Geospatial Analysis of Depressional Wetlands near Peace River Watershed Phosphate Mines, Florida, USA

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ABSTRACT

Mining throughout the Floridan aquifer system alters groundwater conditions. Determination of magnitude and extent of groundwater alterations in this regional karst aquifer system is difficult due to preferential flow paths, blasting, and widespread aquifer withdrawals and injections. Additionally, hydrologic models do not reveal subsurface impacts to the biotic environment, such as destruction of vegetative buffers, which are essential habitat for endangered and threatened species and other wildlife, and degradation from invasive species responding to hydroperiod disruptions. Our case study uses remote sensing and a geographic information system (GIS) to evaluate near-infrared (NIR) data for natural herbaceous depressional (wet prairie) wetlands in a central Florida phosphate mining area. These wetlands characteristically are dominated by graminoids, which have lower NIR reflectance and consequent digital numbers (DNs) in remotely sensed imagery than invasive species associated with hydroperiod alterations. Maximum aquifer withdrawals of 76,457 m^3/d were permitted in November 1977 and remain active for study-area mines, which are surrounded primarily by un-irrigated pasture. Digital color infrared aerial imagery acquired in winter 2003–04 (1-m ground resolution) was used to extract NIR values within depressional wetlands. Digital historic (mid-1950s) U.S. Geological Survey topographic quadrangle maps (1:24,000 scale) were selected to delineate baseline wetland boundaries using ESRI ArcGIS 9.2. The study area included 567 of these wetlands, totaling 1,367 hectares. High mean NIR values (≥100 DN) consistent with hydroperiod-altered wetlands dominated by invasive plant species characterized 284 wetlands (50 and 60 percent total number and area, respectively), including some >5 km from study-area mines. Only 108 wetlands (20 and 10 percent total number and area, respectively) had low mean NIR values (≤80 DN) indicative of natural wet prairies without invasive species. Shallow ditches were not a statistically significant factor influencing NIR signatures in these wetlands. The spatial distribution of wetlands with high NIR DNs was inconsistent with conical groundwater drawdown predicted by groundwater models but suggests more linear fluid movement via subsurface preferential NW-SE flow paths.

INTRODUCTION AND BACKGROUND

Problem Statement

Natural depressional wetlands are characteristic of the regional ecology throughout the karstic southeastern coastal plain of the United States. These wetlands are regulated by local, state, and federal laws (e.g., Rule 9J-5.013, Florida Administrative Code; Section 163.3177[6][d], Florida Statutes; U.S. Clean Water Act; U.S. National Environmental

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Policy Act) to conserve, protect, and ensure no net loss, including from hydrologic alterations and cumulative impacts.

Regional hydrogeology, previous hydrologic studies, and the extent and magnitude of excavations and groundwater withdrawals (~76,500 m^3/d within the area of this case study) consequent to phosphate mining all suggest a substantial probability that mining has altered groundwater levels and natural hydroperiods at considerable distances from surface footprints of mine operations. Karst depressional wetlands particularly are susceptible to such impacts because, by definition, they are located in areas of concentrated interaction between the aquifer system and surface waters.

Regulation and remediation of hydrologic effects from mining focus on areas within project boundaries, primarily the surface footprints of mining operations, and particularly ignore off-site and cumulative effects on these depressional wetlands. The absence of baseline hydrologic records for natural depressional wetlands throughout the extent of the regional karst Floridan aquifer system makes assessment of the effects of mining on natural wetland hydroperiods a challenging proposition requiring new and flexible methodological approaches.

Phosphate Mining in Florida

Mining for phosphate in Florida occurs extensively in the central Florida Peace River watershed and to a lesser extent in the north Florida Suwannee River watershed. Permit applications from numerous federal, regional, and state agencies for expanding phosphate mining are pending or have been approved recently in both of these environmentally sensitive watersheds. Few scientific publications address the environmental impacts of mining in the Suwannee River watershed compared to the Peace River watershed, possibly because the former is sparsely populated. Groundwater flow reversals and the cessation of flow in major springs due to phosphate mining have occurred in both watersheds (Lewelling et al., 1998).

Related hydrologic impacts of excessive groundwater withdrawals and other mining impacts on natural lake, stream, and aquifer levels, saltwater encroachment, sinkhole development, and long-range adequacy of water supplies were described for the upper Peace River as early as the mid-1960s (Kaufman, 1967).

In the Polk County vicinity of the upper Peace River, the decline in groundwater levels caused a reversal of hydrologic conditions, resulting in the Peace River and shallow, surficial aquifer flowing into the underlying Floridan aquifer rather than the Floridan aquifer supplementing the surficial aquifer and river (Kaufman, 1967). Assessments of impacts from these hydrologic alterations on depressional wetlands in the Peace River watershed and similar mining areas were not found in peer-reviewed literature searches.

The Peace River flows 169 km (105 mi) from its headwaters, in the vicinity of Lake Hancock in central Florida, to Charlotte Harbor in southwest Florida (Figure 1a). The Peace River watershed (basin) falls within the regulatory boundaries of the Southwest Florida Water Management District (SWFWMD) and has been subdivided into five sub-basins for regulatory purposes: (1) above Arcadia, (2) below Arcadia, (3) Horse Creek, (4) Joshua Creek, and (5) Shell Creek (Figure 1b).

The Peace River watershed encompasses 6,110 km^2 (2,359 mi^2) of west-central Florida (Lewelling et al., 1998) in Polk, Hardee, Manatee, Highlands, DeSoto, Sarasota, and Charlotte Counties (north to south), as depicted by the shaded area in Figure 1a. Phosphate mining was initiated in that watershed in the late 1800s. By the late 1990s, much of the Peace River watershed in Polk County had been mined for phosphate and "reclaimed." Those mining and reclamation processes altered natural drainage patterns, lowered groundwater levels and may have contributed to the overall decline of streamflow in the Peace River (Lewelling et al., 1998). It is important to note that reclamation of mined lands in Florida is less stringent than restoration and re-vegetation of other altered environments (378.207, Florida Statutes).

The total area of the Peace River watershed that had been mined at the time of the evaluation by Lewelling et al. (1998) is not known. Mosaic Phosphate Company, LLC (2007), one of several mining companies and producers of commercial fertilizers in the Peace River watershed, released a map for the middle Peace River watershed (Hardee, Manatee, and DeSoto Counties) showing the total areas mined (black areas in Figure 1b) and proposed for mining (dashed line in Figure 1b) by their company as of 2007.

Significant expansion of phosphate mining within the middle Peace River watershed, including in Hardee County, has also been recently proposed. The expansion of phosphate mining described in the C. F. Industries, Inc. (CFI), permit application is one example. This expansion would add 3,005 hectares (7,422 acres) to the existing CFI mine of 70,344 ha (173,750 acres). This proposed expansion would include 680 ha (1,680 acres) of mining in, on, or over wetlands or other surface waters, as identified by the mining company (C. F. Industries, Inc., 2009), but

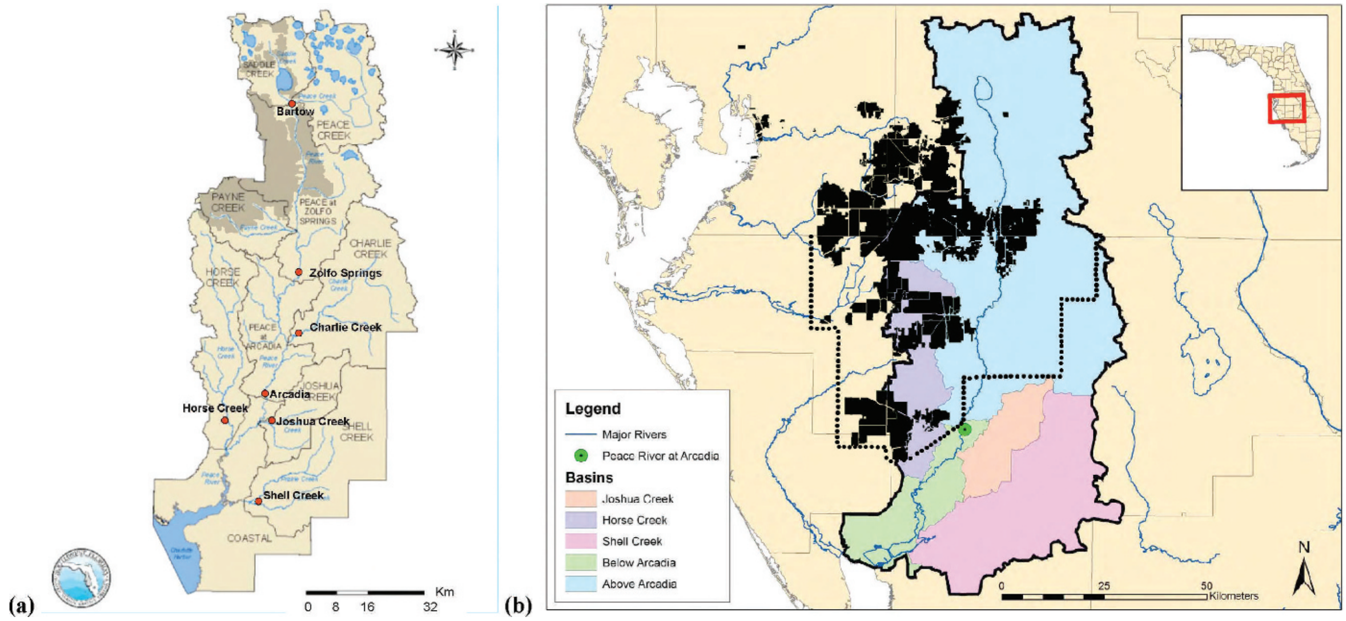

Figure 1. Peace River (a) watershed and (b) sub-basin boundaries (modified from Figure 3 and Figure 21, respectively, in SWFWMD, 2009), with the extent of phosphate mining prior to 1998 represented in (a) by the shaded area in the north (from Figure 16 Lewelling et al., 1998) and the extent of Mosaic Fertilizer, LLC (2007) mine-area holdings and its proposed boundary for mining represented in (b) by solid black fill and dashed lines, respectively (Exhibit A from Mosaic Fertilizer, LLC, 2007).

indirect and cumulative impacts to wetlands and other surface waters have not been determined.

Perception of Damage from Hurricanes and Rainfall Fluctuations

A common perception of local commissioners, municipal and regulatory staff, and the public is that environmental degradation and destruction in the vicinity of mined areas in southern Florida are the result of impacts from the 2004 hurricane season or periods of low rainfall rather than mining, as described by Bacchus (2007). Examples include statements and testimony by proponents of proposed mining projects and local permitting authorities associated with 2007 mine-permit hearing procedures in Charlotte and Sarasota Counties and with the 2008 mine-permit hearing procedures in Hardee County for proposed expansion of phosphate mining in that county. No published or unpublished data were identified to support those beliefs.

