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Landscape Diversity: Florida Phosphate Mine Pit Lakes[1]

M. Wilson and E.A. Hanlon[2]

Introduction and Purpose

Phosphate is a critical nutrient for plant growth and an essential component of the fertilizer used in agriculture that helps to sustain the world's growing population. During 2010, seven mines in Florida produced approximately 10% of the world's phosphate supply and more than 65% of the phosphate in the United States (USGS 2011). Florida phosphate production depends on strip-mining, which results in the excavation of thousands of acres annually. Removal of the phosphate ore (matrix) from the ground causes a deficit in the volume of materials available for land reclamation. Restoring the landscape to near pre-mining elevations necessitates the creation of lakes, and mine pit lakes constitute significant components of post-phosphate mining landscapes. In 1975, Florida passed laws requiring mandatory reclamation of lands mined for phosphate (FDEP 2006). All lands mined after June 30, 1975, are subject to mandatory reclamation requirements to return the landscape to a beneficial use following mining.

The mine reclamation rules acknowledge the necessity of creating lakes and prescribe criteria for their reclamation. Reclaimed phosphate mine pit lakes must be contoured to no steeper than 4 feet horizontal to 1 foot vertical to at least 6 feet in depth below the seasonal low water line. At least 20% of the lake area is required to be less than 6 feet in depth to provide shallow zones for fish bedding. Reclaimed lake shores are required to be constructed such that seasonal fluctuations in water levels result in annual drying and wetting of at least 25% of the lake surface area (FDEP 2006). Many of the phosphate pit lakes in Florida were created before the advent of mandatory mine reclamation regulations. These lakes typically have relatively straight shorelines with relatively steep shoreline slopes and may contain islands of uncontoured mine spoil.

As significant components of the post-mining landscape, these lakes serve multiple functions, including uses for wildlife habitat, boating, fishing, water supply, and aesthetic value. A basic understanding of the limnology, water quality considerations, and ecological functions of mine pit lakes will enhance their potential for use. This document contains a synopsis of findings obtained through research funded by the Florida Institute for Phosphate Research (now the Florida Industrial and Phosphate Research Institute) contrasted with limnological studies of natural lakes in central Florida. The audience for this document includes reclamation planners, government regulators, non-governmental organizations, and managers of phosphate mine pit lakes. This document will help them quickly become informed of the published research and characteristics of the phosphate mine pit lakes in Florida.

Natural Florida Lakes Summary

Most natural Florida lakes formed from or were influenced substantially by dissolution of limestone. Natural Florida lakes are generally shallow (<10m deep), have smooth bottoms, and are usually mixed by wind-action (Boody et al. 1985a; Shannon and Brezonik 1972). Most do not experience stable thermal stratification and development

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2. M. Wilson, graduate student, Soil and Water Science Department; and E.A. Hanlon, professor, Soil and Water Science Department, Southwest Florida Research and Education Center, Immokalee, FL; Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611.

of depressed oxygen concentrations in the bottom waters (anoxic hypolimnia), though many do (Canfield and Hoyer 1988; Shannon and Brezonik 1972). In terms of biological productivity, the majority of natural lakes in Florida could be classified as mesotrophic (intermediate level of biological productivity) to eutrophic (high level of biological productivity) (Canfield and Hoyer 1988; Shannon and Brezonik 1972).

The high level of biological productivity caused by eutrophic conditions can lead to water quality problems. Severe algal blooms resulting from eutrophic conditions can impact water quality and decrease the value of lakes for fishing and recreation. Because eutrophic conditions are often problematic for water quality, management of most Florida lakes is focused on attaining a trophic state closer to the mesotrophic range.

Typically, biological productivity in freshwater systems is limited by the availability of phosphorus. However, many Florida lakes are nitrogen-limited, indicating that sufficient phosphorus is present in the system (Canfield and Hoyer 1988).

Phosphate Mine Pit Lake Morphology

In contrast to natural Florida lakes, the shorelines and bottoms of phosphate pit lakes are typically more irregular. Phosphate pit lakes also generally have a smaller surface area and less "shallow zone" than most natural Florida lakes. Most phosphate mine pit lakes are similar in mean depth to natural Florida lakes (3 m – 4 m), though their maximum depth is usually substantially greater (Boody et al. 1985a; Boody et al. 1985b).

Thermal Stratification and Development of Hypoxic Hypolimnia

Most phosphate mine pit lakes develop at least some stratification with regard to temperature and dissolved oxygen (DO) (Boody et al. 1985a; Boody et al. 1985b).

