topography, hydrology, soil properties, and other environment conditions such as soil temperature and redox potential. Degree of microrelief was greater in reference wetlands than in the associated constructed wetlands. Seasonal fluctuations in water-table levels were similar in both wetland types. Two of the paired wetlands showed considerable differences (15 to 20 cm) in the depth to the water table. Redox potentials were similar in reference and constructed wetlands. Paired wetlands with water-table levels at or near the soil surface throughout the year showed similar soil temperatures. At the site where the summer water levels were 80 to 100 cm below the soil surface, summer temperatures were substantially higher in the poorly shaded, constructed wetland. At the two sites with high water-table levels throughout the year, percent clay and silt, levels of organic C and N, and cation exchange capacity were significantly greater ($p < 0.05$) in the reference wetlands. At the drier site, only 3 of the 16 soil parameters compared were significantly different. In this limited study, observed differences in soil and other environmental conditions between paired wetlands suggest that constructed wetlands may not function in the same capacity as adjacent reference wetlands.

Key Words: wetland mitigation sites, hydric soils, reference wetlands

INTRODUCTION

Wetlands are being disturbed and destroyed daily by the practices of road building, urban and rural development, agriculture, and surface mining (Tiner 1984, Salvesen 1990). Over 50% of the pre-settlement wetlands in the U.S. have been lost to such activity (Tiner 1984, Dahl 1990). In order to compensate for those wetlands now being lost or disturbed, many of the permits issued under the Clean Water Act (P.L. 95–217) that allow for the filling or draining of wetlands are accompanied by mandates to create or restore wetlands. Such wetlands are often called mitigation sites.

Restoration of a wetland for mitigation is much easier than the creation of a new wetland because of the difficulty in establishing the necessary hydrology in created wetlands (Kusler 1990). Most of the created wetland mitigation sites have been established in estuarine areas along the coast of the eastern U.S. (Shisler 1989). These wetlands have a flat landscape and a fairly simple hydrology; the vegetation is dominated by only a few species (Kusler and Kentula 1989). In contrast, most freshwater systems are very complex and difficult to replicate (D'Avanzo 1987, Zedler 1987, Kusler 1990). The Florida Department of Environmental Regulation (1991) reported that of the 34 permits issued for creation of freshwater mitigation wetlands, only two were successful in meeting all of the permit requirements. Both forested and herbaceous mitigation wetlands were equally difficult to create. In Washington State, permitting created wetlands for mitigation purposes resulted in a net wetland loss of 33% (Kunz et al. 1988). Failures were attributed primarily to unsuitable wetland hydrology and associated topography, which in turn resulted in a lack of hydric soil development and establishment of upland plant species (Kunz et al.1988, Florida Department of Environmental Regulation 1991).

In order to evaluate the success of a wetland mitigation project, we must ask whether the constructed site functions as a ''natural wetland'' (D'Avanzo 1987, Larson 1987, Kusler and Kentula 1989, Confer and Niering 1992, Malakoff 1998) One approach to answering this question is to use a reference wetland for setting creation or restoration goals (D'Avanzo 1989, White et al. 1990, Florida Department of Environmental Regulation 1991, Kentula et al. 1992, Brinson 1993, Brinson and Rheinhardt 1996, Wilson and Mitsch 1996, Ashworth 1997). Reference wetlands are natural ecosystems that are usually adjacent to the wetlands being created. The reference wetland vegetation is the long-term ecosystem target of the created wetland.

Soils are the physical foundation of every wetland ecosystem. Plants and animals alike are dependent upon the hydric soil for many vital resources. An integration of the hydric soils with the plant and animal communities provides the structure for the many functions we associate with wetland ecosystems (Brinson 1993, Mitsch and Goselink 1993, Brinson and Rheinhardt 1996). Many of these functions, such as traps for sediment, sinks for various non-point source pollutants, and zones for denitrification of nitrate-laden ground water, are difficult to directly measure. In the place of direct measurements, soil and landscape properties can be recorded and then related to the potential of the wetland to function in one or more of these capacities (Maltby 1987, FICWD 1989, Kentula et al. 1992). Soil properties, such as the degree of stratification, the presence of redoximorphic features, and organic matter distribution, reflect the wetland environment (Fanning and Fanning 1989) and are often used to examine and compare wetlands (Environmental Laboratory 1987, Maltby 1987, Bishel-Machung et al. 1996). Because soil properties such as texture and organic matter content affect hydrology, Hunt et al. (1999) suggest that comparisons of the physical conditions of natural and constructed wetlands be evaluated prior to analysis of the hydrologic and vegetative parameters. This paper presents results from our study of three constructed wetlands and their adjacent natural counterparts (reference wetlands). The objectives of this study were to (i) compare the topography and hydrology of constructed and reference wetlands, (ii) document soil environmental parameters such as temperature and redox potential in paired constructed and reference wetlands, and (iii) examine differences in soil properties between paired wetlands. The underlying assumption was that if topography, hydrology, soil properties, and environmental conditions were found to be similar between the paired wetland types, the constructed wetland would likely function in a manner similar to the associated reference wetland.

MATERIALS AND METHODS

Constructed wetlands were examined across Virginia, USA in order to find representative sites for detailed study. Three sites were chosen, each with an adjacent natural wetland for reference and comparative purposes. Relative elevations were determined along transects at each site using a rod and level within a representative 0.25- to 0.35-ha area. Transects were spaced 10 m apart, and elevations were recorded every 10 m along the transect. Three wells, screened between 30 and 150 cm, were installed within each of the reference and constructed wetlands to monitor water-table levels. Wells were randomly located in the wetlands. Wells were installed in auger holes and backfilled with coarse sand. At the soil surface, the wells were encased in cement to keep them in place and to ensure that surface water did not enter around the edge. Water levels were measured each month for a year using a voltmeter water-table gauge. Data reported for water-table depths were calculated by averaging the water-table levels of the three wells in each wetland. At the depths of 10, 45, and 95 cm, three thermocouples and three Pt electrodes were installed at each depth around selected wells. The Pt electrodes (with welded junctions) were constructed and monitored following the procedures described by Faulkner et al. (1989). A calomel reference electrode was used in the field for redox measurements. Redox data were corrected for the standard electrode by adding +244 mV to the measurements. Potentials are reported within oxidized (>400 mV), moderately reduced (100 to 400 mV), and reduced (< 100 mV) fields (Patrick and Mahapatra 1968). Soil redox potential and temperature were measured monthly for 8 and 9 months, respectively. Data reported for redox potential and soil temperature are means calculated from the readings collected from the three redox and temperature probes in each of the wetlands.