Anthropogenic hydrologic alterations, rather than annual fluctuations in rainfall, have been identified as the determining factor in the demise of both herbaceous (e.g., wet prairie) and forested depressional wetlands in Florida (Hofstetter and Sonenshein, 1990; Sonenshein and Hofstetter, 1990; and Southwest Florida Water Management District [SWFWMD], 1996). Despite those findings, which refute rainfall fluctuations as the cause of wetland destruction in southern Florida, we considered historic rainfall and relevant hurricane-season factors with respect to potential influence during the baseline and assessment periods of this case study as conservative elements. In fact, rainfall contributed by these tropical cyclones (hurricanes) in the southern United States accounted for approximately 8–17 percent (mean 12.8 percent) of cumulative rainfall during the hurricane season of 1998–2006 (Shepherd et al., 2007) and should be beneficial to depressional wetlands.

Hydrologic and Environmental Impacts of Mining

Major Effects of Mining

The three major effects (impacts) of mining and reclamation on streamflow conditions in the Peace River watershed are described in Lewelling et al. (1998). The first is the lowering of the potentiometric surfaces in underlying aquifers by large groundwater withdrawals. This impact resulted in the cessation of spring discharge and a reversal of natural head gradients, causing permanent cessation of flow from Kissengen Spring and other smaller springs in the upper Peace River watershed in April 1960. Peek (1951, p. 75) reported historic discharge of groundwater from the spring at "approximately 30 cubic feet per second" (73,398 m^3/d, or 20 million gallons per day [MGD]) from 1898 to 1931. The second major

effect is the significant alteration of local natural surface-drainage patterns. Exposure of the aquifer because of mining is the third major effect. This results in lowering of groundwater head, groundwater impoundment, and loss of groundwater to evaporation (Lewelling et al., 1998). Relevant examples 2 through 5 of the alterations described by Lewelling et al. (1998, p. 2) are as follows:

(2) reduced or eliminated base flow;
(3) reduced surface runoff in mined and reclaimed areas where overland flow is impounded in pits and surface depressions;
(4) replacement of natural surface drainage by a system of reclaimed ditches, swales, and modified topography; and
(5) lowering of water levels in the upper Floridan aquifer from groundwater withdrawals by the mining industry to transport and process phosphate ore.

Large clay-settling areas resulting from the phosphate mining process can be more than 12 m (39 ft) deep and require decades to reach final design elevation. These settling areas cover hundreds of hectares, are the dominant reclaimed landform type located along the Peace River, and result in significantly less groundwater recharge and downward movement of water than in natural conditions (Lewelling et al., 1998). Additionally, shrinkage of the consolidating clays can cause surface depressional features to form, increasing ponding and evaporation and, thus, reducing runoff (Lewelling and Wylie, 1993). All of these factors result in adverse impacts to off-site depressional wetlands.

Natural Hydroperiods

Both water quality and water quantity impacts may result from phosphate mining. In this case study, we focus on the latter, including impacts to the biotic environment resulting from the types of alterations described by Lewelling et al. (1998). Similar water quantity (hydroperiod) impacts also occur from other types of mineral extractions (e.g., aggregate, "fill dirt," "lime rock," sand, shell). Hydroperiod components include: (1) the depth/stage of fluctuating groundwater and surface water; (2) the duration of the water level at a given depth and stage; and (3) the periodicity and seasonality of the water-level fluctuations. Disruption of any one of the components can result in degradation and ultimate destruction of wetlands and associated biota (Bacchus, 1995, 1998). Hydrologic monitoring in depressional wetlands and natural lakes in Pinellas, Pasco, and northern Hillsborough Counties, north of Hardee County and within the same water management district, confirmed that water levels in the upper Floridan and surficial aquifers are linked and that Floridan aquifer withdrawals are a driving force in surficial-aquifer fluctuations (Watson et al., 1990; SWFWMD, 1999).

Hydrologic alterations can affect one or all of the essential components of natural hydroperiods (depth, duration, and season). Native amphibians are examples of biota unable to complete their life cycle and reproduce if even one of the natural hydroperiod components is altered. Specific hydroperiod requirements for these important food-chain organisms vary by species (Moler and Franz, 1987). Those requirements include species-specific water-level requirements for successful reproduction, such as very shallow (<10 cm), shallow (10–30 cm), moderate (30–100 cm), or deep (>100 cm) water. Duration and season of water-level fluctuations also are essential hydroperiod components for the successful reproduction of these important organisms (Moler and Franz, 1987).

Ranges of the three hydroperiod components for depressional wetlands prior to hydroperiod alterations from mining, or similar activities that result in groundwater alterations, were not found in the literature. Kushlan (1990) described the hydroperiod duration of Florida's wet prairie depressional wetlands as 50–150 days but did not address seasonal or depth components. That range is consistent with the minimum larval period (time required from the hatching of eggs through the tadpole stage to adult) for frog species such as the southern cricket frog (*Acris gryllus*), which uses wet prairie wetlands as breeding habitat (Moler and Franz, 1987). Consequently, the hydroperiod duration range provided by Kushlan (1990) may have been derived from biological data, such as documentation that the wetlands were being used for successful breeding of frog species in which the number of days of standing water for the larval period has been established. No continuous records of surficial aquifer/wet prairie hydrologic conditions were found for the study area. Therefore, the pre-mining hydroperiod of wet prairie wetlands in the study area and Peace River watershed must be assessed using means other than conventional hydrologic data and modeling.

In addition to the amphibian species dependent on these types of depressional wetlands for survival, five federally threatened or endangered animal species and 14 animal species listed by the state as threatened, endangered, or species of special concern have been documented within the study area (Table LSS-3 from C. F. Industries, Inc., 2009). These data confirm the

use of areas rich in depressional wetlands by a multitude of animal species that have limited ranges and declining populations. These data also emphasize the need for more extensive scientific evaluations of the condition of these sensitive wetlands to hydrologic impacts of mining beyond the surface footprint of mining operations.

Depressional versus Isolated and Ephemeral Wetlands

Bacchus (2007) describes how Florida's depressional wetlands frequently are referenced as "isolated" or "ephemeral" wetlands and "temporary" or "ephemeral" ponds (Means, 2008), because the natural hydroperiod of these ecosystems alternates between inundation and lack of standing water. References to depressional wetlands as "isolated" or "ephemeral" are misnomers, implying ecosystems that lack hydrologic connections and are temporary or short-lived. In fact, these are ancient natural wetlands formed in relict sinkholes, also known as solution features, which have preferential connections to the underlying regional karst aquifer system and surrounding surface waters (Watson et al., 1990; Bacchus, 2007). Therefore, depressional wetlands represent a natural community type particularly sensitive to the hydrologic alterations associated with phosphate and other mining (Bacchus, 2007). Historically, these wetlands were connected to streams and other regulated waters by both surface-water connections, as confirmed by historic U.S. Geological Survey (USGS) topographic quadrangle maps for southern Florida, and by groundwater connections (Watson et al., 1990). These historic connections imply that subsurface alterations of the natural hydroperiod for depressional wetlands in this karst landscape can result in adverse impacts to stream ecosystems in various ways. For example, Patton and Klein (1989) analyzed sinkholes that had formed in the floodplain of the upper Peace River watershed in proximity to phosphate mines and concluded that those sinkholes and other solutional conduits act as influent channels into the Floridan aquifer that can affect the flow of the Peace River during both high-water and low-water stages. Their study did not appear to include an evaluation of relict sinkholes associated with depressional wetlands.

Despite the documented environmental impacts of groundwater alterations on depressional wetlands, the primary focus of regulatory agencies and the mining industry has been impacts to streams and riparian wetlands confined to the surface footprint of the mining operation. For example, Lewelling et al. (1998) conducted a seismic-reflection survey along the Peace River to evaluate the integrity of the lower permeability zones of the aquifer system. That evaluation focused only on the area of the pronounced river channel and did not evaluate associated depressional wetlands. Seismic-reflection profiles representing disruption of confinement associated with the middle Peace River in Hardee County, in proximity to phosphate mining in central Florida, included Max Branch confluence, Little Charlie Creek confluence, and north of Hog Creek confluence (Lewelling et al., 1998, figures 31a, b and c, respectively). The similar exclusion of depressional wetlands from monitoring and evaluation required by regulatory agencies and agency-supported research was addressed by federal court rulings that identified depressional wetlands as an important consideration when endangered or threatened species will be affected by proposed activities (Sierra Club v. Flowers, No. 93-23427 [S.D. Fla. March 22, 2006] Case No. 03-23427-CIV-Hoeveler). The case resulting in these rulings was initiated when the U.S. Army Corps of Engineers (Corps) and U.S. Fish and Wildlife (USFWS) issued a single permit for ten "rock" mines in the Miami-Dade County Everglades. That case is similar to the pending case against the U.S. Army Corps for the proposed expansion of phosphate mining in central Florida (Sierra Club et al. v. U.S. Army Corps of Engineers and Pantan, Jr., Case No. 3:10-cv-00564-HLA-JBT). In the rock-mine case, the court found that the agencies failed to consider fully the impact those mines would have on the wood stork, a federally endangered species dependent on depressional wetlands for recovery and survival. The generally accepted explanation for the decline in wood storks as a U.S. breeding species is loss and hydrologic alteration of its wetland habitat (Bentzien, 1986), providing additional support for the need to create a scientific means of evaluating cumulative environmental impacts of hydrologic alterations associated with mining.

Assessing Cumulative Environmental Impacts of Mining

Currently, the federal regulatory agencies have not adopted any scientific methodology for assessing cumulative environmental impacts associated with mining. Additionally, no specific scientific methodology has been developed for using remote sensing to evaluate cumulative environmental impacts from mining and hydroperiod alterations in the southeastern United States. Color and color infrared (CIR) aerial photographs and digital images have been used widely for mapping and distinguishing invasive vegetation at the plant community level (Bogucki et al., 1980; Welch et al., 1988; Nohara, 1991; Everitt et

al., 1996; Lachowski et al., 1996; Lake et al., 1997; Osborn et al., 2002; Madden, 2004; and Parker Williams and Hunt, 2004). The CIR films and digital images recording near-infrared (NIR) wavelength bands are particularly useful for this type of vegetation analysis because infrared reflectance varies more than red or green reflectance for individual plant species. Thus, a CIR image or photograph will exhibit a variety of red hues specific to particular vegetation communities or even individual species that imagery without NIR bands lacks (Murtha et al., 1997; Madden, 2004).

Invasive Species

Invasive species represent one type of cumulative impact that may occur from mining. No published data were identified regarding remote sensing analysis of phosphate mining related to the distribution of invasive plant species. Narrow-leaved graminoids (e.g., maidencane and similar dominant species of natural depressional wet prairie wetlands) reflect less NIR radiation than broad-leaf plants having multiple layers of leaves in a woody shrub or tree canopy (Lillesand et al., 2008). Therefore, reflectance measurements in the NIR range allow discrimination between some individual plant species, particularly invasive and non-invasive species, using remote sensing. For example, the leaves of Johnson grass (*Sorghum halapense* [L.] Pers.), native to Europe and Africa and initially introduced in South Carolina for livestock forage about 1830, respond distinctly to solar radiation and therefore are distinguished easily from other plants using remote sensing (McWhorter, 1989). This conceptual basis supports the presumption that relatively natural graminoid-dominant vegetation characteristic of depressional herbaceous wetlands such as wet prairies will exhibit a lower NIR reflectance (and digital numbers) than depressional wetlands dominated by non-graminoid invasive plant species, including shrubs and other woody species. Therefore, this type of analysis could be useful in evaluating invasive plant species associated with mined areas.