Dissolved oxygen is necessary for aerobic aquatic organisms to survive. The main source of lake dissolved oxygen is from photosynthetic activity in the photic zone, though diffusion from the atmosphere also contributes a substantial amount of DO (Cole 1994). The lake water is mixed primarily by wind-action, which distributes the dissolved oxygen throughout a portion of the lake. Seasonal stratification

Figure 1. The future shores of a phosphate pit lake during reclamation to contemporary reclamation standards. Slopes on the lake exterior can be no steeper than 4H:1V (4 feet horizontal to 1 foot vertical) to at least 6 feet below the water's surface during seasonal lows. Credits: M. Wilson

Figure 2. Phosphate mine pit lake during reclamation. Water levels in this lake are expected to increase by 5–10 feet following reclamation. The slopes in the foreground have been contoured to reclamation standards. The slopes in the top right have yet to be contoured to reclamation standards. Note the flattened platform (middle left), which will be a fish bedding/littoral zone. The inundated areas are the mine pit bottoms and will become the deeper pockets in the lake. Credits: M. Wilson

of temperature and dissolved oxygen is common for the majority of lakes and reservoirs in the southeastern United States. Stable thermal stratification and development of depressed dissolved oxygen concentrations in the bottom waters are not common in natural Florida lakes partly because of their generally shallow nature (Shannon and Brezonik 1972). Stratification in phosphate mine pit lakes is likely not a function of depth alone and is probably related to irregularities in the lake bottoms. Deeper pockets in the irregular lake bottoms remain outside of prevailing

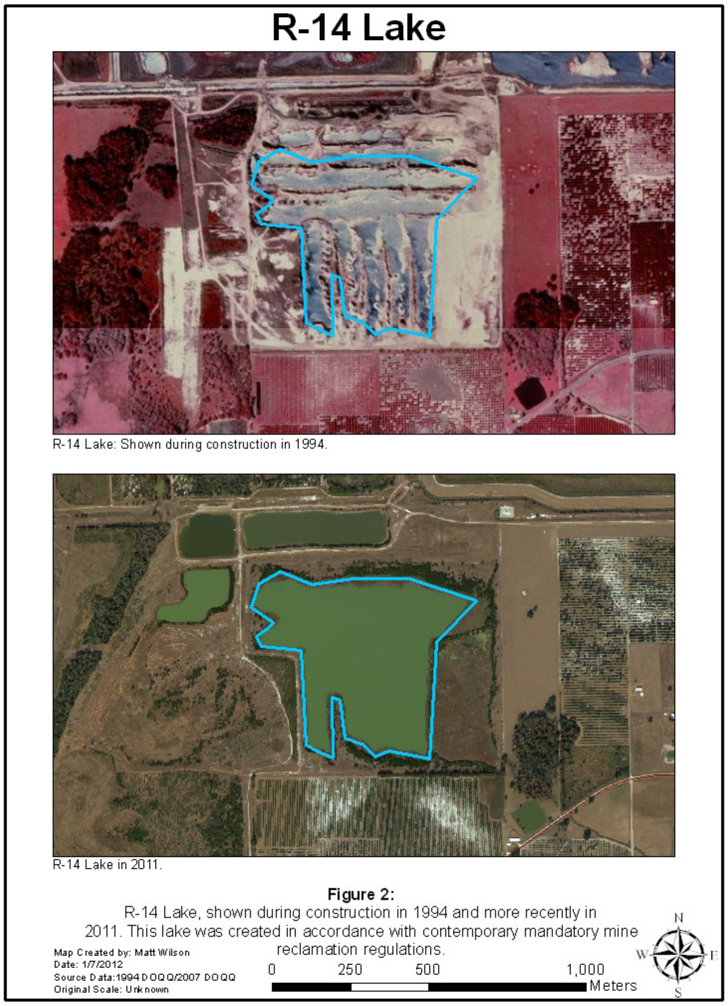

Figure 3. Phosphate mine pit lake (R-14) under construction in 1994 (top) and after reclamation (bottom). The spoil rows in the 1994 photo typically remain following reclamation and are a common bathymetric feature of phosphate mine pit lakes. The areas without spoil rows will become deeper pockets, resulting in a highly irregular lake bottom. Credits: M. Wilson

lake-mixing patterns and promote development of hypoxic conditions (Boody et al. 1985b; Rampenthal and Ferraro 1987).