Soils were sampled in 1995 using a bucket auger and described using standard methods (Soil Survey Staff 1993). Samples were collected at depths of 5–15, 40–50, and 90–100 cm at 9 locations within both reference and constructed wetlands. At each location, three samples were collected from each depth to form a composite sample for that depth. Samples were returned to the lab, dried, ground, and passed through a 2-mm-mesh sieve prior to analysis. Samples having considerable organic matter were pre-treated with hydrogen peroxide to remove organic matter prior to particle-size analysis. Sand fractions were determined af-

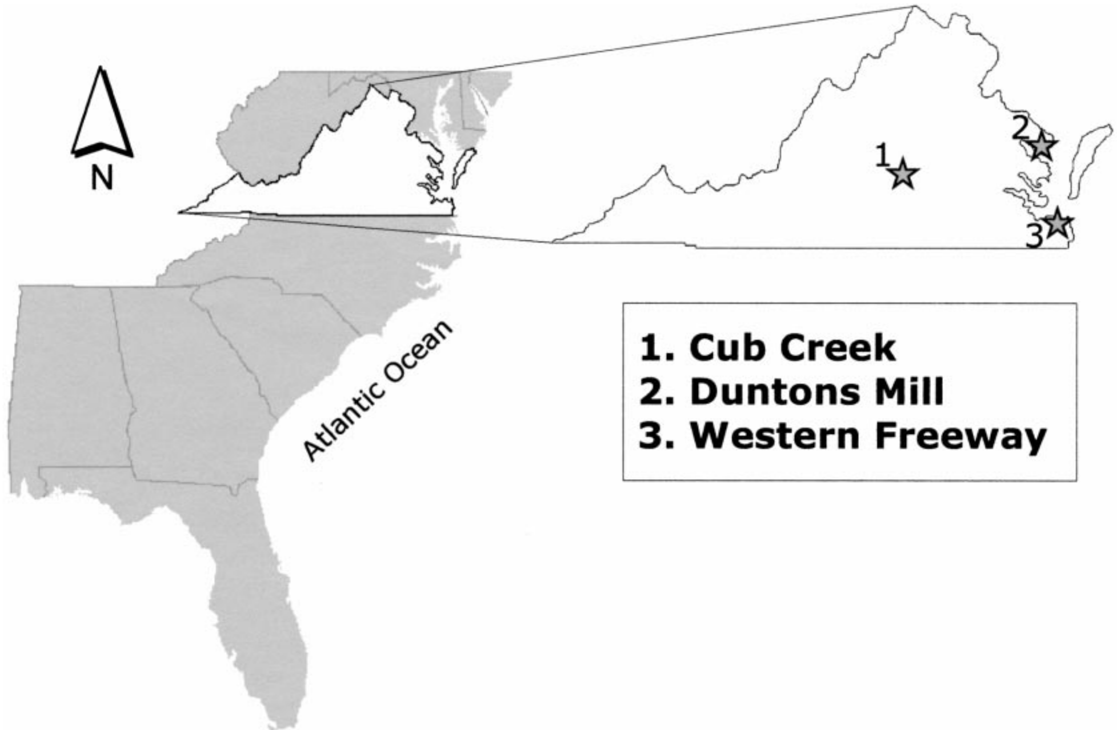

Figure 1. Location of paired constructed and reference wetlands in Virginia.

ter mechanical sieving. Percent silt and clay were determined by pipette (Gee and Bauder 1986). Organic carbon was determined by dry combustion (Rabenhorst 1988). Total Kjeldahl nitrogen (TKN) was determined after digestion using the colorimetric method described by Mulvaney (1996). Soil pH was determined at a 1:1 soil-to-water ratio. Samples were analyzed for extractable bases and exchangeable acidity (Rhoades 1982, Thomas 1982). Cation exchange capacity (CEC) was determined by summing the bases and the acidity. Statistical comparisons of soil parameters between the constructed and reference wetlands were made using a two-tailed t-test (Zar 1984).

Study Site Descriptions

Three types of reference wetlands were examined: Forested Piedmont, Forested Coastal Plain, and Scrub-Shrub Coastal Plain. Mitigation wetlands were constructed to match the reference wetland vegetation at maturity (i.e., forest for forest). Cub Creek is the forested site in the Piedmont (Figure 1, Table 1). This floodplain wetland is located directly adjacent to a third order stream. In relation to the other 2 sites, Cub Creek is in a relatively high-energy depositional environment. The reference wetland is directly across the stream from the constructed wetland. Hydrology is

Table 1. Reference soil types, wetland types, water sources, water regimes, and locations of the three paired reference-constructed wetlands.

Site	Location	Reference Soil Types	Wetland Type +	Water Sources	Water Regime
Cub Creek	Piedmont	Udifluvents and Dystrudepts	Forested	Flooding and ground water	Temporarily Flooded*
Western Freeway	Coastal Plain	Humaquepts	Forested	Ground water and flooding	Seasonally Saturated#
Duntons Mill	Coastal Plain	Fluvaquents and Endoaquepts	Scrub-shrub	Ground water	Saturated*

+ Wetland type based on the classification of Cowardin et al. (1979).
* Water regime based on the classification of Cowardin et al. (1979).
# Water regime based on the classification of Golet et al. (1993).

governed by surface (flooding) and ground-water sources. The mitigation wetland was constructed in 1988 by down-cutting 0.5 hectares of the upland to the elevation of the mean high water level in Cub Creek. In addition, a small ditch was dug from the stream into the wetland to focus floodwaters into the created wetland. The edge of the constructed wetland was 10 m from the banks of Cub Creek. Willow oak (*Quercus phellos* L.), red-osier dogwood *(Cornus stolonifera* Michx.), river birch (*Betula nigra* L.), speckled alder (*Alnus rugosa* Du Roi), switchgrass (*Panicum virgatum* L.), and three-square (*Scirpus pungens* Vahl) were planted at the end of construction. Predominant vegetation in the reference wetland was red maple (*Acer rubrum* L.), sycamore (*Platanus occidentalis* L.), sweet gum (*Liquidambar styraciflua* L.), sweetpepper bush (*Clethra alnifolia* L.), poison ivy (*Toxicodendron radicans* L.), and greenbriar (*Smilax rotundifolia* L.).

