ONTOGENY OF ACCIDENTAL WETLANDS AND HYDRIC SOIL DEVELOPMENT IN SURFACE MINED LANDSCAPES

by

Robert B. Atkinson, W. Lee Daniels, and John Cairns, Jr.

Abstract. Reducing conditions are periodically present in hydric soils and are essential for chemical processes that support wetland functions and values. Indicators of these conditions, i.e., redoximorphic features, can be useful in determining the presence of a hydric soil. However, young wetlands, i.e., those recently formed, may not possess reducing conditions and/or may not exhibit redoximorphic features. Few studies have addressed the time needed for hydric soil development. In this study, we present data on redoximorphic features, including chroma and oxidized rhizospheres, gathered from two sets of wetlands in southwestern Virginia, including (1) constructed wetlands that are 3 years old and (2) accidental wetlands that are 10 to 30 years old. Under conditions described for these sites, there is strong evidence that discernable redoximorphic features form in accidental wetlands within 10 years, but not within 3 years in constructed wetlands. Since accidental wetlands have been in existence for longer than most man-made wetlands, they provide clues to the development of hydric soils in recently constructed wetland systems.

Additional Key Words: litter, hydrophytic vegetation, redoximorphic features, sedimentation, SMCRA, wetlands.

Introduction

Small depressions that formed accidentally following contour surface mining in southwestern Virginia may meet all three criteria to be considered wetlands, according to the Corps of Engineers Wetlands Delineation Manual (Environmental Laboratory 1987), which is the delineation manual currently in use. According to this manual, accidental wetlands (referred to as "man-induced") may not exhibit hydric soil indicators for "hundreds of years." A more accurate and precise estimate of time required for establishment of hydric soil indicators is needed (1) to aid in delineation of recently formed wetlands and (2) to aid in structural and functional assessment of constructed wetlands by providing evidence of functions that depend on reducing soil conditions.

Many wetland functions depend upon hydric soils. Hydric soils influence decomposition rate (Reddy et al. 1986) and distribution of organic matter (Megonigal and Day 1988), as well as plant distributions (Pearsall 1938). Many nutrients and other chemicals are transformed in wetlands, including nitrogen (Broadbent and Clark 1965), phosphorus, and iron (Gambrell and Patrick 1978). Pesticide and metal transformations also take place in hydric soils (Gambrell and Patrick 1978). Considerable methane is oxidized in hydric soils and may influence atmospheric gas balances (King et al. 1990).

Under certain conditions, soil redox potential decreases and hydric

[1]Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, Tennessee, May, 1996.

[2]Rob Atkinson is currently in the Department of Biology, Chemistry, and Environmental Science at Christopher Newport University, Newport News, VA 23606. Lee Daniels is in the Department of Crop and Soil Environmental Sciences, Virginia Tech, and John Cairns is in the Department of Biology at Virginia Tech, Blacksburg, VA 24061.

Proceedings America Society of Mining and Reclamation, 1996 pp 516-528

DOI: 10.21000/JASMR96010516

https://doi.org/10.21000/JASMR96010516

soil indicators begin to develop. The rate of oxygen diffusion in soil decreases by a factor of approximately 10,000 once a soil becomes saturated (Gambrell and Patrick 1978). Aerobic soil microbes consume organic matter and use oxygen preferentially as an electron acceptor. Some oxygen demand can also be attributed to oxidation of reduced elements diffusing up from anaerobic layers (Simpson 1978). Microbial activity and chemical transformations continue to occur under anaerobic conditions and the redox potential of the soil is lowered, i.e., reducing conditions become established (Ponnamperuma 1972).

Once reducing conditions become established for sufficient frequency and duration each year, several years may be required for redoximorphic features such as low chroma and oxidized rhizospheres (iron oxide coatings on fine roots) to develop.

Naturally occurring wetlands typically exhibit redoximorphic features within 25 cm of the surface or just below the A horizon, which are used in wetland delineation (Vepraskas 1995). Specifically, matrix chroma must be 1 or less if no color pattern (depletions and masses) occurs (Environmental Laboratory 1987; Federal Interagency Committee for Wetland Delineation 1989). According to the Environmental Laboratory (1987), wetlands that have been "incidentally created by human activities" are considered "atypical situations." This section states that hydric soil indicators may be lacking, and delineation may not require that hydric soil indicators be present. Thus, assessments of constructed wetlands, including wetlands constructed as mitigation for destruction of natural wetlands, may not currently consider soil chroma and oxidized rhizospheres for measuring success. This paper provides information on the time required for development of redoximorphic features in small depressions in southwestern Virginia.

Site Description

Accidental Wetlands

Contour surface mining for coal disturbed over 385,000 ha in the Appalachian Mountains prior to enactment of the Surface Mining Control and Reclamation Act of 1977 (SMCRA). Topographic features left by mining included vertical "high walls" and fairly flat "benches" consisting of severely compacted spoil with bulk density of 1.7 g/cc (Daniels and Amos 1982). Sediment was deposited over compacted mine spoil in many small depressions on benches. As a result, wetland hydrology became established and hydrophytic vegetation colonized the depressions (Atkinson and Cairns 1994). Over time, these conditions led to lowered soil redox potential and establishment of redoximorphic features in the accidental wetlands we studied.

Table 1. Indicator categories and probability of a plant species occurring in a wetland (Reed 1988)

Indicator Category	Wetland Frequency
Obligate wetland	>99%
Facultative wetland	67-99%
Facultative	34-66%
Facultative upland	1-33%
Obligate upland	<1%

Sites were located in Wise County in southwestern Virginia. Selection criteria included the presence of hydrophytic vegetation and depressional wetland hydrology and the absence of significant acid mine drainage inputs. Each wetland exhibited two plant community types: (1) a community dominated by obligate wetland plants and (2) a community dominated by facultative wetland plants (Table 1).