Buffers and Habitat Protection

An analysis of cumulative impacts that may occur from mining also should include an assessment of wildlife habitat and buffers intended to protect that habitat. No published data were identified regarding remote sensing analysis of phosphate mining impacts on wildlife habitat and buffers intended to protect that habitat. Kushlan (1990) described wet prairies as Florida's most species-rich herbaceous wetlands, dominated by maidencane and a variety of native grasses, sedges, and flowering forbs, such as cordgrass (*Spartina* spp.), beakrush (*Rhynchospora* spp.), or muhly (*Muhlenbergia* spp.). The state and global rankings of wet prairie wetlands are S2 and G3, respectively. The S2 rank is applied to natural communities that are imperiled in the state because of rarity or because of some factor(s) making those natural communities especially vulnerable to extinction. The G3 rank is applied to natural communities that are very rare and local throughout the range of a community or are found locally in a restricted range or because of other factors, making those natural communities vulnerable to extinction throughout its range. Those rankings emphasize the importance of wet prairie wetlands (Florida Natural Areas Inventory and Florida Department of Natural Resources, 1990).

Depressional wetlands provide nesting and feeding habitat for myriad species of native wildlife, including habitat critical for the survival and recovery of federally endangered wood storks (*Mycteria americana*) and other species with declining populations. Considering only amphibians, a critical lower link in the wildlife food chain, these depressional wetlands have been documented as breeding habitat for 18 species of frogs and 10 species of salamanders listed by Means (2008). These important food-chain species also require upland habitat surrounding these wetlands. Means (2008) described widths of the required contiguous upland habitat ranging from ~288 m to 2,012 m (944 ft to 6,600 ft).

Local, state, and federal laws require protection of wildlife habitat, particularly habitat for federally endangered and threatened species such as wood storks, as described in the court orders related to mining in Sierra Club v. Flowers, No. 93-23427 (S.D. Fla. March 22, 2006) Case No. 03-23427-CIV-Hoeveler. Municipalities and state and federal regulatory agencies presume that habitat is protected when buffers are provided and often include references to buffers in regulations related to wetland impacts from proposed actions such as mining. Although the minimum width of the upland buffer zone recommended by Means (2008) to maintain important wetland functions is ~503 m (1,650 ft), required widths for buffers included for any type of permit in Florida generally are much smaller. For example, a recent analysis of ordinances in 39 counties (excluding Hardee County) and nine cities in Florida revealed that 13 required no buffers between wetlands and developments, including mining. Those municipalities defer to state recommendations, "which require an average of 25 feet and minimum of 15 feet to prevent secondary impacts."

Buffer widths required by other municipalities ranged from ~3.1 m (10 ft) to ~91 m (300 ft), excluding wider buffers restricted to streams (Jones, Edmunds, and Associates, 1999). Those regulatory buffer widths were not based on scientific determinations of the extent of cumulative impacts but on surveys of other municipal requirements and political decisions.

The important role of these buffers is to protect depressional wetlands that maintain natural storage of water during the rainy season, water quality, and habitat critical for native wildlife. Thus, a scientific methodology for evaluating mining impacts to these wetlands and wildlife habitat is critical. The sensitivity of these depressional wetlands to subsurface alterations of the natural hydroperiod makes these wetlands ideal ecosystems for monitoring secondary (indirect) and cumulative adverse hydroperiod impacts beyond the surface footprint of mines.

Purpose and Scope

The purpose of this case study was to develop a methodology for remotely sensed assessment and classification of natural wet prairie depressional wetland conditions associated with phosphate mining operations in central Florida that is representative of this mining within the U.S. southeastern coastal plain. The objective was to utilize quantitative data collected from the NIR spectral band of high-resolution public domain airborne images, ground truthing, and qualitative rapid ground assessments to identify the distribution of spatial patterns in these depressional wetlands that may be correlated with groundwater alterations from existing mine operations. To exclude any adverse or beneficial impacts of the 2004 hurricane season such as wind damage and increased rainfall, respectively, imagery acquired prior to that abnormally active hurricane season was used for this evaluation. Historic rainfall records also were reviewed. The presence of shallow ditches associated with some of the depressional wetlands in proximity to the mines also allowed evaluation of the relative impact of those ditches on the NIR values of depressional wetlands. The results of this case study should provide a framework for future hydroecological investigations, including cumulative impacts from mining in the U.S. southeastern coastal plain and other karst regions.

STUDY AREA

An 8 × 16 km (5 × 10 mi) study area was selected in northwest Hardee County, Florida, approximately 2.5 km (1.6 mi) east of the Manatee County line and 5 km (3.1 mi) south of the Polk County line (Figure 2a). The 128-km^2 (50-mi^2) study area extends across the central portion of the Duette, Ft. Green, and Wauchula 1:24,000-scale USGS topographic quadrangle maps (Figure 2b).

The study area was selected based on the proximity of a cluster of mine pits to un-mined natural areas in and adjacent to Hardee County, including forested riparian wetlands and wet prairie (herbaceous) wetlands. The study area also included un-irrigated pasture used for cattle grazing. Study-area mines were permitted in November 1977, initiating maximum aquifer withdrawals of 76,457 m^3/d (20.2 MGD), and they remain active today (SWFWMD Consumptive Use Permit No. 27703669). This permitted withdrawal exceeds the volume of Kissengen Spring groundwater discharge from 1898 to 1931 (Peek, 1951), before that spring ceased to flow. In comparison, the largest municipal groundwater withdrawals in Hardee County in proximity to the mines is for a permitted volume of 5,616 m^3/d (1.48 MGD) for a service area of 11,405 ha (28,512 acres) by the City of Wauchula, the county seat (SWFWMD, 2007).

The cluster of phosphate mine pits is located south of Highway 62 in the central portion of the study area. West of the Ft. Green Ona Road (Highway 663), the study area includes portions of the upstream reaches of Horse Creek, a western tributary of the Peace River; as well as Brushy Creek, an eastern tributary of Horse Creek; and Lettis Creek, an eastern tributary of Brushy Creek (Figure 2a).

METHODOLOGY

Focus of Geospatial Analysis

Natural depressional wetlands were selected for geospatial evaluation in this case study based on: (1) the general lack of regulation and scientific monitoring of these environmentally important wetlands; (2) the susceptibility of these wetlands to adverse subsurface hydrologic impacts off-site or several kilometers from withdrawal wells (House Committee on Natural Resources, 1994; Southwest Florida Water Management District, 1996; and Bacchus et al., 2003); (3) the paucity of scientific data that could be used to determine widths of buffers required to protect these wetlands; and (4) the potential for using these wetlands to detect adverse impacts beyond the surface footprint of mine projects. Hardee County was an ideal location for the case study because of the limited quantity of groundwater withdrawals by other activities surrounding existing mines selected for evaluation. The focus of the case study was narrowed further to wet prairie depressional wetlands in Hardee County because of the relative abundance of those

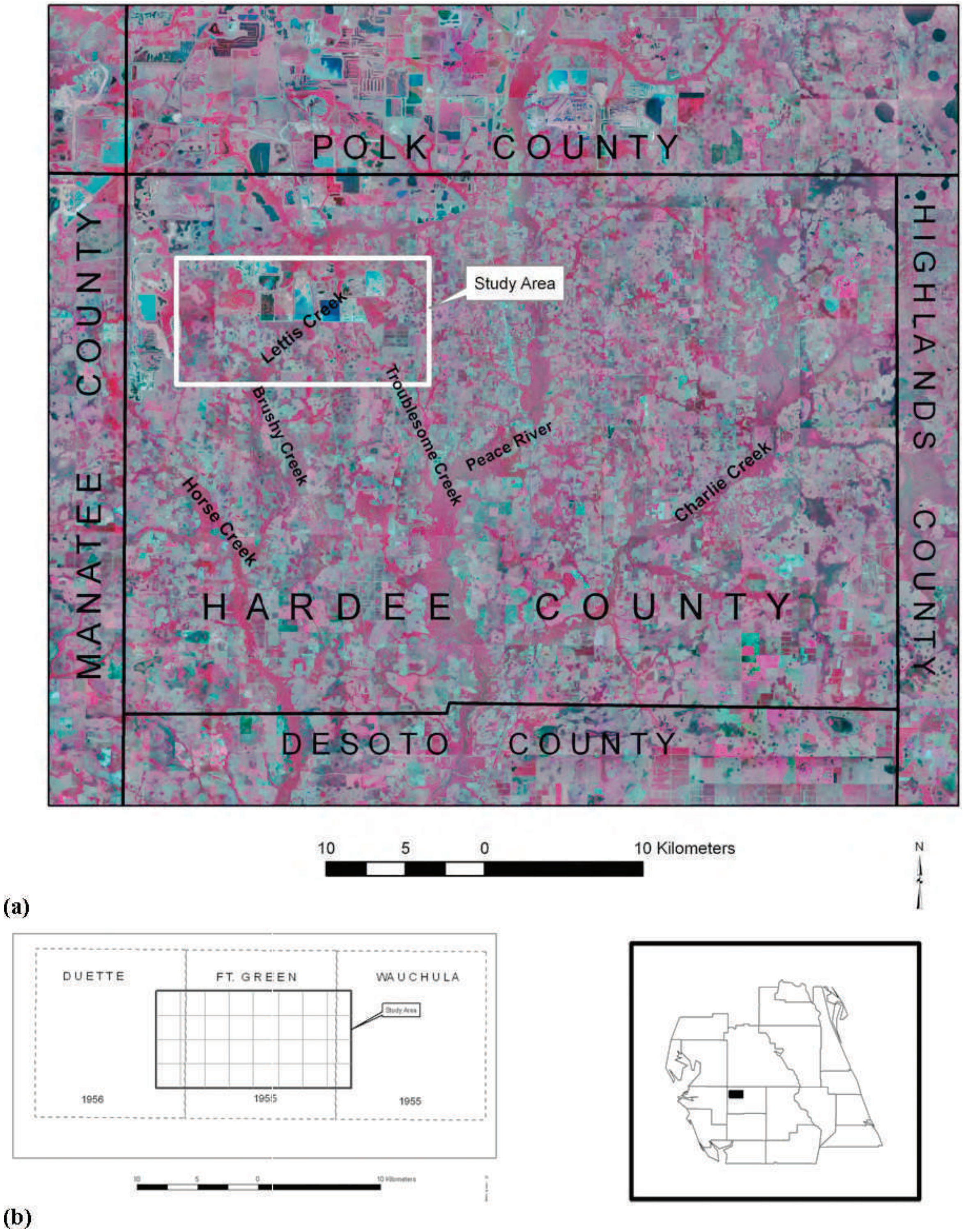

Figure 2. Location of the 8 × 16 km study area over: (a) the 2003–04 U.S. Department of Agriculture (USDA) color infrared (CIR) aerial imagery for Hardee County, Florida, and (b) historic U.S. Geological Survey (USGS) topographic quadrangle maps.