Western Freeway is the forested site in the Coastal Plain (Figure 1, Table 1). This site is located adjacent to second order stream and, compared to the other two sites, is in a relatively moderate energy depositional environment. The stream separates the reference wetland from the constructed wetland. Hydrology is mostly governed by ground water, but surface water is added occasionally during flooding. The wetland was created in 1991 by downcutting 0.8 ha of the upland to the level of the predicted high water table. The constructed wetland was treated with 30 cm of topsoil, seeded with a grass mix (various species), and planted with black gum (*Nyssa sylvatica* Marshall), river birch, red maple, sweet gum, bayberry (*Myrica sp.*), and buttonbush (*Cephalanthus occidentalis* L.). Vegetation in the reference wetland was dominated by red maple, sweet gum, willow oak, sweetbay magnolia (*Magnolia virginiana* L.), sweet pepperbush, lizards tail (*Saururus cernuus* L.), and false nettle (*Boehmeria cylindrica* L.).

In the Duntons Mill reference wetland, woody shrubs, such as hazel alder (*Alnus serrulata* Ait.), buttonbush, and silky willow (*Salix sericea* Marsh.) are very common (40% cover). Herbaceous plants are the predominant understory species and consist primarily of sensitive fern (*Onoclea sensibilis* L.), arrow arum (*Peltandra virginica* L.), smartweed (*Polygonum hydropiper* L.), and soft rush (*Juncus effusus* L.). This site is located on the Coastal Plain and is adjacent to an old mill pond (Table 1). Ground water is the primary source controlling the hydrology. The mitigation wetland was constructed in 1991 by down-cutting 0.4 ha of the upland to the level of the predicted high water table. The constructed wetland is directly adjacent to the reference wetland. The constructed wetland was planted in buttonbush, elderberry (*Sambucus canandensis* L.), woolgrass (*Scirpus cyperinus* L.), rice cutgrass (*Leersia oryzoidea* L.), and switchgrass after adding 15 cm of topsoil.

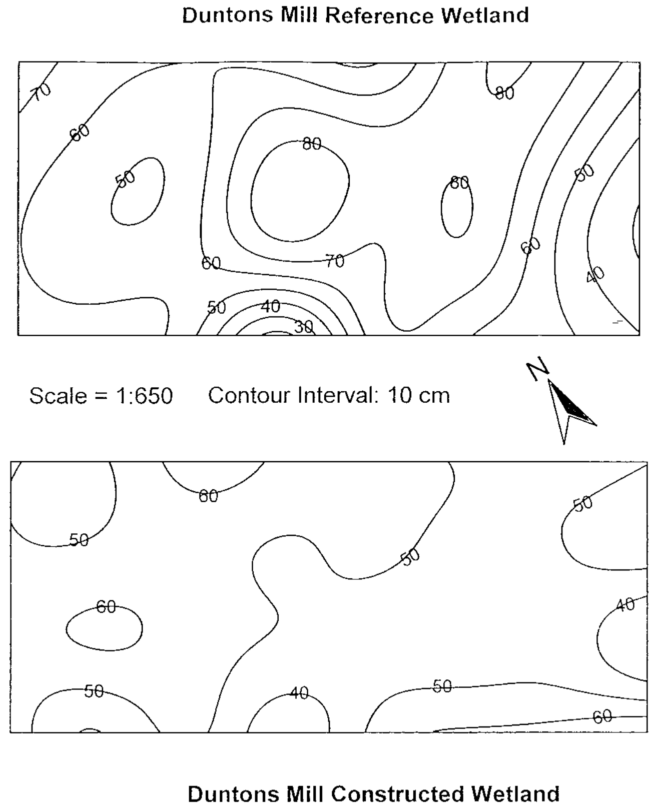

Figure 2. Contour map of the Duntons Mill constructed and reference wetlands.

RESULTS AND DISCUSSION

Topography

Wetlands are generally characterized by low relief. The difference between highest and lowest elevations in each of the wetland sites was less than 1.2 m. The constructed wetlands had 40 to 60% less of an elevation change across the entire area than the reference wetlands. In addition, microrelief was much greater in the reference wetlands (Figure 2). In the reference wetlands, processes such as tree-throw, animal burrowing and building, channeling during flooding, and sediment deposition and erosion, have resulted in varied topography but low relief. Microrelief helps establish biodiversity in wetlands by providing adjacent low and high areas of habitat for various plants and animals (Golet et al. 1993). Soil properties, such as nutrients levels (Paratley and Fahey 1986), pH (Beatty 1984), and aeration (Huenneke 1982), may all be affected by subtle changes in relief.

Constructed wetlands were created by cutting and scraping with heavy machinery, leaving a flat surface

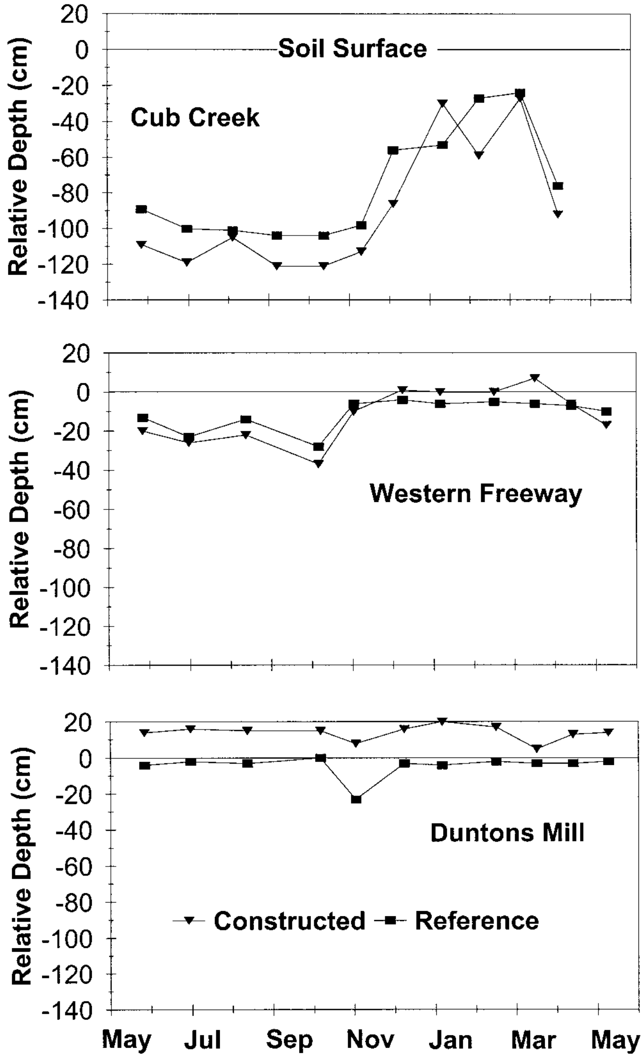

Figure 3. Relative water-table level and fluctuations in the paired constructed and reference wetlands. Data were collected from May 1994 to May 1995.