Year of accidental wetland formation ranged from 1965 to 1986. Maximum water depth in accidental wetlands ranged from 89 cm in site 3 to 8 cm in site 2 (Table 2). Aboveground biomass estimates in 1994 for the facultative wetland community were 442 g/m^2 and were 398 g/m^2 for the obligate wetland community. Total precipitation over a 7-year period

Table 2. Site reference number, hydrology (sources of water, duration dry, and hydrology modifier), and age (year formed) for 12 accidentally formed wetlands in this study

Site	Inlets/ outlets	Water depth[1]	Draw-down[2]	Hydrology[3]	Year formed
1	No/no	40	0.0	PEMe	1978
2	Temp/temp	7.9	66	PEMb,a	1986
3	Temp/perm	89	0.0	PEMe	1974
4	No/temp	18	25	PEMc	1974
5	No/no	18	13	PEMc	1973
6	No/temp	62	13	PEMc	1973
7	Temp/temp	20	4.2	PEMd	1983
8	Perm/perm	44	0.0	PEMe	1974
9	Temp/temp	8.4	21	PEMc	1965
10	Temp/temp	60	4.2	PEMd	1970s
11	No/no	32	8.3	PEMd	1970s
12	Temp/temp	73	0.0	PEMe	1970s

[1]Maximum measured depth in cm
[2]Percent of three growing seasons without inundation
[3]Modifiers based on Cowardin et al. (1979)include PEM=palustrine system and emergent class; water regime modifiers include: a=temporarily flooded, b=seasonally flooded, c=semipermanently flooded, d=intermittently exposed, and e=permanently flooded

(1988 to 1994) in Wise, VA, showed significantly low precipitation in 1989 and 1993 (Fig. 1). Mean monthly maximum temperatures during that period ranged from a low in February of 7°C to a high in July of 27°C(National Weather Service Cooperative Observer, Wise, VA; Fig. 2).

Most of the adjacent uplands were characterized by herbaceous species, including *Festuca elatior*, *Lespedeza cuneata*, *Trifolium repens*, and *Solidago gigantea*. Terrestrial vegetation dynamics in the region are discussed elsewhere by Holl and Cairns (1994).

Constructed Wetlands

In 1992, six wetlands were constructed at two sites by excavating depressions and creating small berms. Mean wetland size was approximately 10 m x 30 m, and maximum depth was approximately 1 m. Because of the small size, data collection was limited to nondestructive techniques, e.g., vegetation cover estimates and soil probes. Species with highest modified importance values (sum of relative cover and relative frequency) were *Echinochloa walteri*, *Eleocharus obtusa*, *Scirpus cyperinus*, and *Typha latifolia*.

The Powell River Project (PRP) in Wise County, VA, was the site of three constructed wetlands. Sedimentation rates were low since wetland construction occurred after the site had been revegetated with the perennial ryegrass *Lolium perenne* and various legumes (Fabaceae). Three wetlands were also constructed near Wise, VA. Sedimentation rates were much higher at this site since wetland construction coincided with final grading and preceded revegetation efforts.

Methods

Twelve accidental wetlands in Wise County, VA, were studied between 1992 and 1995. Parallel transects and permanent plots were established and monitored for 3 years. Accidental wetland sampling was conducted within two communities: (1) a community dominated by obligate wetland plants and (2) a community dominated by facultative wetland plants. Constructed wetland sampling was not conducted on a community basis due to

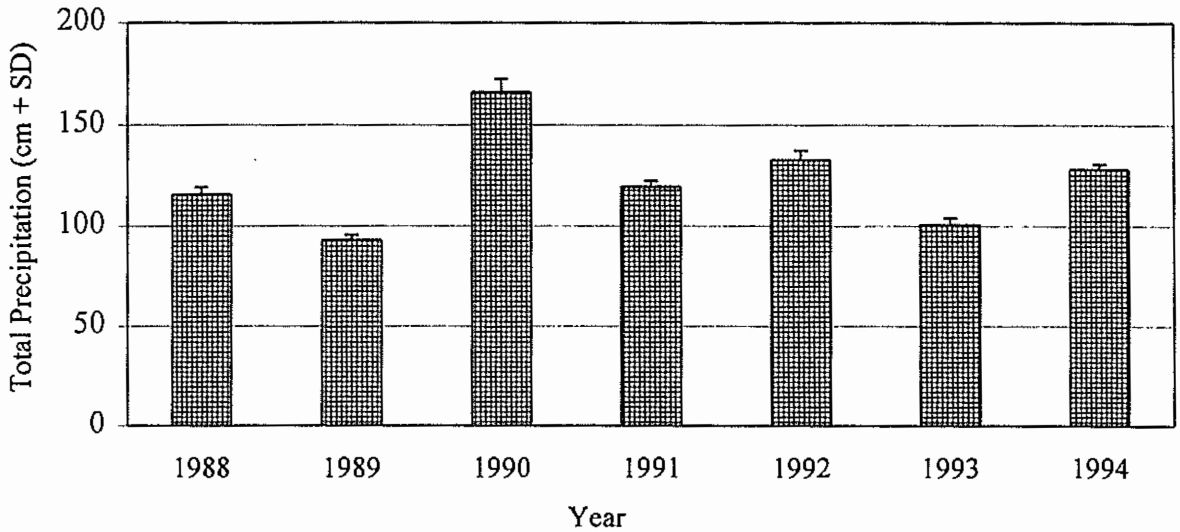

Fig. 1. Annual precipitation totals during a 7-year period (1988-1994) recorded in Wise, VA

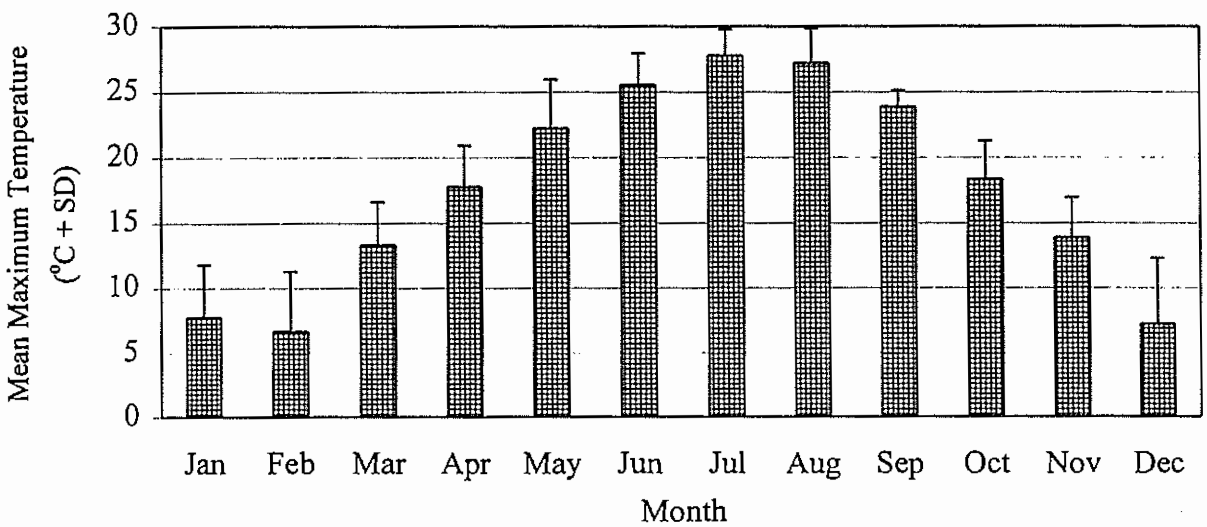

Fig. 2. Mean monthly maximum temperatures during a 7-year period (1988-1994) recorded in Wise, VA

small dimensions and poorly defined vegetative zonation. Several parameters were studied and those that aid in characterizing soils are described here.