depressional wetlands in proximity to the mines. Despite the narrowed focus of this case study, results of this study are relevant to impacts from groundwater alterations throughout the Peace River and Suwannee River watersheds as well as throughout the U.S. southeastern coastal plain. Similar impacts

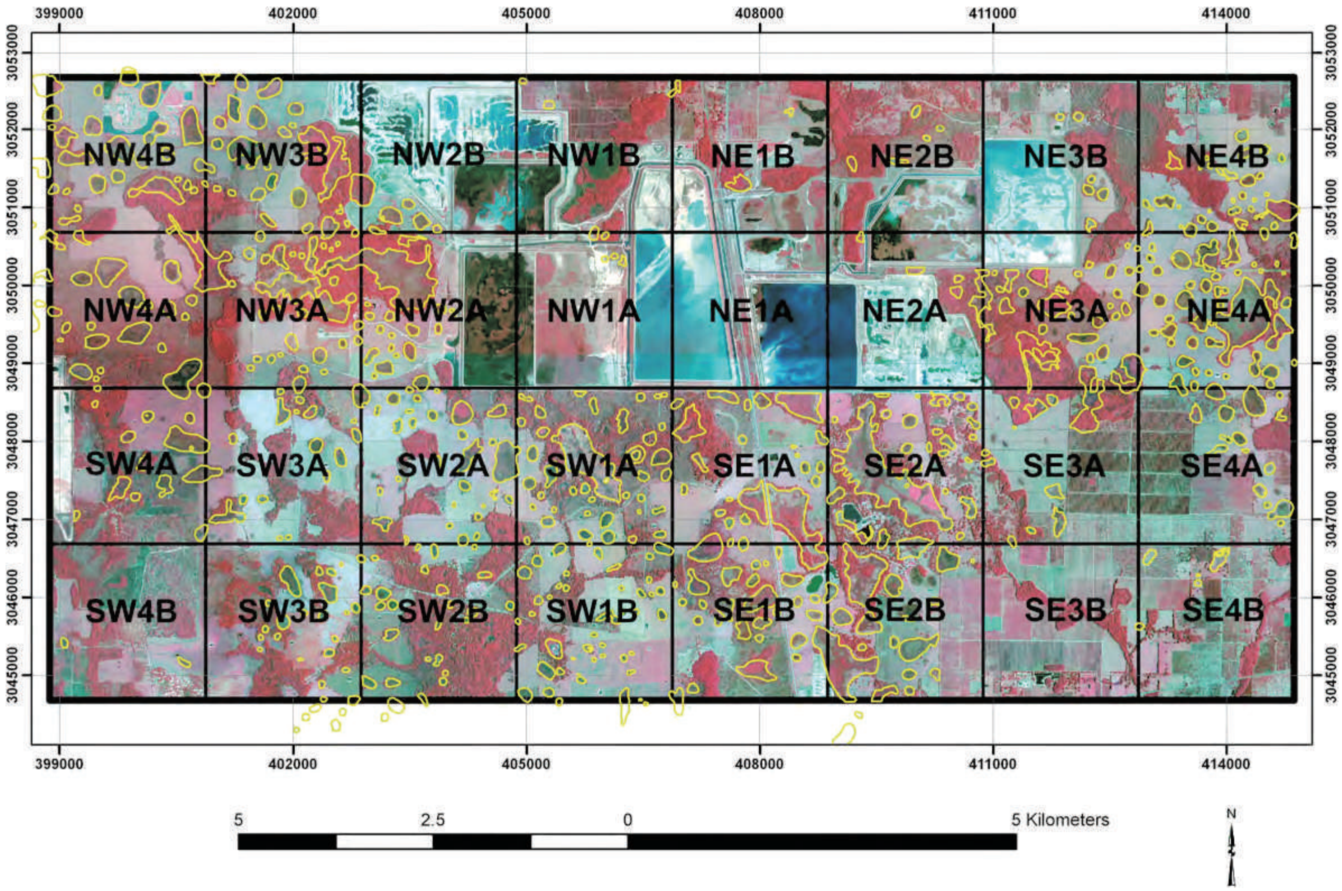

Figure 3. Plot locator map for the study area composed of 2003–04 CIR digital images with overlay depicting grid of 4-km^2 imagery plots and wet prairie wetland polygons digitized from historic U.S. Geological Survey (USGS) topographic quadrangle maps.

from groundwater alterations in this region should be expected on comparable herbaceous and forested depressional wetlands historically characterized by graminoids such as maidencane (*Panicum hemitomon* Schult.) and pond cypress (*Taxodium ascendens* Brongn.), respectively. Pond cypress depressional wetlands are restricted to the U.S. southeastern coastal plain (Godfrey, 1988; Godfrey and Wooten, 1979), which coincides with the extent of the regional karstic Floridan aquifer system (Bacchus, 2000).

Data Sources

Color infrared (CIR) aerial imagery, acquired during December 2003 to March 2004 by USGS and orthorectified as digital orthophoto quarter quadrangles (DOQQs), was obtained online from the U.S. Department of Agriculture (USDA), Geospatial Data Gateway (USDA, 2009). The imagery has a pixel ground resolution of 1 m (3.3 ft) and preceded any potential damage or beneficial rainfall that may have occurred to the wetlands from the 2004 hurricanes.

The USGS Digital Raster Graphics (DRGs), georeferenced versions of historic 1:24,000-scale USGS topographic quadrangle maps encompassing the study area (Duette, 1956; Ft. Green, 1955; and Wauchula, 1955), were used to define "baseline" wetland boundaries. The digital map coordinate system was matched to the UTM NAD 83 coordinate system for the CIR imagery. Software used for geospatial analysis of the study area, creation of the 8 × 16 km study-area grid of 2 × 2 km plots (Figure 3), and creation of graphic images included ESRI ArcGIS 9.2, Leica Geosystems ERDAS Imagine 9.1, Microsoft Excel 2003, and Adobe Photoshop CS2, version 9.0.

Annual rainfall data reviewed for this case study included long-term data collected at SWFWMD and 27 National Weather Service (NWS) stations within or adjacent to the Peace River watershed (Figure 4) and analyzed by Basso and Schultz (2003). The rainfall data included NWS annual rainfall data for the 105-year period from 1895 to 2000 and 5-year running mean rainfall averaged from Peace River stations and 27 long-term stations, in addition to

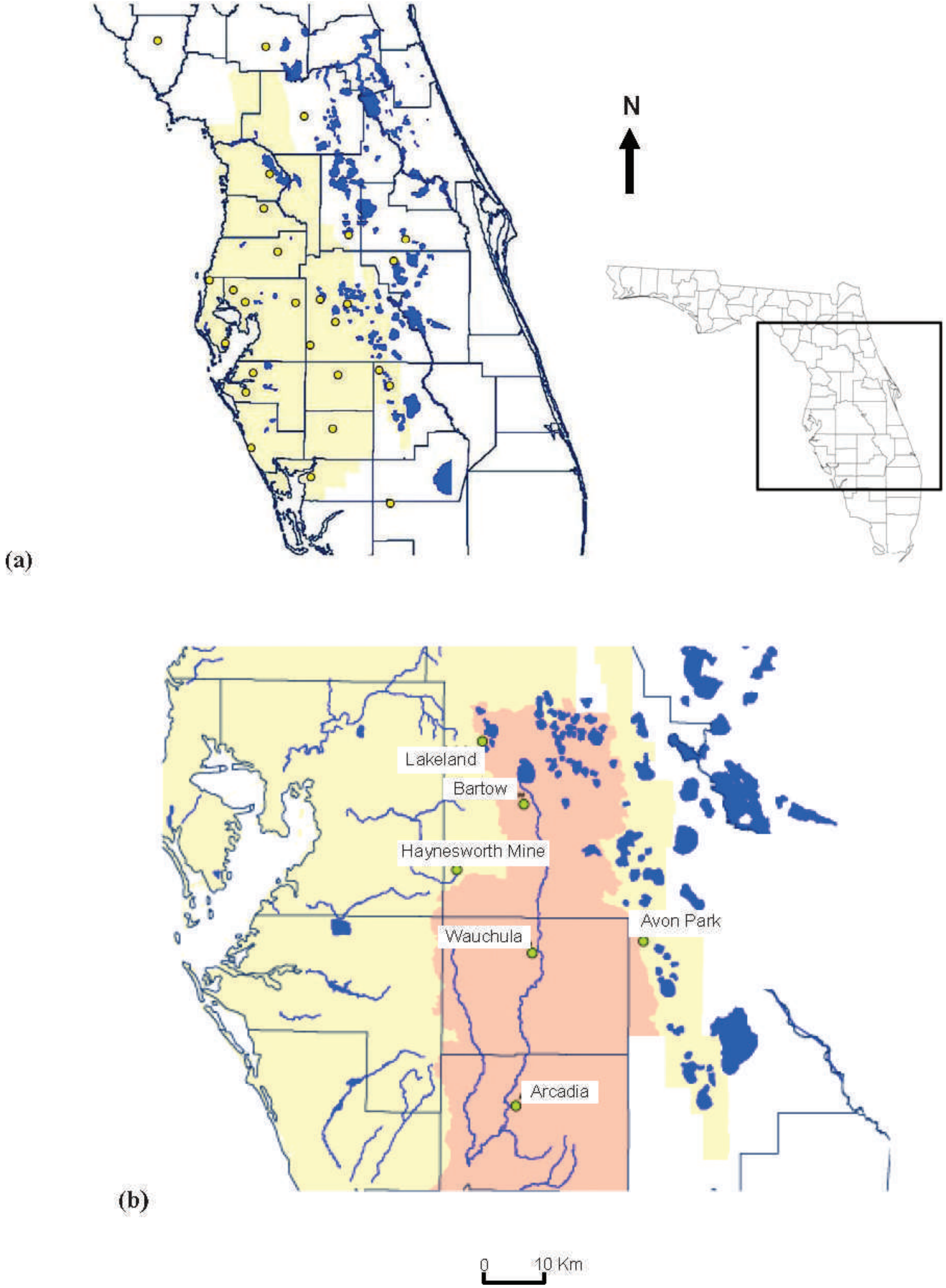

Figure 4. Location of long-term rainfall stations (a) for SWFWMD and 27 National Weather Service stations and (b) within or adjacent to the Peace River watershed (from Basso and Schultz, 2003).