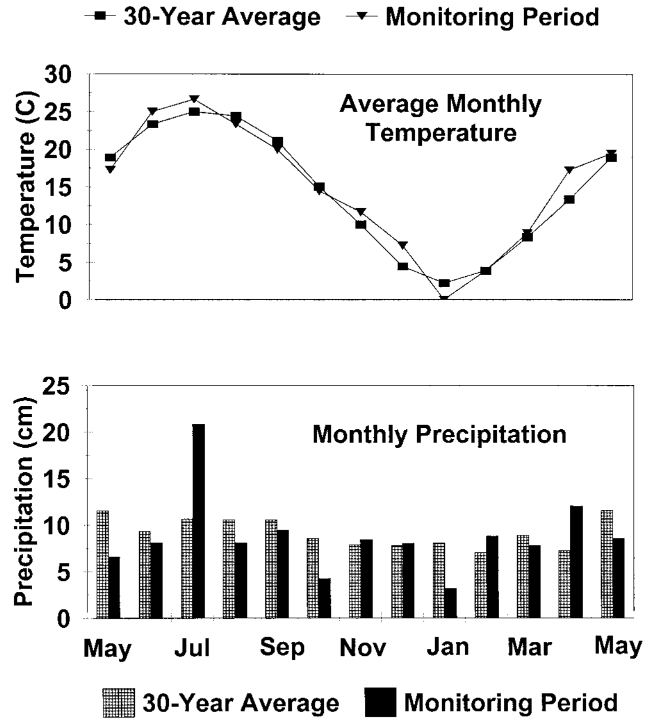

Figure 4. Average monthly temperature and total monthly precipitation for May 1994 to May 1995 (monitoring period), and 30-year averages for the Warsaw Virginia weather station (10 km from the Duntons Mill site).

with little microrelief. With time, natural cutting and depositional processes, as well as plant and animal activity, will add relief to the topography of the constructed wetlands.

Water-Table Levels

Water-table levels and hydroperiod often control the function and structure of a wetland by affecting aerobic conditions, nutrient cycling and dynamics, microbial populations, plant composition, and soil chemistry (Entry et al. 1995). Constructed and reference wetlands showed similar water-table fluctuations during the year (Figure 3). Forested sites, Cub Creek and Western Freeway, showed similar seasonal fluctuations. Water tables were highest from November through March in response to decreases in evapotranspiration. Total precipitation for the month of July was more than 10 cm above the 30-year normal (Figure 4). A response in the water tables to the excess precipitation can be observed in the August readings for the mitigation site at Cub Creek and both reference and mitigation sites at Western Freeway (Figure 3). Monthly precipitation totals for the remainder of the monitoring period were within 5 cm of the 30-year average, suggesting that the water tables observed are representative of a normal year.

The greatest differences between seasonal high and low water tables occurred in Cub Creek (Figure 3). The difference was on the order of 80 to 100 cm, excluding periods of flooding. Water levels only reached the soil surface in the Cub Creek reference and constructed wetlands during periods of flooding. These periods are not recorded on the graph, but levels 45 to 60 cm above the surface were observed on several days other than the monthly readings. Except for the January and March readings, water-table depths in the reference wetland at Cub Creek were consistently higher than in the constructed wetland, which is on the opposite stream bank. The average difference from June through December was 18 cm. Therefore, downcutting the upland to an elevation even with the opposite stream bank is not necessarily going to provide the proper elevation to establish a similar water-table level.

Soil, vegetation, landscape, and hydrologic factors may explain the differences in water-table levels between the Cub Creek reference and constructed wetlands. One side of Cub Creek may have a higher ground-water head and thus higher water-table levels. Another possibility is that depth to bedrock or similar restrictive zones in the soil may be much less in parts of the adjacent upland; thus, increased subsurface water flow above the restrictive zone may elevate water-table levels on the reference side of the adjacent wetlands. Woody vegetation in the Cub Creek constructed wetland is still in its infancy compared to the adjacent mature forested reference wetland. Lockaby et al. (1994) found that wetlands with vegetation limited because of logging and tree harvest had significantly lower water-table levels compared to an adjacent natural forested wetland. These researchers concluded that elevated surface temperatures and increased evaporation may be the most important factors in lowering the water-table levels. Differences in soil texture between reference and mitigation wetlands may also affect water-table levels by controlling the hydrologic response to additions and losses of water (Hunt et al. 1999). Textural classes for horizons below 50 cm in a typical reference wetland pedon at Cub Creek are sand and sandy clay loam (Table 2). At this depth in the constructed wetland, the textural class is sandy loam. Average clay contents for nine samples collected from 40- to 50-cm depths in the constructed wetland at Cub Creek were significantly greater than in the reference wetland for the same depth (Table 3). These data support the possibility that water-table differences between paired wetlands could be related to different soil particle-size distributions. With all of these factors affecting the wetland hydrologic patterns, it is understandable why establishing hydrology in a constructed wetland is often the most difficult task for a wetland scientist.

Mean water-table levels in Western Freeway were within 10 cm of the soil surface from November through April (Figure 3). The maximum differentials between seasonal high and low water levels in both reference and constructed wetlands were less than 45 cm, indicating a water table that is rather stable. Water tables that are stable are primarily influenced by ground-water discharge (Hunt et al. 1999), suggesting that water levels in both the constructed and reference wetlands at Western Freeway are strongly governed by ground water. From May through October, reference water-table levels were consistently higher than in the constructed wetland. During the remainder of the year, the opposite occurs. On average, the difference between monthly readings was only 6 cm, indicating that the hydrology of the reference wetland is very similar to the constructed. Therefore, in the case of Western Freeway, using the predicted high water-table level in the soil to design the elevation of the constructed wetland seems to be a successful approach.

Water-table levels were mostly at or near the surface throughout the year in both reference and constructed wetlands at Duntons Mill (Figure 3). Month-to-month readings for both the reference and constructed wetlands varied little more than 10 cm. The notable exception was the drawdown that was observed in November when the reference water-table levels dropped over 20 cm, only to rebound the next month. The constructed wetland water-table levels were consistently above the soil surface and higher than the water tables of the reference wetland. Confer and Niering (1992) found that in 4 of the 5 paired (reference-constructed) emergent wetlands they examined in Connecticut, the surface was ponded longer and the level of the water table was higher in the constructed wetland. These researchers attributed the differences in water-table levels to different sources of water for the paired wetlands. The constructed and reference wetlands at Duntons Mill share a boundary and likely have a similar water source. In order to construct the mitigation wetland, the upland was cut to the expected mean water-table level. The average surface elevation in the constructed wetland is 18 cm lower than the reference. This lower elevation is most likely the reason water-table levels are higher in the constructed wetland. Having continuously ponded conditions at the constructed wetland may make it difficult to establish and maintain the same vegetation that occurs in the reference wetland at Duntons Mill.