Stratification in phosphate mine pit lakes develops in the early spring (March to April) and generally lasts through fall turnover (October) (Boody et al. 1985a; Boody et al. 1985b). Despite the stratification, the majority of water in phosphate mine pit lakes remains oxygenated throughout the year, and average DO concentrations typically remain more than 5 mg/L. DO concentrations in the surficial waters of phosphate mine pit lakes rarely decrease to less than 5.0 mg/L. However, lake-wide DO concentrations may temporarily decrease to less than 5 mg/L after fall turnover (Boody et al. 1985a). Winter DO depression in phosphate mine pit lakes is not a serious concern as it is in northern lakes since Florida lakes typically do not freeze for any length of time.

Physico-Chemical Parameters

The physico-chemical characteristics of phosphate mine pit lakes generally fall within the range of variability observed in natural lakes in central Florida (Boody et al. 1985a; Boody et al. 1985b; Pratt et al. 1985; Rampenthal and Ferraro 1987). The pH (a measure of acidity or basicity) is generally lower in phosphate mine pit lakes than in natural lakes in central Florida, and the waters in phosphate mine pit lakes are generally neutral to slightly acidic. The pH of phosphate mine pit lakes appears related to DO concentration, which is consistent with what occurs in natural lakes (Rampenthal and Ferraro 1987). Alkalinity (a measure of water's buffering capacity, or capacity to neutralize acidity) is generally estimated as the concentration of calcium carbonate ($CaCO_3$) in milligrams per liter (mg/L). Lake systems with higher alkalinity typically are more resistant to changes in pH (Cole 1994). Alkalinity in phosphate mine pit lakes is typically higher than the minimum standard of 20 mg/L and is generally slightly higher than natural lakes in central Florida (Boody et al. 1985b; Pratt et al. 1985). This finding means that wide pH fluctuations in phosphate mine pit lakes should not be a concern.

Hardness (a measure of mineral content in water, generally calcium and magnesium) is also estimated as the concentration of $CaCO_3$ in mg/L. While it is not harmful to human health, hard water can be problematic for industrial and residential uses. Hardness in the phosphate mine pit lakes is generally higher than in most natural lakes in peninsular Florida (Boody et al. 1985b; Pratt et al. 1985), and phosphate mine pit lakes are classified as "moderately hard" (75–150 $CaCO_3$ mg/L equivalent), using the classification scheme employed by the U.S. EPA (US EPA 1986). Hardness of water also affects the solubility and availability of several metals in solution, such as cadmium, chromium, copper, lead, nickel, and zinc. Minerals in hard water form complexes with the metals, resulting in decreased metal bioavailability.

Electrical conductivity (EC) is a measure of electrolyte concentrations (or ionic content) in water. Most of the phosphate mine pit lakes have slightly higher EC than natural lakes, and EC is higher in the bottom waters (Boody et al. 1985a; Boody et al. 1985b; Pratt et al. 1985; Rampenthal and Ferraro 1987). Higher EC in the bottom waters may reflect the presence of colloidal materials at or near the phosphate mine pit lake bottoms.

Concentrations of most cations, such as calcium, magnesium, and sodium, in phosphate mine pit lakes are similar to concentrations observed in natural Florida lakes. The dominant cations in the phosphate mine pit lakes are calcium and magnesium. However, potassium concentrations are lower in phosphate mine pit lakes than in most natural lakes in central Florida (Boody et al. 1985b). Potassium concentrations are also lower in the sediments of the phosphate mine pit lakes. It is not clear what process is responsible for reduced potassium concentrations observed in phosphate mine pit lake waters and sediments, as potassium is a component of many soil minerals. However, potassium can be captured within the structure of expanding clays such as montmorillonite in a process known as potassium fixation.

Sulfate concentrations are higher in the sediments and the water column of phosphate mine pit lakes. In some phosphate mine pit lakes, sulfate concentrations have been measured at exceptionally high levels (more than 170 mg/L) (Boody et al. 1985b). In water depleted of oxygen (such as occurs in the hypolimnia of many phosphate mine pit lakes) sulfate (SO_4^{2-}) may be reduced to hydrogen sulfide H_2S, which is a toxic gas that smells like rotten eggs. Produced by the reduction of sulfate, hydrogen sulfide ions are quite reactive and may complex with metal ions to form insoluble sulfide precipitates. This process could be an effective mechanism for removal of metal ions from the water column.