Soil value and chroma, prevalence of oxidized rhizospheres, and presence of iron depletions and masses were assessed at a minimum of two plots within each accidental wetland community and within the deeper portion of each constructed wetland. Soil samples were extracted by shovel and were broken open manually for inspection. Value and chroma estimates were made using a wetted sediment sample in full sun using a Munsell Soil Color Chart. Oxidized rhizosphere frequency and intensity were assessed by visual inspection. No iron depletions and masses were detected in any soil samples in this study, although low chroma matrices were commonly described.

Water depth at the deepest point in each accidental wetland was measured biweekly during each growing season from 1992 through 1994. Each accidental wetland was assigned a water regime modifier based on the classification scheme set forth in Cowardin et al. (1979). Elevation in all plots was measured using a transit and stadium rod, and the mean of three estimates was calculated for each plot. Plot depth was calculated based on elevation and biweekly water depth estimates. Water depth in constructed wetlands was also measured biweekly. Sediment depth was measured using a soil probe penetrated to depth of compacted mine spoils, and the mean of three estimates was determined for each plot. Grand means were calculated for each community in the accidental wetlands and for each constructed wetland site. Soil particle size analyses were conducted at each accidental wetland and were compared to published data on upland soils that was also collected at PRP by Daniels and Amos (1982).

Litter estimates were made in both communities within the 12 accidental wetlands in 1994. Litter, including surficial organic material as well as standing dead biomass, was collected in 0.25-m^2 quadrats, dried, and weighed. No quantitative estimates of litter were made in constructed wetlands; however, cover estimates were made from 1-m^2 quadrats along two belt transects in each of the six constructed wetlands.

Belowground biomass estimates were made in both communities within the 12 accidental wetlands in 1994. All plant biomass between underlying compacted mine spoils and the litter layer were collected within 0.25-m^2 quadrats. No attempt was made to separate live and dead roots. Material was washed and sieved through a #10 seive, dried, and weighed. Because of the small dimensions of constructed wetlands, no estimates of belowground biomass were made at these sites.

Results

Accidental Wetlands

Redoximorphic features were present in all 12 accidental wetlands in this study. Low chroma (1 or less) matrices and oxidized rhizospheres were common in accidental wetlands; however, no pattern of iron depletions and masses was observed in any wetlands in this study (Fig. 3).

Hydric soil criteria for chroma were met in all 12 obligate wetland communities and 11 of 12 facultative wetland communities (Fig. 4). A chroma of 0 was common in the obligate wetland community of all four accidental wetlands that exhibited permanent inundation and in site 11, which was inundated throughout the study except for July, 1993, during a drought. Only the facultative wetland community at site 10 failed to meet the chroma criterion of 1 or less. Mean soil chroma in the obligate wetland community (0.67; SD 0.70) was somewhat lower than for the facultative wetland community (1.1; SD 0.68)(Fig. 4).

Oxidized rhizospheres were present at all accidental wetlands except site 12. Obligate wetland communities that exhibited chroma greater than 0 were found to have "prevalent and bright" oxidized rhizospheres. Oxidized rhizospheres were described as "absent" (sites 8, 10, and 12) or "present and dull" (sites 1, 3, and 11) in obligate wetland communities that exhibited chroma of 0. Oxidized rhizospheres in the facultative wetland community were described as "prevalent and bright" for all accidental wetlands except site 12, which exhibited dense growth of a moss, *Sphagnum* sp., associated with negligible mineral material above compacted mine spoil.

The duration criterion for wetland hydrology (Environmental Laboratory 1987) was exhibited by all accidental wetlands except site 2. Water regime modifiers for accidental wetlands included permanently flooded (4 sites), intermittently exposed (3 sites), semipermanently flooded (4 sites), and seasonally flooded (site 2)(Table 2). After August, 1992, inundation was not detected at site 2, which is the youngest of the 12 accidental wetland sites (formed 1986)(Table 2). Precipitation totals for 1993 were the second lowest on record in Virginia (National Oceanic and Atmospheric Administration 1993). Surface water disappeared from 8 of the 12 accidental wetlands during

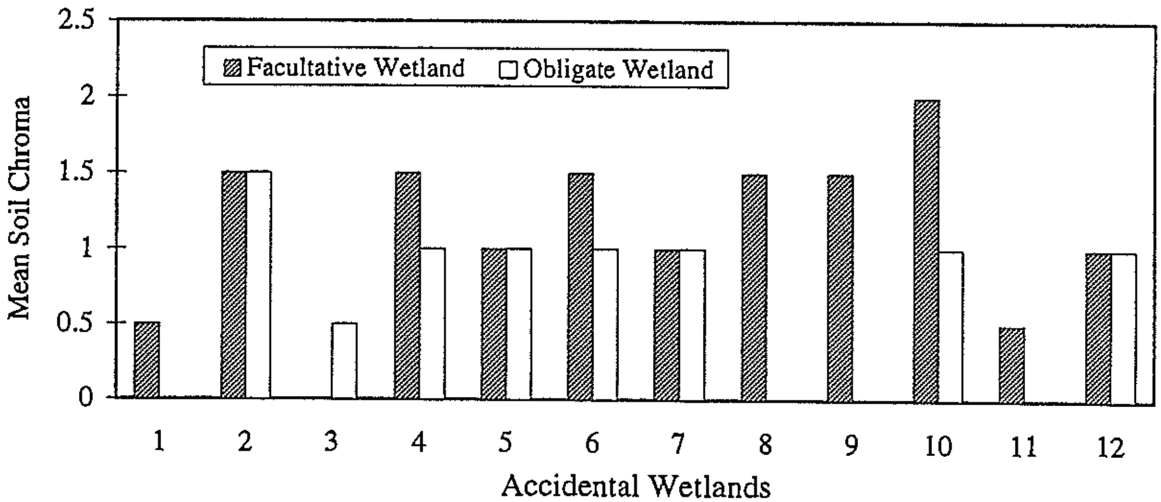

Fig. 3. Mean soil chroma for facultative wetland and obligate wetland communities at 12 accidental wetlands