Soil Temperature

Similar changes in soil temperature due to seasonal effects were observed in the reference and constructed wetlands for all of the sites (Figure 5). Average monthly air temperatures during the monitoring period were very similar to the 30-year monthly average (Figure 4); thus, the soil temperatures observed were likely representative of an average year. Soil temperatures at 10 cm were higher than those at 95 cm during the warmer months (August, September, April, May, and June) and lower during the winter. During most of the fall and parts of early spring, temperatures at each depth were about equal for the reference and constructed wetlands. Changes in temperature between sampling dates were quite drastic for the 10-cm depth and rather uniform for the 95-cm depth. For example, at Duntons Mill, the temperature at 10 cm dropped 7^0 C between the December and January readings, while at 95 cm this drop was only 2 to 3^0 C.

Table 2. Profile descriptions and subgroup classification of typical reference and constructed wetland soils.

Horizon	Depth (cm)	Color	Texture	Roots	Notes
			Cub Creek Reference (Oxyaquic Dystrudept)		
C	0–10	10YR 6/2	sand	—	recent overwash
A1	10–19	10YR 3/3	sandy loam	many fine and medium	—
Bw	19–50	10YR 4/4	loam	common fine and medium	—
C1	50–75	10YR 6/3	sand	few fine	common 10YR 4/6 Fe concentrations
C2	75–110+	10YR 4/6	sandy clay loam	—	many strong brown (7.5YR 5/6) Fe concentrations and many grayish brown (2.5Y 5/2) Fe depletions
			Cub Creek Mitigation (Aeric Endoaquent)		
A	0–17	10YR 4/4	sandy loam	many fine and few medium	—
C1	17–50	7.5YR 5/6	loam	few fine	few pinkish gray (7.5Y5 6/2) Fe depletions
C2	50–100+	7.5YR 5/6	sandy loam	—	common light gray (10YR 6/2) Fe depletions
			Western Freeway Reference (Fluvaquentic Humaquept)		
Oa	0–5	7.5YR 3/2	—	many fine, medium and coarse	some mixing of overwash
A1	5–15	10YR 3/2	mucky loam	many fine and medium	—
A2	15–40	10YR 3/2	sandy loam	common fine and medium	—
A3	40–60	10YR 4/2	sandy loam	common fine and few medium	—
C	60–80	10YR 6/3	loamy sand	few fine	—
2Ab	80–90	10YR 3/2	sandy loam	common fine	—
2C	90–120+	10YR 5/3	loamy sand	—	fluid
			Western Freeway Mitigation (Aeric Humaquept)		
A	0–40	2.5Y 3/2	sandy loam	many fine and few medium	some overwash at the surface
2C1	40–100	2.5Y 6/4	sandy clay loam	—	common gray (5Y 5/1) and strong brown (7.5YR 5/8) redoximorphic features
2C2	100–120+	2.5Y 6/4	sand	—	common gray (2.5Y 6/2) and strong brown (7.5YR 5/8) redoximorphic features
			Duntons Mill Reference (Typic Fluvaquent)		
Oa	0–5	5YR 3/2	—	many fine, medium and coarse	—
A1	5–15	10YR 2/2	mucky loam	many fine and medium	—
A2	15–25	10YR 4/2	loam	common fine and medium	—
Cg	25–70	5Y 4/1	loam	few fine	few fine brownish yellow (10YR 6/6) Fe concentrations
2Ab	70–110+	10YR 2/2	sandy loam	—	—
			Duntons Mill Mitigation (Aeric Endoaquent)		
A	0–15	2.5Y 4/2	sandy loam	many fine and few medium	—
2C1	15–45	10YR 6/6	sandy clay loam	few fine	common light gray (5Y 7/2) Fe depletions
2C2	45–100+	10YR 6/6	sandy loam	—	common light gray (5Y 7/2) Fe depletions

Factors such as water-table depth and the type and presence of vegetation can affect soil temperatures (Ghildyal and Tripathi 1987). Soil temperature at 10 cm was consistently 3 to 6^0 C warmer in the Cub Creek constructed wetland during the late summer and early spring than in the reference wetland (Figure 5). Elevated temperatures in the constructed wetland were also evident at the 95-cm depth in August, September, and October. Aust and Lea (1991) found that wetlands disturbed from logging and tree harvest had higher soil temperatures than adjacent forested wetlands. Hunt et al. (1999) reported elevated temperatures in 2-year-old constructed wetlands when compared to adjacent shrub/sedge meadow and forested riparian reference wetlands in Wisconsin. Both of these studies concluded that the elevated temperatures were the result of

Table 3. Means for selected physical and chemical soil properties. Ranges appear in parenthesis. Statistical comparisons were made between constructed and reference means for the same depths using a two-tailed t test (n = 9). Means with a different letter are significantly different at the 0.05 level.