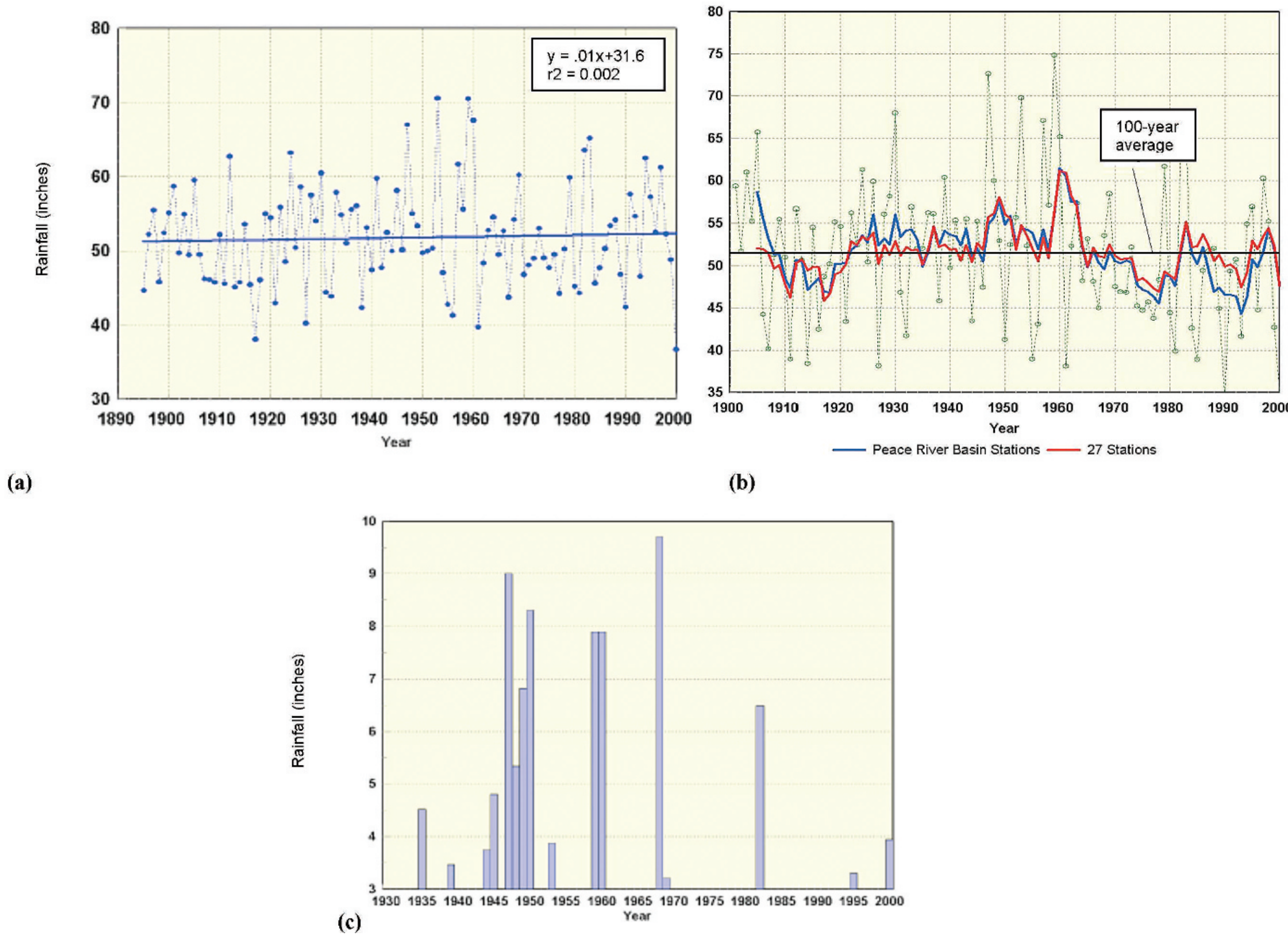

Figure 5. Annual rainfall for study-area vicinity (a) for 105 years, with linear regression, from National Weather Service (regions 3 and 4); (b) with 5-year running mean rainfall averaged from Peace River stations and 27 long-term stations; and (c) tropical cyclone contribution (>7.5 cm [3 in.]) to wet season rainfall in the Peace River watershed (Figures 4, 8, and 24, respectively, from Basso and Schultz, 2003).

cyclone (hurricane) contribution to wet-season rainfall in the Peace River watershed (Figure 5).

Creation and Analysis of the Hardee County Geodatabase

Historic (mid-1950s) topographic quadrangle maps were used to derive baseline conditions because neither documentation of, nor reference to, historic pre-mining baseline wetland conditions established by the regulatory agencies, the mining industry, or other agencies or studies could be found. The winter 2003–04 CIR aerial imagery was used in conjunction with standard ground-truthing and qualitative rapid ground assessments at more than 500 locations to identify conditions of wetlands and surrounding uplands and patterns of non-invasive characteristic plant species and invasive plant species. Other signs of wetland disturbance indicative of groundwater alterations, such as soil subsidence, also were recorded. Ground assessment locations included multiple points in individual study-area wetlands exhibiting different signatures in the selected CIR imagery, as well as representative wetlands with similar and different CIR-imagery signatures throughout the study area and in numerous other counties throughout Florida with and without mining. The most concentrated ground assessments occurred in 2008 on July 7, November 25, and December 6 through 8. Additional ground assessments occurred in 2009 on January 2 through 11 and February 24 through 25. Because suitable CIR aerial imagery was not available for the same period as the ground assessments, qualitative ground assessments were not possible. Rapid ground assessments were consistent with those described by Bacchus et al. (2003) and were not intended to map plant species. Specifically, rapid ground assessments included recording the presence, in or surrounding the wetlands, of any of the following indicators commonly associated with areas of hydroperiod alter-

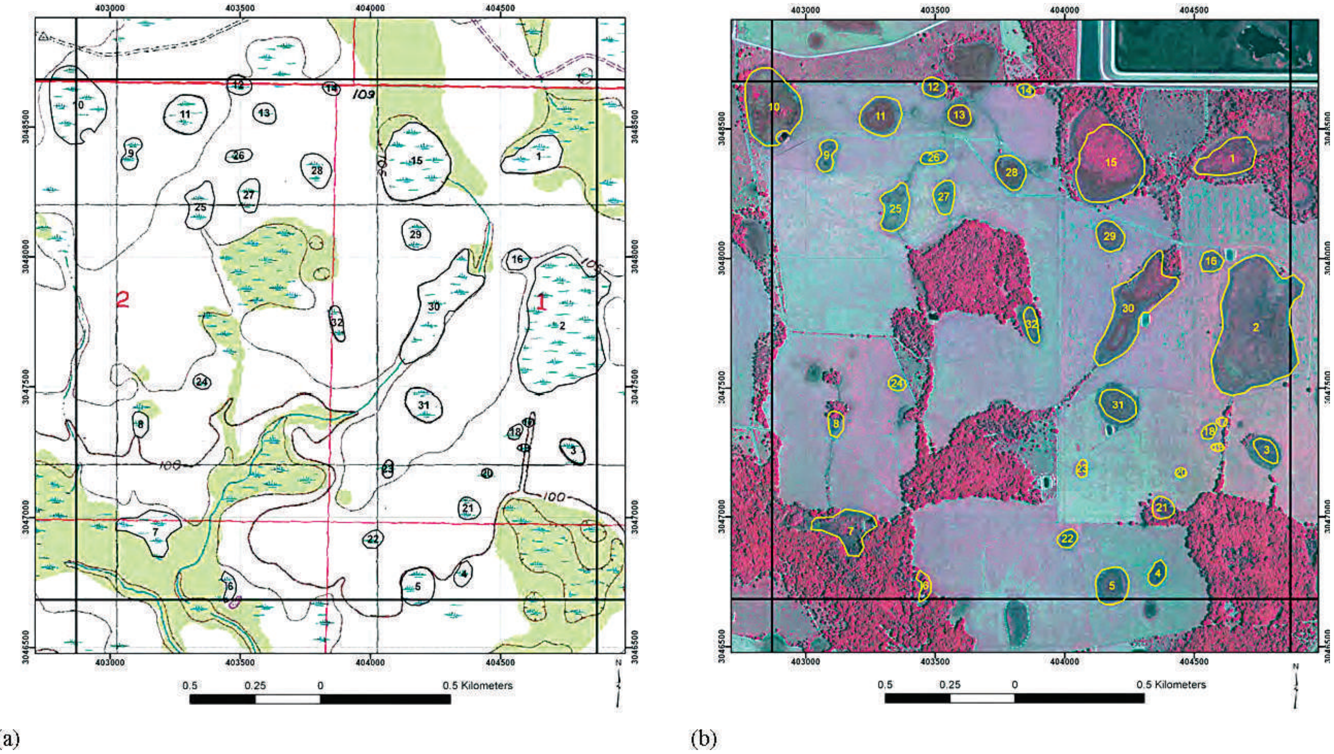

Figure 6. Example of wet prairie study-area wetlands (consecutively numbered) having center points in 4-km^2 plot SW2A (bold black square) with: (a) baseline wetland boundaries digitized from the 1955 Ft. Green U.S. Geological Survey topographic quadrangle map and (b) superimposed over the 2003–04 CIR image. The southwest corner of the C. F. Industries, Inc., phosphate mine is shown in the northeast corner of image.

ations in the U.S. southeastern coastal plain: (1) premature tree mortality or decline; (2) poor crown condition; (3) insect and disease damage; (4) degraded soil conditions such as subsidence; (5) fragmentation of habitat; (6) invasive species (insects and plants); and (7) significant fire damage in fire-adapted ecosystems. The locations of ground assessment observations were recorded with a handheld Garmin HCV global positioning system (GPS) with wide area argmentation system (WAAS)-enabled differential corrections to approximate ± 3 m positional accuracy.

Several geospatial techniques were used to create the Hardee County geodatabase. The selected CIR imagery and historic DRGs were input to ESRI ArcGIS for spatial analyses such as summarizing characteristics of wetlands, computation of landscape metrics, and spatial correlation of wetlands within the study area. A grid of 2×2 km plots was created as an overlay to tile the Hardee County imagery and facilitate wetland morphometric calculations (e.g., number and size) and condition descriptions. The north-south axis of the grid was aligned along the southern boundary of the cluster of mine pits in the selected CIR imagery. The east-west axis of the grid was positioned through the center of the central mine pit in the selected CIR imagery, with the central point of the study area located at the center of the southern boundary of the largest mine pit (Figure 3). To facilitate analysis and discussion of results, each of the four equal quadrants of the study-area imagery, representing the southwest (SW), northwest (NW), northeast (NE), and southeast (SE), was subdivided into two rows of four 4-km^2 (1.5-mi^2) plots, for a total of 32 equal-size, uniquely coded plots, as illustrated by the black cross bars in Figure 3.

The baseline boundaries of the wetlands within the study area were digitized over the historic DRGs using ArcGIS 9.2 software to create individual wetland polygons (Figure 6a). These maps delineated the boundaries of herbaceous depressional (wet prairie) wetlands in the study area during the mid-1950s. Wetland boundaries were adjusted to exclude non-wetland components (e.g., roads, fill material, and excavated areas) that appeared on the selected CIR imagery, but not on the historic (mid-1950s) baseline maps, thus excluding the spectral data of those non-wetland components from the later analysis. Wetland polygons were numbered sequentially within each plot, beginning in the NE corner of the plot and proceeding in a clockwise spiral direction to the center of each plot. Each 4-km^2 plot included only wetlands in which the center of the wetland polygon

was within the plot. Wetland polygons were not segmented by plot boundaries. Each wetland was analyzed as an island, independent of other wetlands, as described in the following.