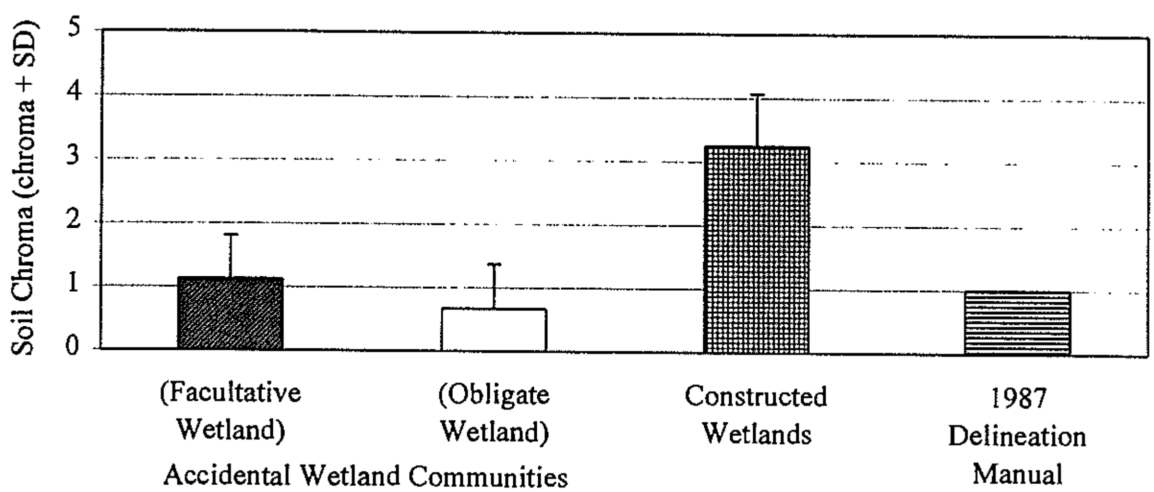

Fig. 4. Mean soil chroma for accidental wetlands, constructed wetlands, and maximum according to the 1987 delineation manual

1993, but inundation was reestablished during the 1993 growing season except at sites 2, 4, and 9. Precipitation in 1994 was within the range considered normal, and inundation was reestablished at sites 4 and 9, but not site 2.

Hydrology also differed within accidental wetlands. Mean water depth in obligate wetland communities (25 cm) was 24 cm deeper than mean facultative wetland community water depth (1 cm)(Fig. 5). Thus, inundation periods were shorter for facultative wetland communities than for obligate wetland communities in most sites. Soil saturation may have persisted longer than inundation, but was not quantified in this study.

Sediment depth in accidental wetlands differed both among and within the two communities. Mean sediment depth for both communities was greatest at site 10, which functioned as a sediment retention pond throughout this study. Sediment depth exceeded the maximum measured depth of 80 cm in five of the six

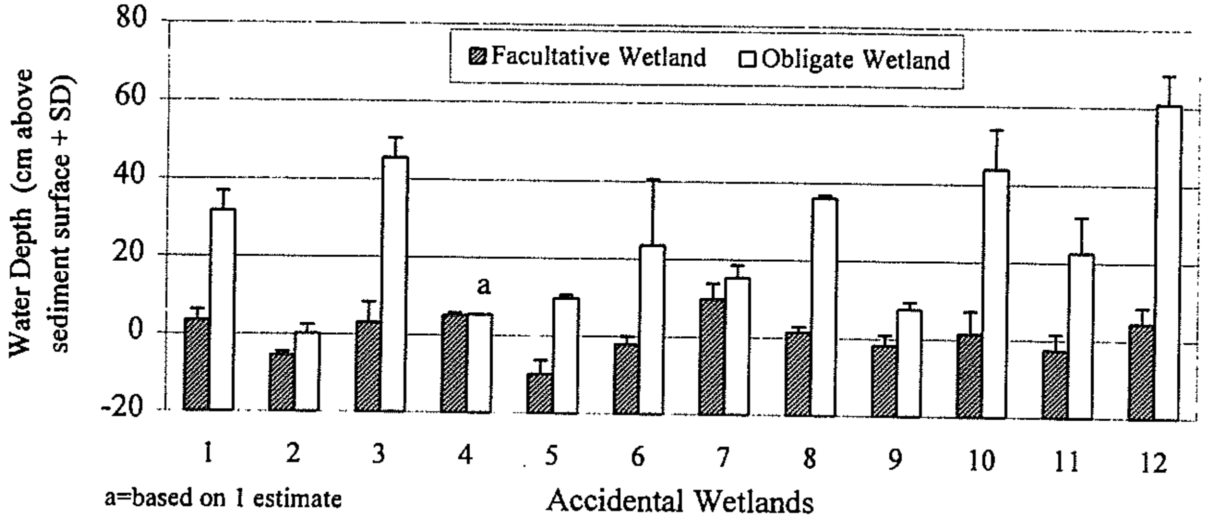

Fig. 5. Mean water depth from April through September, 1994, for facultative wetland and obligate wetland communities at 12 accidental wetlands

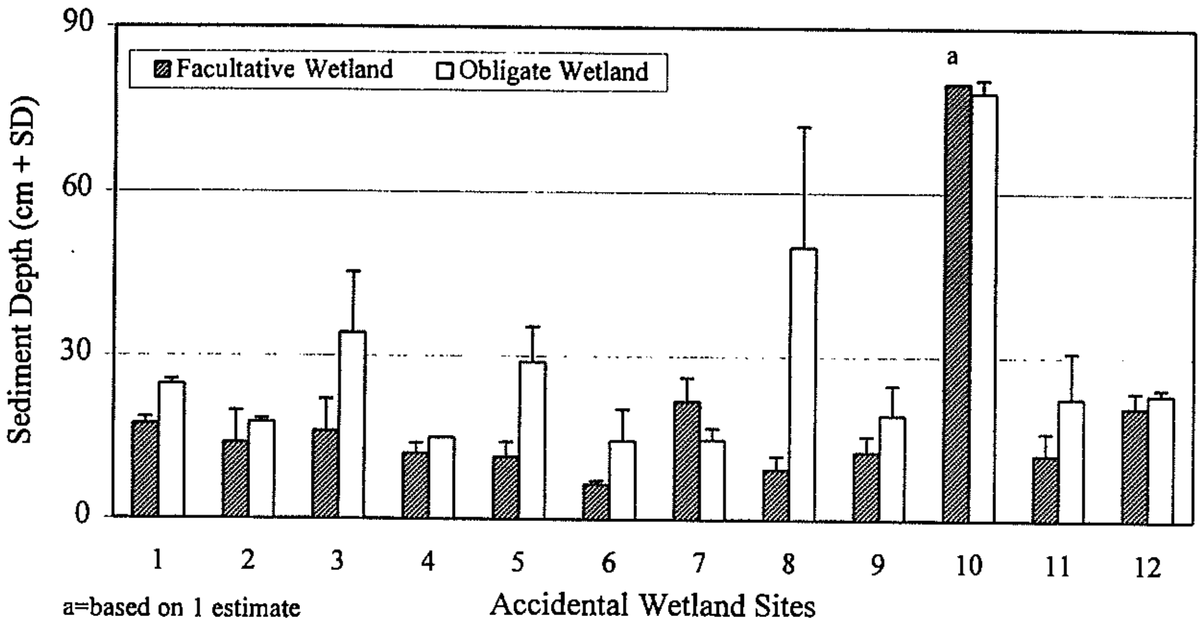

Fig. 6. Sediment depth for facultative wetland and obligate wetland communities at 12 accident wetland sites