Phosphate mine pit lakes have decreased concentrations of potassium and chloride in the sediments and water column in comparison to natural lakes in central Florida (Boody et al. 1985b; Rampenthal and Ferraro 1987). Fluoride concentrations may be approximately three times higher in phosphate mine pit lakes relative to water from natural lakes in central Florida. However, fluoride concentrations observed in phosphate mine pit lakes are consistently less than Florida's Class III water quality standard of 10.0 mg/L (Boody et al. 1985b; FDEP 2010).

Water Chemistry

For the first few months following reclamation, the chemistry of phosphate mine pit lakes enters a transitional stage. During this transitional stage, the waters may be turbid; pH may be low; and the lakes may be high in hardness, conductivity, selenium, aluminum, and magnesium (Pratt et al. 1985). This transitional stage has been observed to affect colonization and community composition patterns of indicator species, such as protozoans. Within two years following reclamation, turbidity and concentrations of aluminum, magnesium, and selenium decrease to levels comparable to natural lakes in central Florida. At this point, protozoan colonization rates and community composition patterns become similar to the rates and composition characteristics observed in natural lakes (Pratt et al. 1985).

Based on the limited data available, phosphate mine pit lakes generally have good water quality. However, both natural and phosphate mine pit lakes in central Florida often exceed Class III water quality standards for one or more contaminants (Boody et al. 1985b; Pratt et al. 1985; Rampenthal and Ferraro 1987). Beryllium concentrations in phosphate mine pit lake sediments were similar to the concentrations observed in natural lakes in central Florida, and phosphate mine pit lake waters did not exceed the Class III standard for beryllium. Concentrations of nickel, silver, zinc, and selenium in phosphate mine pit lake sediments are generally lower than in the natural lakes in central Florida, and phosphate mine pit lake waters typically do not exceed the Class III water quality standards for any of these four contaminants (Rampenthal and Ferraro 1987). Concentrations of manganese appear to be lower in the water column of phosphate mine pit lakes.

Barium in phosphate mine pit lake sediments is generally higher than in natural lakes in central Florida. However, barium in the water column of phosphate mine pit lakes is much lower than in natural lakes in the area, suggesting that barium is removed from the water column of phosphate mine pit lakes (possibly via precipitation with SO_4^{2-} into barite, which is highly insoluble and has low bioavailability) (Boody et al. 1985a; Boody et al. 1985b; Rampenthal and Ferraro 1987). Aluminum concentrations in phosphate mine pit lake sediments are highly elevated in comparison to sediments from natural lakes, and aluminum concentrations are generally higher in phosphate mine pit lake waters (Pratt et al. 1985; Rampenthal and Ferraro 1987). The concentrations of chromium and arsenic appear to be higher in the sediments of phosphate mine pit lakes relative to other natural lakes in central Florida, and the concentrations of chromium and arsenic in the water column were observed to be slightly higher than the concentrations found in natural lakes in the region. However, the studies referenced in this paper found that no phosphate mine pit lakes exceeded the Class III water quality standards for either of these two elements (Boody et al. 1985a; Boody et al. 1985b).

Some trace metal concentrations may potentially be problematic in phosphate mine pit lakes. For example, cadmium levels are significantly elevated in phosphate mine pit lake sediments, and there are documented instances where phosphate mine pit lakes have exceeded the Class III water quality standard for cadmium (Rampenthal and Ferraro 1987; Boody et al. 1985a). Iron also appears to be elevated in the sediments of some phosphate mine pit lakes, and occasional instances have been recorded where phosphate mine pit lakes have exceeded the Class III water quality standards for iron. Mercury concentrations in excess of the Class III water quality standard were found in all lakes (natural and phosphate mine pit). Mercury concentrations may be elevated in phosphate mine pit lake sediments relative to natural lakes in central Florida; however, mercury concentrations in the water column were observed to be consistently lower in phosphate mine pit lakes relative to natural central Florida lakes (Rampenthal and Ferraro 1987).

Lead concentrations are elevated in sediments from phosphate mine pit lakes. However, lead concentrations observed in the water column were lower than the concentrations observed in natural lakes in central Florida. Using a hardness value of 90 for phosphate mine pit lakes (Pratt et al. 1985), all of the natural and phosphate mine pit lakes analyzed in the studies referenced in this paper (all of which were conducted during the 1980s) exceeded the Class III water quality standard for lead. The reader should keep in mind that in the time since the studies referenced in this paper were conducted, lead concentrations have declined significantly in waterbodies throughout the United States because of environmental regulations and the removal of lead additives from gasoline. Therefore, lead concentrations measured today are likely to be substantially lower in both natural lakes and phosphate mine pit lakes.