The NIR spectral data for the entire Hardee County study area were extracted from the three-band (NIR, red, and green) CIR image using ERDAS Imagine 9 image-processing software. Zonal attributes for spectral data from individual wetland polygons were assessed using the same software, by designating all of the wetland polygons in a single plot as the "area of interest" (AOI) for processing, while excluding the rest of the image. This process was repeated for each plot. Microsoft Excel software was used to calculate mean NIR ± standard deviations for the resulting digital numbers (DNs) in individual wetlands within each plot and to graph the results.

Statistical analysis of the spectral data included chi-square and Fisher's exact tests and two-sample t-tests to evaluate whether ditches associated with wetlands had significant effects on NIR values of vegetation in depressional wetlands. The null hypothesis for these tests was no significant difference between NIR values for ditched and un-ditched depressional wetlands. The Getis-Ord G test was applied to mean NIR values of vegetation in individual wetlands to analyze clustering of wetlands based on those NIR values. The highest and lowest Z scores of the Getis-Ord G test indicate the strongest intensity of clustering, with a Z score near zero indicating no apparent clustering of depressional areas based on mean NIR values within the study area. A positive Z score indicates clustering of high mean NIR values, while a negative Z score indicates clustering of low mean NIR values.

RESULTS

Examples of baseline wetland boundaries digitized from the historic USGS topographic maps and the corresponding wetlands in the winter 2003–04 CIR imagery are depicted in Figure 6a and b for one of the 32 study-area plots (SW2A). Only depressional wetlands with center points within plot boundaries are included in the plots. The clearly delineated topographic depressions of these wetlands are evident in Figure 6a, while the extent and condition of the 32 wetlands having center points within the boundaries of that plot are shown in Figure 6b.

Characteristics of the historic study-area wetlands remaining in the winter of 2003–04 are summarized in Table 1. The study area included a total of 567 wet prairie wetlands, with a total area of 1,367 ha (3,376 acres). The total number of wetlands per plot ranged from 0 to 43. The total area of the wet prairie wetlands in the plots ranged from 0 to 112 ha (0 to 276 acres). Wet prairie wetlands generally lacking invasive species and other rapid assessment indicators of disturbance indicative of hydroperiod alterations had low mean NIR values (≤80 DN), while wet prairie wetlands exhibiting invasive species and other rapid assessment indicators of disturbance had high mean NIR values (≥100 DN). In total, 108 and 284 wetlands comprised the low and high DN categories, respectively.

Figure 7 illustrates the variation in mean NIR DN for wet prairie wetlands within one plot (SW2A) in the study area. Individual wetland numbers are shown along the x-axis. Mean NIR values for wetlands in the plot ranged from 56 to 139 DN. Although this case study was not designed to evaluate change in wetland size, our evaluations revealed that some wetlands in the selected imagery were larger (L) than the baseline size, while other wetlands within the same plot were smaller (S), as illustrated by the data from plot SW2A in Figure 7. Wetlands that increased in size occurred in both the low-DN and high-DN classes.

Table 2 summarizes the number of wetlands, the percent of the total wetlands, the area of wetlands, and the percent of the total wetland area within each quadrant by NIR class. The NIR class with the highest NIR values (≥100 DN), indicative of invasive species, included the greatest area (893 ha) and number (284) of wetlands, and represented 60 and 50 percent of the total wetland area and number, respectively, of wetlands in the study area. The NIR class with the lowest NIR values (≤80 DN), indicative of wetlands with characteristic wet prairie species, had the smallest area (149 ha) and number (108) of wetlands, and represented 10 and 20 percent of the total wetland area and number, respectively, of wetlands in the study area (Table 2).

The spatial distribution of the three classes of depressional wetlands in the study area, based on mean NIR values in each wetland, is shown in Figure 8a. Consistent with the summarized data in Table 2, the greatest number and area of wetlands with high mean NIR values were concentrated in the NW and SE quadrants, west and southeast of the mine, respectively. The Getis-Ord G test for cluster analysis confirmed that depressional wetlands with high and low NIR values are clustered. These clustered wetlands are depicted in red and blue, respectively, in Figure 8b, with highly significant overall Z-score (−3.519809) and overall p-value (0.000432).

Wetlands with ditches did not consistently exhibit high mean NIR values and were not clustered within the high-DN (disturbed) class of depressional wet-

Table 1. *Characteristics of historic wet prairie wetlands remaining in each of the 32 4-km² plots within the study area in winter 2003–04.*

Quadrant	Plot Number	Number of Wet Prairies	Area of Wet Prairies		Average Area of Wet Prairies		Wet Prairies w/Mean NIR Value ≤80 DN		Wet Prairies w/Mean NIR Value ≥100 DN	
			(acres)	(ha)	(acres)	(ha)	(number)	(percent)	(number)	(percent)
SE	1A	22	225	91	10	4	1	5	16	73
	2A	25	260	105	10	4	2	8	18	74
	3A	11	83	34	8	3	0	0	8	73
	4A	15	80	32	5	2	3	20	6	40
	1B	27	168	68	6	3	2	7	17	63
	2B	18	276	112	15	6	1	6	10	56
	3B	0	—	—	—	—	—	—	—	—
	4B	5	17	7	3	1	1	20	4	80
SW	1A	39	209	85	5	2	18	46	11	28
	2A	32	127	51	4	2	7	22	6	19
	3A	16	56	23	3	1	5	31	4	25
	4A	14	101	41	7	3	2	14	7	50
	1B	41	87	35	2	1	25	61	6	15
	2B	25	59	24	2	1	15	60	4	16
	3B	21	53	21	3	1	7	33	4	19
	4B	2	5	2	2	1	1	50	0	0
NW	1A	5	10	4	2	1	0	0	5	100
	2A	19	182	74	10	4	1*	5	17	90
	3A	31	145	59	5	2	1	3	24	77
	4A	21	219	89	10	4	2	10	9	43
	1B	2	4	2	2	1	0	0	2	100
	2B	6	51	21	9	3	0	0	6	100
	3B	25	186	75	7	3	5	20	16	64
	4B	26	197	80	8	3	0	0	21	81
NE	1A	0	—	—	—	—	—	—	—	—
	2A	5	34	14	7	3	0	0	5	100
	3A	25	148	60	6	2	1	4	19	76
	4A	43	268	109	6	3	7	16	14	33
	1B	3	15	6	5	2	0	0	3	100
	2B	5	12	5	2	1	0	0	5	100
	3B	6	13	5	2	1	0	0	3	50
	4B	32	86	35	3	1	1	3	14	44
Total		567	3,376	1,367	170	69	108		284	

*Includes standing water.
NIR = near infrared; DN = digital number.

lands, but they were distributed throughout all three NIR classes. For example, wetland 22 in plot SW2A exhibited one of the lowest mean NIR values, suggesting an undisturbed wetland when, in fact, the wetland was characterized by ditches. Other wetlands in the highest mean NIR DN range, indicative of disturbed wetlands, did not have ditches, such as wetland 23 (Figure 7). This distribution of ditched wetlands throughout the NIR DN range in the study-area plots suggests that ditches within the study area were not the controlling factor influencing mean NIR values of vegetation in the wetlands. Results of chi-square and Fisher's exact tests failed to reject the null hypothesis ($p = 0.9741$ and $p = 0.8855$, respectively), supporting the conclusion that the effect of ditches on vegetation NIR values in depressional wetlands was not statistically significant. The box plot in Figure 9, based on a two-sample t-test ($p = 0.7703$), provides further support for the lack of significant difference between mean NIR values of 100.42 and 101.48 for ditched and un-ditched wet prairie wetlands, respectively, in study-area plots.

DISCUSSION

Conservative Aspects of the Geodatabase and Analyses

The Hardee County geodatabase incorporated several conservative components to minimize the presumed effect from periods of reduced rainfall and the 2004 hurricane (tropical cyclone) season on native vegetation. The conservative components included: (1) a period of low annual rainfall levels during and immediately prior to the mid-1950 period used to determine the baseline wetland boundaries, which could have reduced the calculated extent of those wetlands; (2) aerial CIR imagery flown prior to the

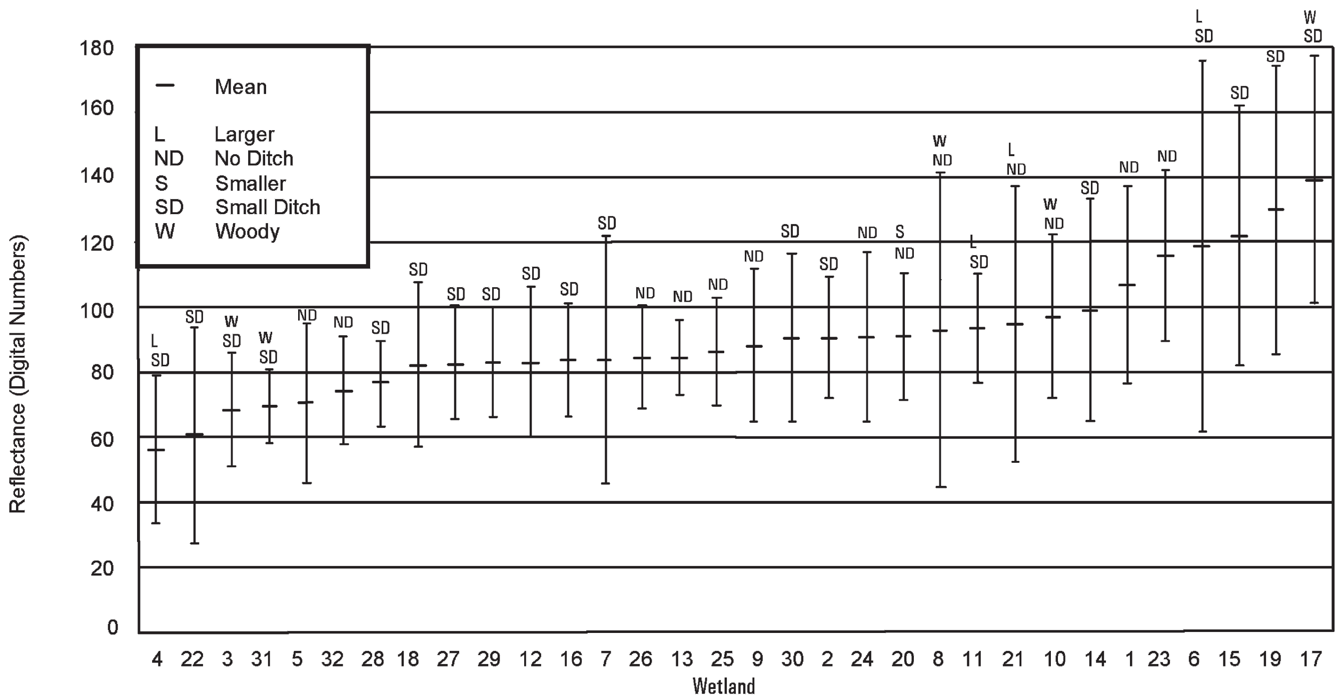

Figure 7. Mean NIR values ± standard deviation for wet prairie wetlands in example plot SW2A, south of the C. F. Industries, Inc., phosphate mine in Hardee County, Florida. See text for further explanation.

2004 hurricane season; and (3) exclusion of areas of post-baseline dredging, filling, construction, and similar alterations evident on the selected CIR imagery.