plots where measurements were taken at site 10. Mean sediment depth was lowest at site 6 for both the facultative wetland (6 cm) and obligate wetland (14 cm) communities. In 10 of the 12 accidental wetlands, obligate wetland sediment depth exceeded that for the facultative wetland. Median sediment depth for facultative wetland communities was 13 cm compared to 23 cm for obligate wetland communities (Fig. 6). Particle size analyses for accidental wetlands indicated a significantly higher percent clay (31%) than that for upland areas (15%). Silt content in accidental wetlands (58%) was also somewhat higher than that for uplands (41%)(Fig. 7).

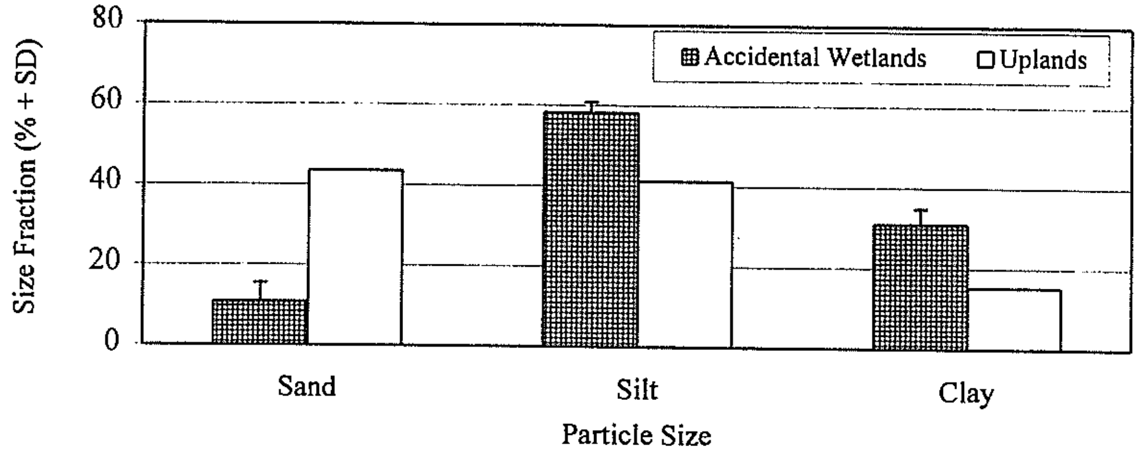

Fig. 7. Particle size analysis for accidental wetlands (this study) and for uplands at the Powell River Project (Daniels and Amos 1982)

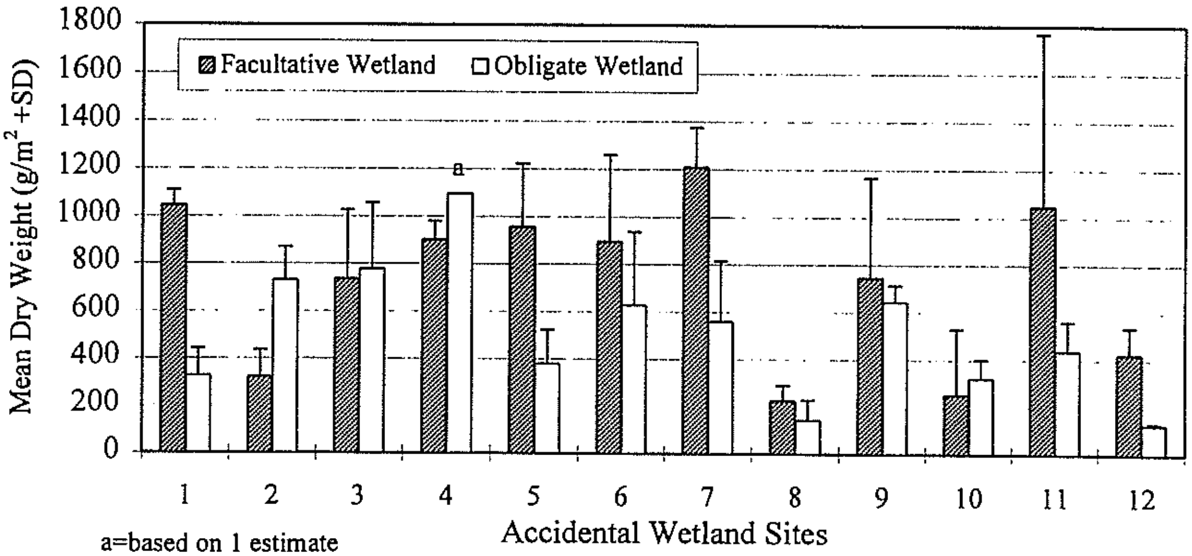

Fig. 8. Mean dry weight of litter for facultative wetland and obligate wetland communities at 12 accidental wetlands

Mean litter content in accidental wetlands was 621 g/m^2 in 1994. Facultative wetland litter content (730 g/m^2) was significantly greater than litter content in obligate wetland communities (514 g/m^2). Litter content was lowest in site 8 (184 g/m^2), which was found to have the highest diversity and abundance of aquatic macroinvertebrates (Jones 1995; Fig. 8).

Dense root mat formations with negligible accumulated mineral material were common in the facultative wetland plant community. Belowground biomass in accidental wetlands was higher in the facultative communities, 442.5 g/m^2, than in obligate wetland communities, 398.4 g/m^2. Site 2 was the most recently formed accidental wetland (1986) and exhibited the lowest mean belowground biomass in the facultative wetland community (135.2 g/m^2)(Fig. 9).