Site	CEC# cmol kg^{-1}	BS* %	pH	C g kg^{-1}	N g kg^{-1}	Sand %	Silt %	Clay %
Cub Creek 5–15 cm depth								
Constructed	15a	40a	5.9a	14a	1.6a	41a	38a	21a
	(9–20)	(21–70)	(5.4–6.8)	(8–22)	(1.1–2.0)	(33–53)	(29–44)	(17–25)
Reference	15a	36a	5.6b	14a	1.6a	44a	34a	23a
	(7–25)	(21–50)	(5.3–5.9)	(7–22)	(0.6–2.6)	(7–86)	(9–55)	(1–55)
Cub Creek 40–50 cm depth								
Constructed	12a	23a	5.6a	4a	0.9a	41a	29a	30a
	(10–16)	(12–43)	(5.2–5.8)	(2–9)	(0.6–1.3)	(32–49)	(23–36)	(25–35)
Reference	11a	38b	5.6a	5a	0.9a	53a	27a	19b
	(5–22)	(16–50)	(5.2–5.9)	(2–10)	(0.2–1.6)	(4–93)	(6–49)	(1–47)
Western Freeway 5–15 cm depth								
Constructed	11a	65a	6.9a	10a	0.9a	79a	14a	6a
	(7–16)	(33–90)	(6.0–7.5)	(7–17)	(0.7–1.2)	(77–83)	(11–16)	(4–9)
Reference	36b	38b	5.5b	63b	4.4b	28b	46b	26b
	(21–53)	(21–49)	(4.9–5.9)	(20–96)	(1.4–6.5)	(4–71)	(24–61)	(5–39)
Western Freeway 40–50 cm depth								
Constructed	9a	47a	6.1a	4a	0.7a	73a	16a	12a
	(6–13)	(29–100)	(5.1–7.4)	(7–10)	(0.3–1.4)	(66–82)	(13–18)	(6–19)
Reference	37b	44a	5.1b	59b	4.1b	23b	51b	26b
	(17–53)	(26–51)	(4.6–5.9)	(13–89)	(0.9–5.8)	(3–69)	(23–64)	(9–38)
Duntons Mill 5–15 cm depth								
Constructed	6a	39a	5.5a	4a	0.3a	88a	7a	5a
	(3–9)	(10–73)	(5.5–5.7)	(1–16)	(0.2–0.6)	(82–96)	(2–11)	(1–13)
Reference	18b	13b	5.0b	36b	2.5b	34b	49b	17b
	(11–53)	(6–29)	(4.4–5.6)	(14–154)	(1.1–9.5)	(11–68)	(19–73)	(10–23)
Duntons Mill 40–50 cm depth								
Constructed	7a	38a	5.5a	1a	0.2a	82a	8a	10a
	(1–12)	(10–58)	(5.3–5.6)	(1–2)	(0.2–0.3)	(75–93)	(5–11)	(1–17)
Reference	10a	14b	4.8b	14b	1.0b	42b	43b	15a
	(2–22)	(7–35)	(4.5–5.0)	(3–38)	(0.2–2.2)	(9–89)	(7–72)	(3–26)

CEC = cation exchange capacity.
* BS = base saturation.

minimal shading in the disturbed or constructed wetlands. In a similar manner, mature trees shade the Cub Creek reference wetland and prohibit the higher temperatures recorded in the constructed wetland. Trees may also moderate low temperatures, and thus, the forested wetland will have a higher average winter temperature (Figure 5).

Soil saturation can also buffer temperature increases (Buol and Rebertus 1988, Aust and Lea 1991). In Cub Creek, however, the water-table level is always below 10 cm (Figure 3). Water tables were also below 95 cm during the late summer and early fall. Elevated summer temperatures in the constructed wetlands should increase rates of physical, chemical, and biological processes such as evaporation, organic matter decomposition, and oxidation-reduction (Patric 1980, Hillel 1982, Taylor and Jackson 1986, Trettin et al. 1996). How long the elevated temperatures in the constructed wetland will exist is unknown. Patric (1980) reported that elevated temperatures will return to normal in riparian deforested wetlands in as little as five years as a result of tree growth and the consequent shading. The temperature effects related to the openness of the Cub Creek constructed wetland should dissipate when the planted trees begin to shade the soil in the summer and add insulation in the winter.

Soil temperatures at the 10-cm depth in the reference wetland at Western Freeway were similar or slightly higher than those in the adjacent constructed wetland during most of the year (Figure 5). Temperatures in the reference wetland were noticeably higher from November through March at the 95-cm

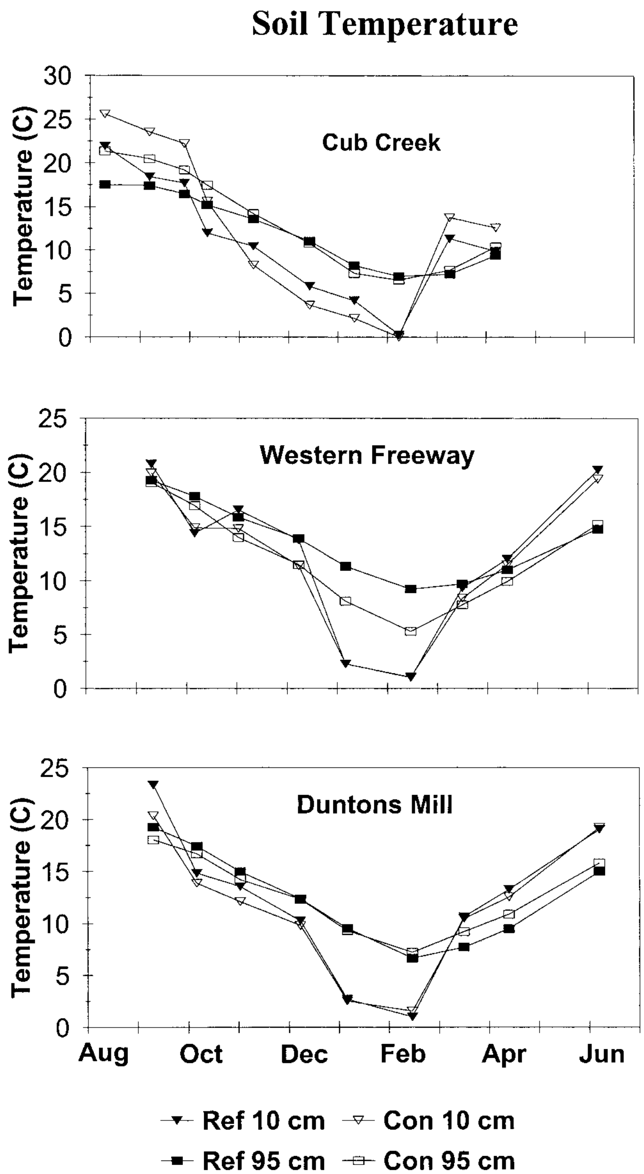

Figure 5. Soil temperatures at 10-cm and 95-cm depths for the paired constructed and reference wetlands. Data were collected in 1994 and 1995.