Physico-chemical interactions between the water column and the lake bottom sediments will likely change with time as organic material accumulates on the phosphate mine pit lake bottoms. Temporally, the organic material on the phosphate mine pit lake bottoms should increase in influence with regard to exchange of material with the water column relative to the original bottom sediments.

Biological Productivity and Trophic Status

Biological productivity in phosphate mine pit lakes shows a relatively strong negative correlation with maximum lake depth (Boody et al. 1985a). The overall greater maximum depths of many phosphate mine pit lakes are caused by deep pockets. These deep pockets are likely outside of the major lake-mixing patterns and develop stable stratification and anoxic conditions. In turn, the deep pockets then accumulate detrital material and function as nutrient sinks (Boody et al. 1985a; Boody et al. 1985b).

Phosphate mine pit lakes are typically mesotrophic to eutrophic, which is consistent with the trophic status of most other Florida lakes (Shannon and Brezonik 1972; Canfield and Hoyer 1988). Algal densities in phosphate mine pit lakes fall within the lower portion of the algal density range established for natural lakes. Phosphate mine pit lakes do not appear to reach their maximum algal growth potential (Boody et al. 1985b). Some of the algal taxa identified in the phosphate mine pit lakes are associated with eutrophic conditions or are responsible for water quality problems. However, these algal taxa are common in natural Florida lakes.

Phosphate mine pit lake waters have significantly higher concentrations of total phosphorus (TP), which is a measure of all phosphorus species (organic and inorganic), and of soluble reactive phosphorus (or ortho-P), which is a measure of the highly bioavailable inorganic soluble form of phosphorus (Boody et al. 1985a; Boody et al. 1985b; Pratt et al. 1985; Rampenthal and Ferraro 1987). Ortho-P is the predominant form of phosphorus in phosphate mine pit lakes. Phosphate concentrations in the phosphate mine pit lakes are high enough that fluctuations in phosphorus concentrations do not appear to have an impact on algal productivity. Phytoplankton densities in phosphate mine pit lakes generally correlate higher with nitrogen concentration than with phosphorus concentration (Boody et al. 1985b).

Nitrate/nitrite (NO_3/NO_2) concentrations in the water column of phosphate mine pit lakes are similar to the concentrations found in natural lakes in central Florida (Boody et al. 1985b). Ammonia (NH_3) concentrations may be elevated in the water column of phosphate mine pit lakes, and many phosphate mine pit lakes may potentially exceed the Class III water quality standard for un-ionized ammonia (Boody et al. 1985a). Algal abundance in phosphate mine pit lakes may be correlated with the concentration of nitrogen in the sediments and the water column. Nitrogen concentrations in phosphate mine pit lake sediments are very low in comparison to natural lakes in central Florida (Boody et al. 1985b).

Despite the possibility of phosphate mine pit lakes being nitrogen-limited, the blue-green algae found to dominate the phosphate mine pit lakes were generally non-N-fixing organisms (Boody et al. 1985b). One hypothesis put forward to explain the lack of dominance of N-fixing species in the water column is the high NH_3 concentrations. Because N-fixation is energy-consumptive, N-fixation is not metabolically efficient in the presence of high NH_3. Therefore, another factor, such as a nutrient (e.g., potassium or manganese) or light attenuation, may limit productivity.

Interpretation of inorganic N data suggests that phosphate mine pit lake productivity depends on inorganic N that originates from within the lake watershed outside of the lake water column (allochthonous sources). Hydraulic residence time is negatively related to trophic status. Lakes with longer residence times may exhibit decreased productivity relative to phosphate mine pit lakes with shorter hydraulic residence times (Boody et al. 1985a).

Most phosphate mine pit lakes likely have not yet reached a steady-state for their water chemistry, nutrient equilibrium, or trophic status (Boody et al. 1985a). Phosphate mine pit lake sediments should function as a net nutrient-sink as detrital material is buried. Nutrient levels in the water column should decrease with increasing lake age until the phosphate mine pit lake and its watershed reach steady-state equilibrium. Once such equilibrium is achieved, the organic material in the sediments should have a stronger influence on biogeochemical processes within the phosphate mine pit lakes. Additional studies are needed to determine how these processes change as organic material accumulates on the lake bottoms and lake biogeochemistry equilibrates with the phosphate mine pit watershed.