Constructed Wetlands

Soil chroma was 3 to 4 in all six newly constructed wetlands in this study. In all three constructed

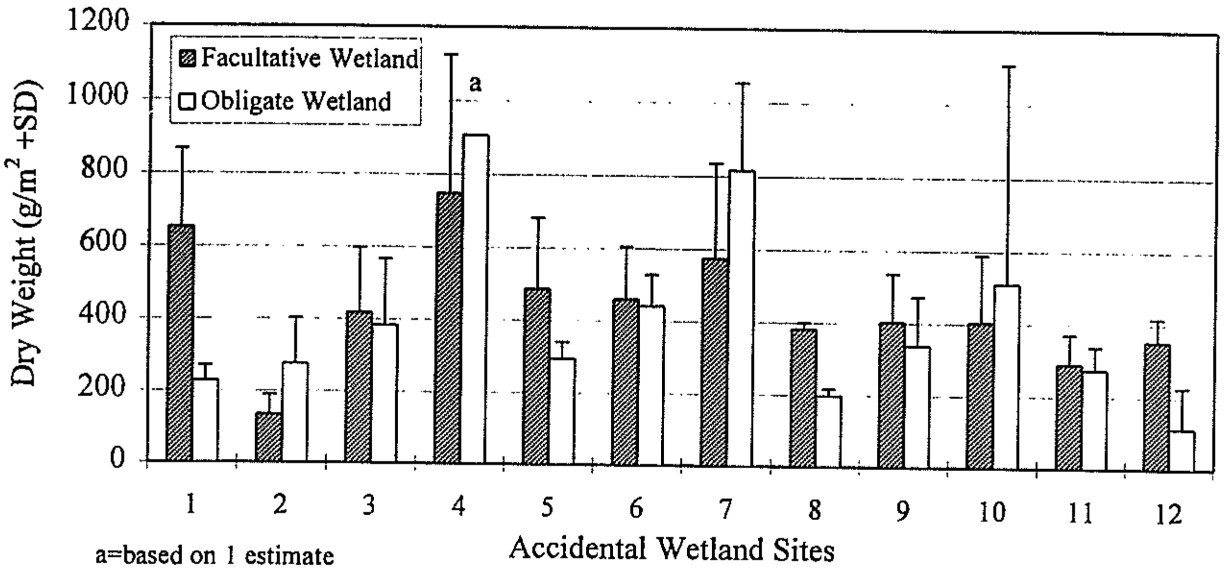

Fig. 9. Mean dry weight of biomass (belowground) for facultative wetland and obligate wetland communities at 12 accidental wetlands

wetlands near Wise, VA, oxidized rhizospheres were present, but were described as "infrequent and dull." No oxidized rhizospheres were found in the three constructed wetlands at PRP. Mean vegetative cover (68%) was significantly greater at the Wise constructed wetlands than at the PRP constructed wetlands (9%).

Sediment depth in constructed wetlands was significantly different among the PRP and Wise constructed wetlands. The mean sediment depth for PRP constructed wetlands was 5.8 cm compared to 19.3 cm for the Wise constructed wetlands (Fig. 10).

Discussion

The hydric soil criteria for chroma (1 or less) and, to a lesser extent, oxidized rhizospheres (Environmental Laboratory 1987) were met by both facultative and obligate wetland communities in all 12 accidental wetlands, including site 2. Since site 2 was formed in 1986, one can infer that a low soil chroma can be exhibited in less than 10 years after a depression becomes established. The minimum time required for chroma of 1 to be exhibited within small depressions is greater than 3 years, based on the survey of six constructed wetlands in this study. Oxidized rhizospheres may form more quickly. They were described as "present and dull" in two of the newly constructed wetlands.

The minimum time required for development of low chroma is probably even shorter, since site 2 failed to exhibit inundation during or after drought conditions began in spring 1993; and, since precipitation in 1989 was even lower than for 1993 in Wise County (National Weather Service Cooperative Observer, Wise, VA), site 2 probably was not inundated in 1989.

The issue of low chroma color development in these materials is complicated by the fact that some of the mine spoil strata encountered are reduced and gray when mined and freshly deposited (Daniels and Amos 1981). However, these reduced sandstones and siltstones are typically chroma 2 or higher, and weathering for even a few years raises the matrix chroma to 3 or 4 under well drained conditions. Thus, the higher chroma sediment colors observed in the constructed wetlands corroborates our assumption that the low chromas (<1.0) observed in the accidental wetlands we surveyed reflect the development of hydric soil conditions rather than simple preservation of relic parent material colors.

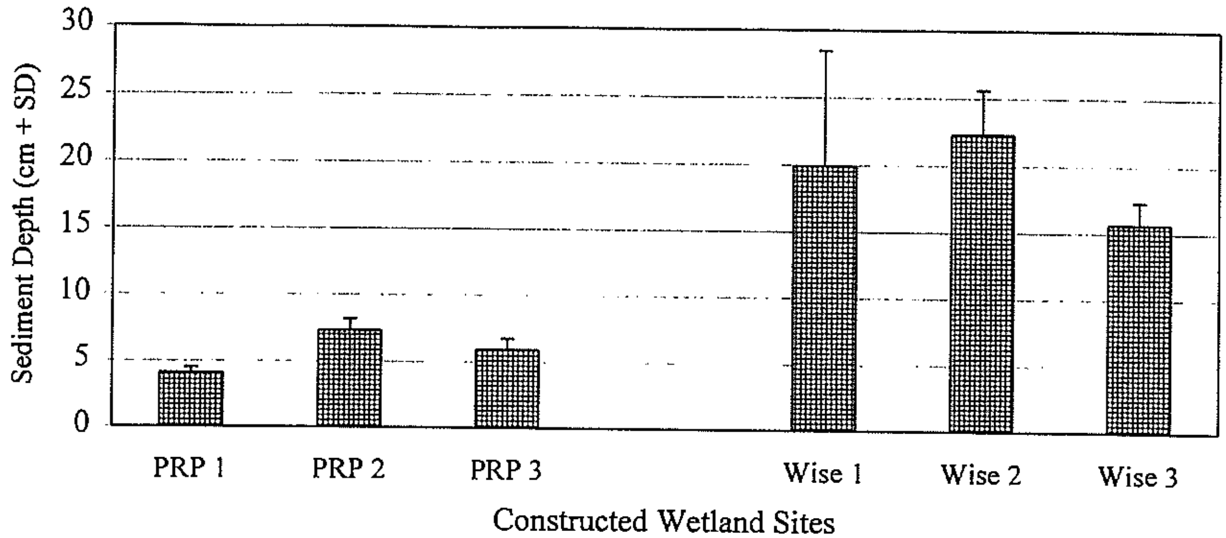

Fig. 10. Mean sediment depth in constructed wetlands at two sites, Power River Project (PRP) and near Wise, VA (Wise)

Mitsch and Gosselink (1993) list three conditions for establishment of low chroma: (1) sustained anaerobic conditions, (2) sufficient organic matter to support microbial activity, and (3) adequate soil temperature. These conditions were met to differing extents in all 12 accidental wetlands and influence the time required for development of hydric soil indicators.