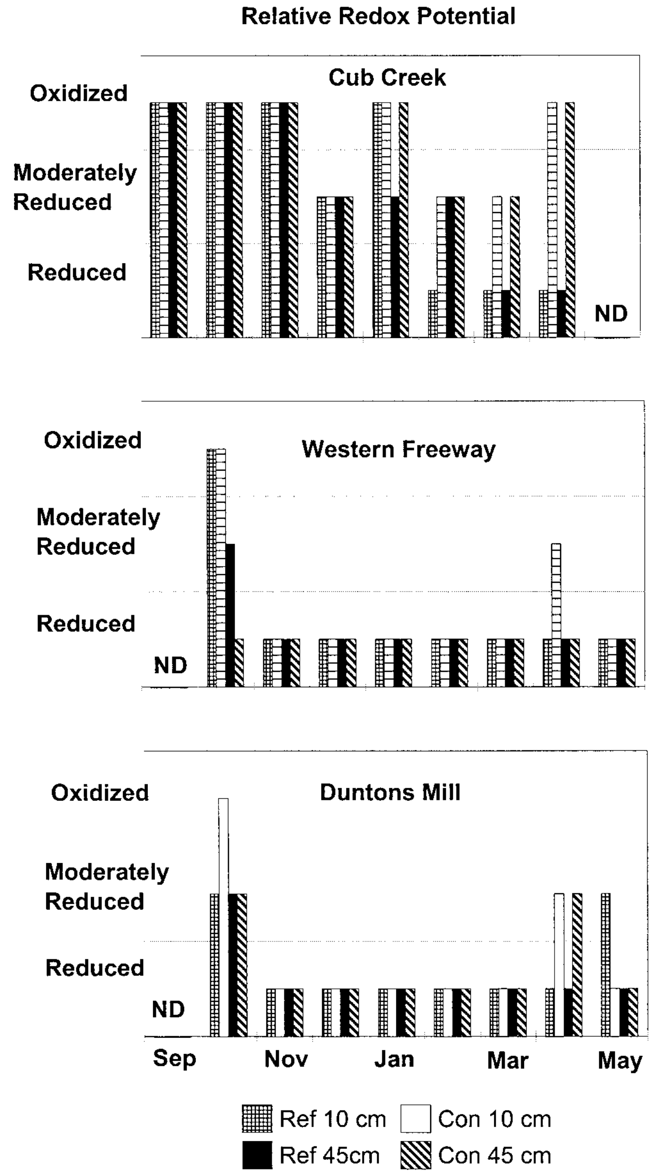

Figure 6. Relative redox potential at 10-cm and 45-cm depths for the paired constructed and reference wetlands. Redox fields follow those described by Patrick and Mahapatra (1968): oxidized (>400 mV), moderately reduced (100 to 400 mV), and reduced (< 100 mV). Data were collected in 1994 and 1995 (ND=not determined)

depth compared to the constructed wetland at the same depth. These trends occurred even though the reference wetland was well-shaded with trees, the constructed wetland trees were still in their infancy, and the water-table levels during the summer and fall months were higher in the reference wetland. One explanation may be that the reference wetland is receiving ground water from a different source than the constructed wetland, which is across the stream.

Similar soil temperatures were recorded in the reference and constructed wetlands at the 10- and 95-cm depths in Duntons Mill (Figure 5). There may be a several reasons why differences do not exist between the two wetlands. Water levels are mostly static throughout the year and the wetlands are directly adjacent to each other. Therefore, the water source likely does not change between the two wetlands. Another explanation may be that the soils rarely, if ever, become dry because the water table in both wetlands is close to or above the soil surface. In addition, the vegetation in both reference and constructed wetlands is predominately herbaceous species and shrubs, so minimal shading occurs in either of the wetlands.

Redox Potential

Redox potential ranged from oxidizing to reducing in all of the wetlands (Figure 6). In general, similar trends were observed between reference and constructed wetlands. Relationships between water-table position and redox potential were evident through most of the year. At Cub Creek, oxidizing conditions prevailed during the summer and fall as the water tables in both reference and constructed wetlands remained more than 90 cm below the soil surface (Figure 3). As the water table rose during December, moderately reducing conditions became established (Figure 6). Moderately reducing and reducing conditions were recorded throughout most of the winter and, for the most part, followed the expected trend as the water tables rose to within 20 cm of the soil surface. The redox data, however, showed some variability during the winter and spring. For example, at the 10-cm depth in the reference wetland, redox potentials ranged from oxidizing to reducing even though the water table never reached this depth during the monitoring period. One explanation may be that water-table measurements do not include the capillary fringe (Hunt et al. 1999), which could induce reducing conditions when present. Another explanation is that redox potentials are measurements representing a microsite in the soil. The microsite is probably about the size of the 5 mm Pt wire that is exposed at the end of the electrode. Measurements of redox potential were made in triplicate to minimize microsite effects. More replications may have reduced the variability encountered. However, if the general trend is focused on through the winter, the redox data suggest that reference and mitigation wetlands were reduced or moderately reduced during this period. Water-table levels fell below 45 cm in April. Consequently, April redox potentials indicated oxidizing conditions in the constructed wetland. The reference wetland, however, was not as fast to respond to the dropping water-table levels and continued to show reducing conditions.

Redox potential for the constructed and reference wetlands at Western Freeway showed similar trends during the year (Figure 6). Oxidizing conditions were pronounced at 10 cm in October when the water tables were at their lowest levels of the year (Figure 3). During the late fall, winter, and spring, water-table levels were at or within 10 cm of the soil surface and redox potentials indicated reducing to moderately reducing conditions in both constructed and reference wetlands. At Duntons Mill, water-table levels were near (reference) or above (mitigation) the surface during the year (Figure 3), and redox potentials indicated reducing to moderately reducing conditions in both constructed and reference wetlands between November and May (Figure 6).

Soil Properties

Soil properties, such as water-holding capacity, permeability, cation exchange capacity, and porosity, are mostly controlled by particle-size distribution (Hillel 1982, Brady 1990). Sand, silt, and clay distributions showed considerable differences between constructed and reference wetlands at each of the depths sampled in Western Freeway and Duntons Mill (Table 3). The differences between means were significant (at the 0.05 level) for all of the Western Freeway and for nearly all Duntons Mill fractions at each depth. Both Western Freeway and Duntons Mill constructed wetlands have significantly more sand compared to the reference wetland. Soils composed primarily of sand-sized particles generally have lower water-holding and exchange capacities, and have a higher permeability and porosity, than soil composed of fine particles (Hillel 1982, Brady 1990). For that reason, constructed wetlands may not function in the same capacity or support the same vegetation as the reference counterparts.

Variability in the particle-size fractions of the reference wetlands was much more pronounced than in the associated constructed wetlands (Table 3). For example, in Cub Creek, the range in sand contents for the 9 values used to calculate the 5–15 cm mean for the reference wetland was from 7% to 86%. In the constructed wetland, the range for the 5–15 cm depth was only 33% to 53%. Similar large dispersions occur for each site and particle-size fraction. The variability in particle sizes in the reference wetlands can be attributed to the transitory depositional environment in the alluvial wetlands and the nature of the parent material. In the alluvial setting, soils are poorly developed and commonly have buried horizons, stratification, or overwash sediments marking different periods of flooding and deposition (Table 2). Natural floodplains commonly have considerable microrelief, and the areas higher in elevation generally have coarser textured soil materials compared to the adjacent lower areas. The basic relief of the constructed wetlands tends to be fairly flat (Figure 1) because the upland was cut down by machinery to create the desired wetland hydrology.