Fish and Wildlife Habitat

The biological communities in phosphate mine pit lakes are likely in a transitional state for several years following reclamation (Pratt et al. 1985). Regardless, an abundance of wading birds, amphibians, and reptiles use phosphate mine pit lake habitats. The studies referenced in this summary indicate that the fish communities in the majority of the phosphate mine pit lakes were similar in species composition to previous fisheries studies conducted in Florida freshwater systems (Boody et al. 1985a; Boody et al. 1985b). Connecting phosphate mine pit lakes to natural streams may have a positive impact on fish diversity and abundance in the phosphate mine pit lakes.

Florida phosphate mine pit lakes are well known for their thriving sport fish populations. Largemouth bass and/or bluegill are often the dominant fish species in the near-shore community of phosphate mine pit lakes (Boody et al. 1985a; Boody et al. 1985b). Limited data suggest that spawning of largemouth bass is enhanced in phosphate mine pit lakes relative to natural lakes. However, neither largemouth bass nor bluegills grow at a significantly faster rate in phosphate mine pit lakes as opposed to natural lakes.

Radioactive Elements

Uranium-238 is enriched in the phosphatic deposits (Hanlon et al. 1988; Guidry et al. 1990), and radium-226 content in sediments from phosphate mine pit lakes is generally higher than in sediments from natural lakes (Boody et al. 1985a). Radium-226 is likely bound to the sediments in phosphate mine pit lakes. The mean radium-226 in the water column of the phosphate mine pit lakes is usually less than concentrations found in natural central Florida lakes and was consistently less than the Class III water quality standard of 5 Picocuries per liter (Pi/L) (Boody et al. 1985a). Therefore, it appears unlikely that elevated radium-226 in the sediments of reclaimed phosphate mine pit lakes is a threat to human health. The higher radium-226 concentrations in phosphate mine pit lake sediments may result in considerably higher radon-222 activities (as high as 119 pCi/L) in the water column (Boody et al. 1985b). There is no Class III water quality standard for radon in Florida (FDEP 2010), though radon is a significant concern for drinking water.

Despite elevated levels of radium-226 in the sediments, radium concentrations are not significantly higher in above-ground plant tissue collected from phosphate mine pit lakes. However, the roots of cattail plants from phosphate mine pit lakes have significantly higher radium-226 levels relative to cattail roots from natural lakes (Boody et al. 1985b). Analyses of Asian clam (*Corbicula* spp.) and multiple fish trophic levels indicate that biomagnification of Ra-226 does not occur in either natural or phosphate mine pit lakes. In fact, fish from natural lakes actually had higher tissue radium-226 concentrations than fish from phosphate mine pit lakes.

One interesting finding by Pratt et al. (1985) was that Mosquito fern *(Azolla caroliniana* Willd.) and some *Lemna* spp. may hyper-accumulate radium-226. In these plants, radium-226 is taken up and incorporated into living tissues at concentrations far in excess of background concentration. Concentrations of radium-226 in *Lemna* and *Azolla* in phosphate mine pit lakes have been observed to exceed background concentrations in the water column by factors of more than 100,000 (*Lemna*) and 54,000 (*Azolla*). This finding should be investigated further.

Morphological Controls on Phosphate Mine Pit Lake Functions

From a nutrient, water quality, radiation, and fish and wildlife perspective, phosphate mine pit lakes are generally equivalent to natural Florida lakes. Most phosphate mine pit lakes appear to fall into the alkaline-clear category per the classification scheme developed by Shannon and Brezonik (1972). This classification is driven by the relatively high levels of calcium, alkalinity, and conductivity. However, the phosphate pit lakes differ from the alkaline-clear lakes described by Shannon and Brezonik (1972) in that they appear to have a neutral to slightly acidic pH.

Summary

Water quality should be the primary consideration for phosphate mine pit lakes. Efforts to manage these lakes should be focused on reducing productivity and maintaining trophic states closer to the mesotrophic range. Because phosphate mine lakes are in a transitional state following reclamation, phosphate mine pit lakes and their contributing watersheds do not likely reach equilibrium for their water or sediment chemistry at the time of sampling. Additional sampling should be conducted to see whether any differences can be observed following 25 years of reclamation.

In general, the amount of research that has been performed on phosphate mine pit lakes is inadequate to draw strong inferences about their limnology. The trends identified in this paper should be tested with further limnological studies to better refine our understanding of these important components of the post-mining landscapes of central Florida.

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