Rainfall Fluctuations

Annual rainfall in Hardee County was approximately 30–53 cm (12–21 in.) greater preceding and during the period over which the selected NIR imagery data were collected (137 cm for 2003 and 161 cm for 2004) than for the period when the baseline wetlands were mapped (105 cm for 1955 and 108 cm for 1956) and was comparable to the period of ground assessments (126 cm), based on rainfall records from the SWFWMD (2010). According to the data for the selected mid-1950 baseline period, annual rainfall was among the lowest during the 105-year period of record and approximately 25.4 cm (10 in.) below the average in that area for that period of record (Figure 5a). Re-analysis by Basso and Schultz (2003) using a 5-year running mean suggested that annual rainfall for the selected baseline period was at or below the 100-year average for the study-area vicinity (Figure 5b). The low rainfall during this period was due, in part, to the lack of hurricane contribution during the wet season (Figure 5c). A similar period of low rainfall also occurred during the mid-1940s, despite a greater contribution to rainfall from hurricanes. Rainfall analysis was not within the scope of this case study. Differences in these rainfall periods, however, may be due to variations in relative intensity and frequency of the El Niño–Southern

Table 2. *Summary of the number, percent, and area of wet prairie wetlands in each study-area quadrant, by NIR class.**

	High Mean NIR Values (≥100 DN)					Medium Mean NIR Values (81–99 DN)					Low Mean NIR Values (≤80 DN)				
			Area					Area					Area		
Quadrant	Number	Percent	(acres)	(ha)	(percent)	Number	Percent	(acres)	(ha)	(percent)	Number	Percent	(acres)	(ha)	(percent)
SE	79	14	902	365	6	34	6	163	66	5	10	2	45	18	1
SW	42	7	215	87	25	68	12	274	111	9	80	14	205	83	6
NW	100	18	785	318	21	26	5	128	52	3	9	2	84	34	2
NE	63	11	304	123	8	47	8	237	96	13	9	2	35	14	1
Totals	284	50	2206	893	60	175	31	802	325	30	108	20	369	149	10

*Discrepancies in figures are due to rounding of data to the nearest unit.
NIR = near infrared; DN = digital number.

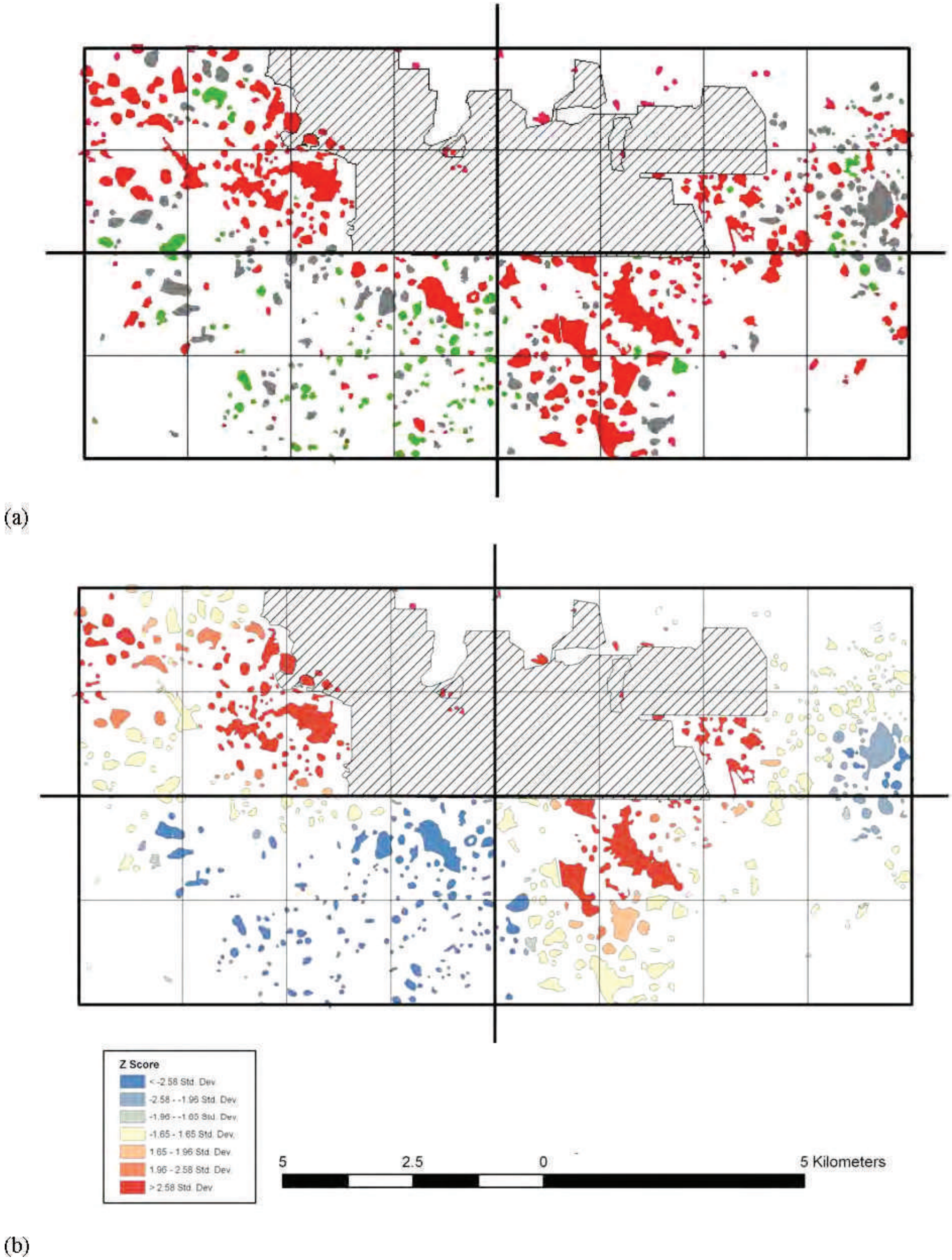

Figure 8. Spatial distribution of wet prairie wetlands in study-area plots by (a) three mean NIR value classes (≤80 DN = green, low-disturbance wetlands; 81–99 DN = gray, variable condition wetlands; and ≥100 DN = red, high-disturbance wetlands); and (b) statistically significant clusters of wetlands with low (blue) and high (red) mean NIR values. The cross-hatched area depicts the extent of phosphate mining in the study area.

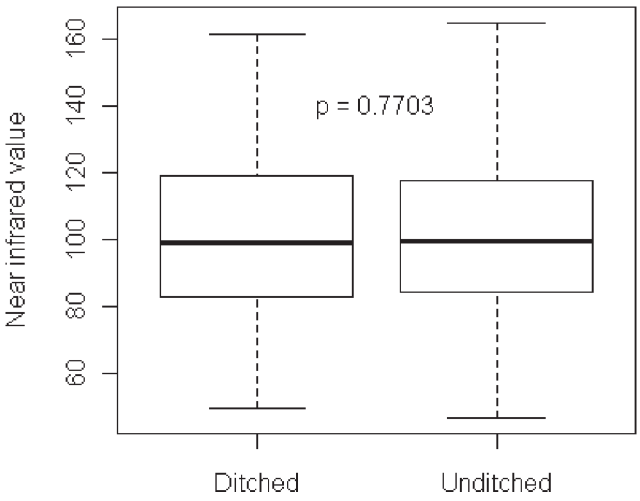

Figure 9. Mean NIR values ± standard deviation and p value for ditched and un-ditched wet prairie wetlands in study-area plots determined by two-sample t-test.

Oscillation (ENSO), which is linked to above-average winter–early spring season rainfall (Basso and Schultz, 2003).

Hurricane Damage

The National Oceanographic and Atmospheric Administration (NOAA, 2004) reported a more active season than average for the Atlantic Basin in 2004, with 15 tropical storms and 9 hurricanes, including 6 major hurricanes. The CIR imagery selected for analysis in this case study was acquired during December 2003 to March 2004, however, preceding the 2004 hurricane season that was initiated in fall 2004. Therefore, this time frame added an additional conservative component to our case study with respect to hurricane influences because the selected CIR images preceded any wind-related damage or rainfall benefits associated with the 2004 hurricane season that might have occurred to wetlands in the study area.

Influence of Ditches

Shallow ditches frequently occur in rural areas of Florida used as pasture for grazing cattle in the vicinity of mining operations or other activities capable of resulting in large-scale groundwater alterations. In the senior author's experience, local, state, and federal regulatory agency staff commonly considers these shallow ditches as the cause of wetland impacts. The presence of more than 100 wetlands with shallow ditches in the study area provided an opportunity to evaluate mean NIR values for both ditched and un-ditched wetlands in proximity to the mines. The distribution of ditched wetlands throughout the NIR DN range in the study-area plots suggested that ditches were not the controlling factor influencing mean NIR values of vegetation in the wetlands (Figure 9). Results of chi-square, Fisher's exact, and two-sample t-tests all supported the conclusion that the effect of ditches on vegetation NIR values in depressional wetlands is not statistically significant and suggest that mining activities rather than ditches are affecting the wetlands.

Wetland Size and Invasive Species

Although an analysis of change in wetland size was beyond the scope of this case study, visual assessments of the mid-1950s baseline wetlands layer superimposed over the winter 2003–04 NIR layer revealed that, compared to the extent of those wetlands in the baseline layer, some depressional wetlands in the study area had decreased in size, while other study-area wetlands had increased in size during the same time period. Examples of study-area wetlands appearing smaller than or larger than the same wetlands in the baseline layer of the 32-plot study area are indicated in Figure 7 by "S" and "L," respectively, in this single plot. This inconsistent response suggests that increases in wetland size from baseline conditions were not due to seasonal or annual rainfall and should not be interpreted as a positive change. In an area the size of a 4-km^2 plot or even the size of the entire study area, it would be improbable that rainfall would cause some wetlands to increase in size while others simultaneously decreased in size or no longer exhibited wetlands vegetation. In fact, some of the wetlands with high NIR DNs no longer supported wetland criteria of saturated soil and wetland vegetation, based on the selected CIR imagery and ground assessments. This suggests un-permitted wetland losses beyond the mine-project boundaries.

The most logical reason for wetlands in this study area to decrease in size is mechanical or non-mechanical dewatering associated with the existing mines. This dewatering also can reactivate underlying relict sinkholes, leading to subsidence, which can result in an initial increase in wetland size. These conditions can result in highly disturbed wetlands, with abnormal increases in water depths and hydroperiod duration in at least the center portions of those wetlands. The resulting hydroperiod alterations are conducive to invasion of the wetland by species such as primrose willow (*Ludwigia peruviana* [L.] Hara) and cattails (*Typha* spp.), which thrive in water that is

deeper or remains longer than natural hydroperiod conditions for wet prairie wetlands.

Primrose willow was one of the invasive species that occurred in some of the study area wetlands exhibiting high mean NIR DN values. Primrose willow is a common woody alien species that has invaded southeastern coastal plain depressional wetlands with natural hydroperiod alterations. Nuisance native species such as cattails and grape vines (*Vitis* spp.) also were found in some of the study area wetlands exhibiting high mean NIR DN values. Based on 30 years of professional experience by the senior author, these species also commonly invade southeastern coastal plain depressional wetlands in proximity to activities such as mining that are capable of subsurface alteration of natural hydroperiods.