Wetland hydrology, especially the duration of inundation, appeared to influence soil chroma. Sites having permanently flooded water regimes were found to exhibit lower chroma than sites with either intermittently exposed or semipermanently flooded conditions (Fig. 11). Water depth did not appear to influence chroma, except for the fact that deeper portions of a wetland may be inundated for longer periods of time. For example, facultative wetland communities were not inundated for as long as the associated obligate wetland communities and exhibited higher chroma.

The actual duration of wetland hydrologic conditions cannot be quantified for the accidental wetlands since there is no data to indicate how much time was required for an impervious layer to form. Particle size analysis in accidental wetlands indicated a significantly higher clay content when compared to spoil material on upland benches (Daniels and Amos 1981), which may have limited infiltration rates. Constructed wetlands at PRP failed to form an impervious layer in the first 2 years after construction, and there was considerable fluctuation in water depth. The shrink-swell characteristics of sediments appeared to permit infiltration following drawdown events.

Vepraskas and Wilding (1983) noted that soils saturated for 120 days failed to show chroma below 3 when organic matter content was less than 1%. Organic matter was measured in both litter and belowground biomass compartments for both communities in the 12 accidental wetlands. The supply appears to be ample to support microbial metabolism, but may have been limiting during early stages of wetland development. There are two possible roles for organic matter in hydric soil development in accidental wetlands. First, organic matter is required for microbial metabolism, which leads to iron reduction and lower chroma. Organic matter may have been available early in accidental wetland development since wind dispersed seeds, e.g., *Typha latifolia* and *Scirpus cyperinus*, could colonize sediments quickly.

Second, the water holding effects of organic matter can increase the duration of soil saturation. Since accidental wetlands form in

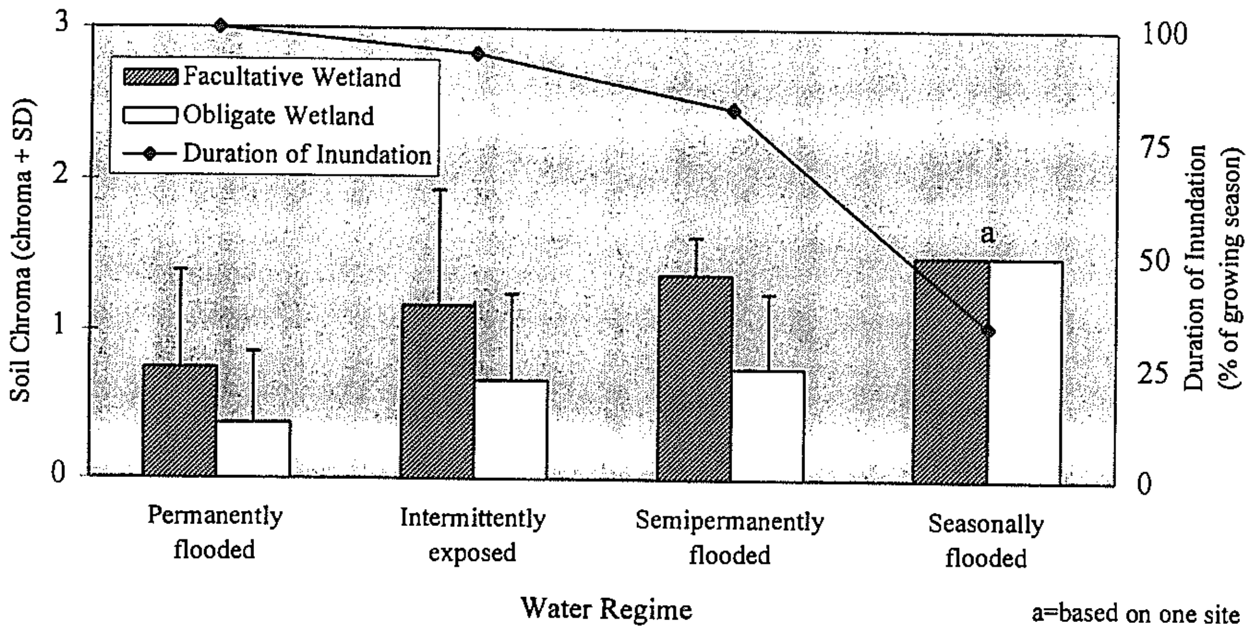

Fig. 11. Soil chroma for four accidental wetlands arranged by water regime (based on Cowardin et al. 1979)

small depressions, export of organic matter is low. Since mean accidental wetland litter content was high (621 g/m² in 1994), absence of inundation for short periods during the growing season may not have led to significant soil aeration. Macroinvertebrates were abundant in some accidental wetlands (e.g., site 8), but they should not inhibit development of hydric soil indicators for several reasons. By reducing the detritus size and increasing surface area, macroinvertebrates facilitate microbial action. The faster mineralization of nutrients should also yield greater primary productivity and organic matter accumulation.

Thus, sedimentation appears to play an important role in accidental wetland formation and development. Sediment deposition can influence hydrology by creating an impervious layer that establishes inundation. Sediment provides a substrate for seeds of hydrophytes and a plant growing medium. If plant growth provides adequate litter following senescence, there will be sufficient substrate to support microbial metabolism and adequate water holding capacity to limit diffusion of oxygen. In addition, it is the supply of iron with sediment that supports color development and provides an indication of oxidation and reduction processes.

Other Hydric Soil Indicators

Oxidized rhizospheres were found to be "prevalent and bright" in most accidental wetlands. The ability of hydrophytes to aerate the soil adjacent to roots has been described for many species (Conway 1940, Bartlett 1961, Armstrong and Boatman 1967). The two communities found in accidental wetlands in this study were identified based on the dominant species. The obligate wetland community was dominated by species which occur in wetlands >99% of the time, and the facultative wetland community is dominated by species that occur in wetlands 67-99% of the time (Reed 1988).