Soils of constructed wetlands have a simple A-C horizon sequence (Table 2). Roots in the constructed sites are limited to the upper 50 cm and, except for a few fine roots, are generally confined to the upper 25 cm. The constructed wetland soils classify into the Aeric subgroup level (Soil Survey Staff 1998), indicating that subsoil horizons have matrix color with a high chroma (3 or more) even though the soil horizons are saturated for much or all of the year. The high chroma colors reflect the parent materials that are exposed to the surface and near-surface after the upland soil was cut down to create the wetland. Particle-size distributions are also controlled, for the most part, by the subsoil materials that were exposed during the creation of the wetland. These soils show minimal effects of either depositional or erosional processes. Parent materials for the upland soils at Duntons Mill and Western Freeway are coastal plain sediments that tend to be dominated by sand-sized particles. Loamy terrace deposits are the parent material for the upland soils adjacent to Cub Creek.

Significant differences were observed in nine of the 10 soil chemistry comparisons for the Western Freeway and Duntons Mill sites (Table 3). Carbon and N levels were on the order of 5 to 10 times higher in the reference wetlands. Similar results were found for C and N by Bishel-Machung et al. (1996) in a pooled-study of 20 reference and 44 constructed wetlands in Pennsylvania. In a study of constructed and reference wetlands in Oregon, Gwin and Kentula (1990) found higher levels of C in the reference wetlands. Natural wetlands with nearly continuous saturation near the soil surface show limited decomposition of organic matter and, therefore, have elevated C levels. Much of the N in these systems is in the organic form, and consequently, the N levels follow the elevated C levels in the reference wetlands. With time, C and N levels in the constructed wetlands will begin to increase. How long this will take is unknown. In 44 constructed wetlands ranging in age from one to eight years, Bishel-Machung et al. (1996) found that there was no relationship between age of the wetland and organic carbon content.

Base saturation and pH levels were higher in the constructed wetlands, and CEC was higher in the reference counterparts (Table 3). Exchange capacities are directly correlated with clay and organic matter contents. Constructed wetlands in this study had lower organic carbon and clay contents than the reference wetlands, and therefore have a lower CEC. The constructed wetlands were created by cutting the subsoil down to the depth of the predicted high water-table level or to the mean high water level in Cub Creek. The subsoil materials were not exposed to the same level of organic acids and intensity of weathering processes as the natural wetland soils. Therefore, constructed wetland soils have more basic cations, such as Ca and Mg, on their exchange sites and also have a higher pH.

Cub Creek is a much drier site than either Duntons Mill or Western Freeway. Water-table levels reach the surface only during brief periods of flooding, and thus, accumulation of organic matter is limited by high decomposition rates and the constant addition of mineral material as a result of flooding. Levels of C and N, therefore, are very similar between reference and constructed wetlands (Table 3). Clay and organic carbon contents are very similar between reference and constructed wetlands and, consequently, CEC levels follow the same trend.

SUMMARY AND CONCLUSIONS

Mitigation wetlands are created to replace natural wetlands that are lost as a result of human activities. The debate continues on whether created wetlands are similar to natural wetlands in their characteristics, environment, and function. Our study of three constructed-natural wetland pairs indicated that a number of factors contribute to the similarities and differences between constructed and reference wetlands. Microrelief was minimal or absent in the constructed wetlands because these areas were created by cutting and scraping using heavy machinery. Plant and animal diversity may be limited in the beginning of the development of the constructed wetlands because microrelief provides adjacent low and high areas of habitat. With time, natural processes such as erosion, deposition, windthrow, and animal activity should create microrelief within the constructed wetlands.

Soil properties such as percent sand, clay, carbon, or nitrogen are important in the function and health of a constructed wetland. The range in particle-size distribution was much greater in the natural wetlands because of sediment deposition and the variety of depositional energies in an alluvial wetland. In the sites with high water-table levels year round, levels of organic C, N, and CEC were much higher in the reference wetlands. Low levels of carbon in the constructed sites may limit processes such as denitrification. Some plants may be growth-limited in the constructed sites because of the low N levels in the soils. Cation exchange sites in the hydric soils are critical for holding essential plant elements such as Ca, Mg, and K. In addition, exchange sites on soil colloids are important for capturing cationic pollutants that enter the wetlands. Levels of C, N, and CEC in the constructed wetlands should begin to approach those in the reference area as organic matter is added to the wetland floor by the hydrophytic vegetation.

Maintaining proper hydrology is critical in the establishment of constructed wetlands. Two of the sites had considerable differences in water-table depth between the reference and constructed wetlands. These differences occurred because mitigation sites were created by downcutting subsoils to a lower elevation than the corresponding reference wetland and because of inaccurate predictions of the depth of the high water table. Such errors are difficult to remedy once the wetland vegetation is established without disturbing the wetland again. How much these differences will affect the eventual success or failure of the created wetland is uncertain. Water levels that are too high, as is the case for one of the constructed wetlands, will not support the target vegetation. In the other case, the constructed wetland had a water–table level about 18 cm lower level than the reference wetland. For this wetland, where the water-table levels are often 50 cm below the soil surface and major functions are likely wildlife habitat, flood water storage, and sediment trapping, the differences between water-table levels may not be significant.

Seasonal fluctuations in temperature and redox potential were similar in the wetland pairs. Redox potentials in both reference and constructed wetlands indicated moderately reducing to reducing conditions for most of the year, suggesting that important anaerobic processes such as denitrification are possible. Organic carbon is necessary to drive the microbially mitigated denitrification process. Thus, denitrification may be limited at greater depths in constructed sites where C levels are low (<4 g kg^{-1}). In the paired wetlands, where summer ground-water levels were nearly a meter below the surface, summer temperatures were substantially higher in the poorly shaded constructed wetlands. Elevated soil temperatures may increase chemical and biological activity, as well as rates of evaporation. These effects should diminish as the constructed wetland matures and the forest vegetation begins to shade the hydric soils.

Results from this study found considerable differences in soil and other environmental conditions between paired wetlands. Although the conditions examined were not a direct measurement of wetland function, each of the parameters measured served as a proxy for comparing the functionality of the paired wetlands. Our data suggest that constructed wetlands examined in this study may not function in the same capacity as adjacent reference wetlands.

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