Oxidized rhizospheres were missing under three distinct conditions observed in this study. First, oxidized rhizospheres were either lacking, infrequent, or dull in the six newly constructed wetlands. Oxidation of iron adjacent to roots of hydrophytes appears to require time to become visible. Bartlett (1961) extracted reduced iron from soil to show that some iron oxidizes around the surface of roots during a single growing season, but did not address the establishment of a visible layer of oxidized iron around roots. Second, oxidized rhizospheres were absent or dull in obligate wetland communities that exhibited a permanently flooded water regime. Oxygen may have been released by roots more slowly at these greater depths, and, since oxygen and redox potential decreases with depth, oxygen may be consumed more quickly under these conditions. Third, oxidized rhizospheres were absent at the facultative wetland community in site 12. This community exhibited high organic matter content and negligible mineral material; thus, iron was probably not available for oxidation.

There was no evidence of iron depletions and masses in this study. These features either have not had sufficient time to form, or conditions are not conducive to mottle development. Color patterns associated with iron depletions and masses become established where water levels fluctuate (Ponnamperuma 1972). The absence of these color patterns may, therefore, be a result of stable water tables in the small depressions, modulated by litter content and slow infiltration rates.

Soil temperature was not measured in this study, but several years of temperature data were obtained from the local Climatological Observer in Wise, VA. Mean monthly maximum temperatures ranged from a low in February of 7°F to a high in July of 27°F). Since water depth in the accidental wetlands ranged from 8 to 89 cm, light penetration to the bottom seems likely. However, vegetative cover of *Typha latifolia* was extensive in many obligate wetland communities, and shading could reduce soil temperatures. It appears that the 12 accidental wetlands were in similar geographic and topographic positions and would experience similar soil temperatures; however, future studies should monitor soil temperature.

Conclusion

Wetland construction has increased in the United States following implementation of Section 404 of the Clean Water Act (1977). However, most construction attempts have occurred in the last 10 years, and monitoring has been limited. Accidental wetlands provide an age class from 10 to 30 years post formation and provide clues to depressional wetland ontogeny. In particular, redoximorphic features, including low chroma matrices and oxidized rhizospheres, were formed within this time period. Newly constructed wetlands showed that certain hydric soil indicators, i.e., oxidized rhizospheres, can form within 3 years.

Literature Cited

Armstrong, W., and D. J. Boatman. 1967. Some field observations relating the growth of bog plants to conditions of soil aeration. Journal of Ecology 55: 101-110.
https://doi.org/10.2307/2257719

Atkinson, R. B., and J. Cairns, Jr. 1994. Possible use of wetlands in ecological restoration of surface mined lands. Journal of Aquatic Ecosystem Health 3: 139-144.
https://doi.org/10.1007/BF00042943

Bartlett, R. J. 1961. Iron oxidation proximate to plant roots. Vermont Agricultural Experiment Station, Journal Series Paper No. 99. University of Vermont.

Broadbent, F. E., and F. Clark. 1965. Denitrification, p. 344-359. In: Soil nitrogen, W. V. Bartholemew, and F. E. Clark, eds. American Society of Agronomy, Madison, WI.

Conway, V. M. 1940. Aeration and plant growth in wet soils. The Botanical Review 6(4): 149-163.
https://doi.org/10.1007/BF02879342

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. US Fish and Wildlife Service, FWS/OBS-79-31, Washington, DC.

Daniels, W. L., and D. F. Amos. 1981. Mapping, characterization and genesis of mine soils on a reclamation research area in Wise, VA, p. 261-275. In: Proceedings of the 1981 Symposium on Surface Mining Hydrology, Sedimentology, and

Reclamation. University of Kentucky, Lexington.

Daniels, W. L., and D. F. Amos. 1982. Generating productive topsoil substitutes from hard rock overburden in the southern Appalachians. Environmental Geochemistry and Health 7: 8-15.
https://doi.org/10.1007/BF01875045

Environmental Laboratory. 1987. Corps of Engineers Wetlands Delineation Manual, Tech. Rep. Y-87-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Federal Interagency Committee for Wetland Delineation. 1989. Federal manual for identifying and delineating jurisdictional wetlands. US Army Corps of Engineers, USEPA, US Fish and Wildlife Service, and USDA Soil Conservation Service, Washington, DC.

Gambrell, R. P., and W. H. Patrick. 1978. Chemical and microbiological properties of anaerobic soils and sediments, p. 375-423. In: Plant life in anaerobic environments, D. D. Hook, and R. M. M. Crawford, eds. Ann Arbor Science Publishers Inc., Ann Arbor, MI.

Holl, K. D., and J. Cairns, Jr. 1994. Vegetational community development on reclaimed coal surface mines in Virginia. Bulletin of the Torrey Botanical Club 121(4): 327-337.
https://doi.org/10.2307/2997006

Jones, D. H. 1995. Macroinvertebrate richness and abundance of accidental wetlands on surface mines, Masters Thesis, Department of Biology, Virginia Polytechnic Institute and State University. Blacksburg, VA.

King, G. M., P. Roslev, and H. Skovgaard. 1990. Distribution and rate of methane oxidation in sediments of the Florida Everglades. Applied and Environmental Microbiology 56(9): 2902-2911.

Megonigal, J. P., and F. P. Day. 1988. Organic matter dynamics in four seasonally flooded forest communities of the Dismal Swamp. American Journal of Botany 75(9): 1334-1343.
https://doi.org/10.2307/2444456

Mitsch, W. J., and J. G. Gosselink. 1993. Wetlands, 2nd ed. van Nostrand Reinhold, New York, NY.

Pearsall, W. H. 1938. The soil complex in relation to plant communities. Journal of Ecology 26: 180-209.
https://doi.org/10.2307/2256417

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Advances in Agronomy 24: 29-96.
https://doi.org/10.1016/S0065-2113(08)60633-1

Reed, P. B., Jr. 1988. National list of plant species that occur in wetlands: Virginia. US Fish and Wildlife Service, St. Petersburg, FL.

Reddy, K. R., T. C. Feijtel, and W. H. Patrick, Jr. 1986. Effect of soil redox conditions on microbial oxidation of organic matter, p. 117-156. In: The role of organic matter in modern agriculture, Y. Chen, and Y. Avnimelech, eds. Martinus Nijhoff Publishers, Dordrecht, The Netherlands.

Simpson, T. W. 1978. Soil morphologic and hydrologic changes associated with wastewater irrigation. Ph.D. dissertation, Pennsylvania State University, University Park, PA.

Vepraskas, M. J. 1995. Redoximorphic features for identifying aquic conditions. North Carolina Agricultural Research Service Tech. Bull. 301, North Carolina State University, Raleigh, NC.

Vepraskas, M. J., and L. P. Wilding. 1983. Aquic moisture regimes in soils with and without low chroma colors. Soil Science Society of America Journal 47: 280-285.
https://doi.org/10.2136/sssaj1983.03615995004700020022x