Remote sensing has been used to map and monitor invasive plant species in the Florida and southeastern U.S. landscape without an attempt to consider causal links regarding the presence of those invasive species (Everitt et al., 1996; McCormick, 1999; Osborn et al., 2002; Hirano et al., 2003; Madden, 2004; Parker Williams and Hunt, 2004; Young et al., 2007, 2009). Remotely sensed data also have been used to assess climate and environmental factors (Goslee et al., 2003) and landscape degradation and fragmentation (Young and Schrader, 2011b) associated with the presence of invasive plants. Knowledge of species ecology and environmental tolerances can be used to predict potential areas of invasive species, achieving more effective ground reconnaissance for early detection (Young and Schrader, 2011a). Analysis of plant samples from forested depressional wetlands throughout the southeastern coastal plain has been successful in identifying chronic stress conditions associated with hydrologic alterations using NIR reflectance (Bacchus et al., 2003). No similar analysis of wetland vegetation *in situ*, to determine possible impacts from phosphate mining in Florida or other areas of the U.S. southeastern coastal plain, was found in literature searches.

Large standard deviation of NIR values within individual wetlands, combined with mean NIR values between 81 and 99 DN, also may be associated with disturbed wetlands indicative of groundwater alteration impacts. Large standard deviation of mean NIR values results from the occurrence of some vegetation with high NIR values and other vegetation with low NIR values within a single wetland. Large standard deviations for individual wetlands suggest areas in a single wetland with invasive plant species commonly associated with groundwater alterations. Alternatively, small standard deviation of a wetland's NIR values is not meaningful in forming conclusions without also considering the mean NIR DN of the wetland. For example, a wet prairie with a small standard deviation of NIR DN and a low mean NIR DN is indicative of a wet prairie without invasive plant species commonly associated with groundwater alterations. Conversely, a wet prairie with a small standard deviation of NIR DNs but a high mean NIR DN is indicative of a former wet prairie currently composed primarily of invasive plant species.

Cumulative Impacts *via* Preferential Flow Paths

High NIR values for depressional wet prairie wetlands located more than 4 km from the western boundary of the mine pits may indicate cumulative impacts from another mine pit west of the western boundary of the study area. That rectangular water-filled mine pit is located in Hardee County adjacent to the Hardee/Manatee County line (Figure 2a). Additional mine pits in Hardee County are located at a similar distance from the southern boundary of the CFI mine pit in the study area, in proximity to the Brushy Creek label in Figure 2a, and also may be indicative of cumulative impacts on study-area wetlands.

The preponderance of depressional wetlands with high mean NIR values in the NW and SE quadrants of the study area also may be indicative of more far-reaching and intense hydroperiod alterations occurring through preferential flow paths in the underlying karst aquifer system, such as fracture networks and dissolution features. The pattern of these depressional wetlands with high mean NIR values appears to be consistent with NW to SE and NE to SW trends of fractures in the bedrock occurring throughout the Florida peninsula, as described by Popenoe et al. (1984), and other areas of the Floridan aquifer system, as described by Brook and Sun (1982).

The distribution of NIR classes is not consistent with a concentric groundwater drawdown pattern commonly produced by standard MODFLOW modeling, originally developed by USGS (see Bacchus, 1998, Figure 3). General assumptions for those models and evaluations during various permit application review processes in Florida are that the aquifer conditions are homogeneous and isotropic. Previous studies support the conclusion that the distribution of wetlands with high mean NIR values is not random but is the result of cumulative impacts from mining due to high-permeability features characteristic of karst aquifer systems, as described next.

Subsurface Impacts and Preferential Flow Paths

Brook and Sun (1982) found that dissolution features such as relict sinkholes are aligned along

linear features known as "fracture traces," presumably reflecting fractures in the underlying Floridan aquifer system. Their findings were similar to findings of Patton and Klein (1989). The latter conducted a sinkhole survey from March 21 to April 7, 1980, within a 22.5-km (14-mi) stretch of the upper Peace River from Bartow to Fort Meade. In that study, they located and described all "sinks and pipes, influent sloughs, and other karst-related features" from the "edge of the low-water channel to the lateral edge of the high-water channel" and concluded (p. 27):

> Most of these sinkholes lie within the high-water channel, although we also noted several complexes within the low-water channel. Such a distribution is to be expected because the areal extent of the meandering low-water channel represents but a small fraction of the entire valley floor.
>
> However, the several sinkholes located within the low-water channel represent a greater percentage of conduits per unit area than simple probability calculation would dictate. This is likely due to the influence of local geologic structure. The partly rectangular nature of the course of the Peace River channel and the linear nature of several of the sinkhole complexes clearly indicate that local drainage and solution are influenced by underlying structure. The coincidence of channel location and structural lineation (joints and fractures) would account for the greater-than-expected sink occurrence in the low-water channel.

The findings by Patton and Klein (1989) and those described by SWFWMD (1999) and Weber (1999) provide additional support for the interconnection of depressional wetlands with the underlying Floridan aquifer system and associated riverine ecosystems. Data collected in conjunction with previous NIR analyses of pond cypress from depressional wetlands in Florida and other areas of the southeastern coastal plain (Bacchus, 1999), in conjunction with the findings of Patton and Klein (1989), SWFWMD (1999), and Weber (1999), provide additional support for the conclusion that depressional wetlands in Florida historically were connected to streams.

The manner in which mining operations alter natural hyroperiods of wetlands in Florida has been described by Bacchus (2006) and includes the groundwater impacts addressed by Lewelling et al. (1998). Phosphate mining results in exposure of the mined surficial aquifer, as well as extraction of large volumes of groundwater *via* pumped wells (mechanical dewatering). Other types of mining operations may include only the exposure of and evaporative loss from the mined surficial aquifer (non-mechanical dewatering), as described by Bacchus (2006).

Impacts from extraction of large volumes of groundwater *via* pumped wells can alter hydroperiods in natural depressional wetlands up to considerable distances from those wells, while similar wetlands closer to the pumping wells appear less affected. The nature of those wetland impacts, which are not dependent solely on distance from the pumping, is due to preferential flow through fractures and karst solution features, such as the relict sinkholes underlying the depressional wetlands (Stewart and Stedje, 1990; Watson et al., 1990).

Both relict and modern dissolution features tend to occur along fractures that may be identified by large-scale linear features visible on aerial photographs (Brook and Sun, 1982; Littlefield et al., 1984). Breaches of groundwater divides also have been attributed to similar large withdrawals of ground water in the U.S. southeastern coastal plain (Krause and Randolph, 1989). The adverse environmental impacts to Florida wetlands from extraction of large volumes of groundwater *via* pumped wells were established in the early 1990s and include rapid invasion of these wetlands by alien and nuisance plant species (Hofstetter and Sonenshein, 1990; Sonenshein and Hofstetter, 1990; and House Committee on Natural Resources, 1994). These hydrologic alterations also were determined not to be the result of variations in rainfall (SWFWMD, 1996).

Assessing Environmental and Cumulative Impacts

New Approach for Assessing Cumulative Impacts from Mining

State and federal laws such as the Clean Water Act (CWA) and National Environmental Policy Act (NEPA) require regulatory agencies to evaluate the cumulative impacts of projects, including mining. The NEPA establishes national environmental policy and goals for the protection, maintenance, and enhancement of the environment and provides a process for implementing those goals within the federal agencies. Those NEPA requirements took effect when the act was signed into law on January 1, 1970, as 42 USC 4321 et seq. (NEPA, 1970). Although that date preceded the date that the initial permit for groundwater withdrawals for the existing CFI mine site was issued by the SWFWMD on November 2, 1977 (Consumptive Use Permit 27703669), no evidence could be found that the NEPA requirements for a cumulative impact assessment were fulfilled for that mine regarding groundwater impacts.

The sensitivity of southeastern coastal plain depressional wetlands to subsurface alterations of the natural hydroperiod was summarized by Bacchus (2000). Subsequent investigations provided additional insight into mechanisms associated with this type of chronic stress (Bacchus et al., 2000, 2003, 2005;

Bacchus, 2006). Despite the documented susceptibility of depressional wetlands to subsurface hydroperiod alterations and the increase in mining of all types in Florida, none of the applications for local, state, and federal mining permits in Florida included scientific evaluations of cumulative groundwater impacts on depressional wetlands within and beyond mine boundaries.

Results based on the methodology developed in this case study suggest that our application of remote sensing analysis may be capable of assessing cumulative groundwater impacts to important depressional wetland ecosystems that provide habitat for a large diversity of wildlife, including endangered and threatened species in this region. Due to the similar habitat and responses of natural depressional wetlands to groundwater alterations throughout the U.S. southeastern coastal plain and over the extent of the Floridan aquifer system (Bacchus et al., 2003), the method of analysis developed in this case study also should be applicable for assessing depressional wetlands throughout this region of the United States.

Research has shown that characteristic native wetland vegetation is replaced by invasive non-native and native plant species with tendencies for monospecific stands and highly aggressive growth habits due to altered hydrologic conditions (Hofstetter and Sonenshein, 1990; Sonenshein and Hofstetter, 1990; and Langeland and Burks, 1998). Monospecific stands typical of invasive species often display a striking contrast from the surrounding native vegetation communities, which are more diverse in species structure (Remillard and Welch, 1992). Characteristic herbaceous vegetation in Florida's depressional wet prairie wetlands associated with groundwater withdrawals has been replaced with woody invasive species (Hofstetter and Sonenshein, 1990; Sonenshein and Hofstetter, 1990). Research also has confirmed that soil conditions and management practices, rather than dispersal processes, determine the distribution of some invasive vegetation, thus enabling predictions of occurrence for those species (Goslee et al., 2003). Conversely, the presence of those invasive species could be used to predict the conditions and management practices indicative of those invasive species, based on the work of Goslee et al. (2003).

The results of our study also suggest that the buffer widths established for municipalities and regulatory agencies, ranging from ~3.1 m to ~91 m as described previously, may be insufficient for protecting associated wetlands and wildlife habitat from hydroperiod alterations associated with mining, primarily because those widths fail to account for subsurface and cumulative impacts to natural hydroperiods associated with mining.

Current Approach

Currently, the regulatory agencies and municipalities have no scientific means of assessing cumulative impacts of mining on the surrounding biotic environment, including wetlands and wildlife habitat in Florida. Based on the senior author's professional experience, the referenced regulatory agencies, and municipalities rely on regional groundwater data and MODFLOW model results by default to evaluate the impacts, including cumulative impacts, from proposed mining projects. The groundwater data and model results generally are unpublished. This approach, however, only provides information regarding the physical (hydrologic) impacts, not impacts to the biotic environment.

Quinlan (1991), Worthington (2003), and Worthington et al. (2002) provide detailed descriptions of the constraints of using borehole data and MODFLOW models that assume porous-media flow to characterize groundwater flow in karstic carbonate aquifers and alternatives. Use of wells to assess flow through karst aquifers is less than ideal because those individual wells have a very low probability (typically 0.01–0.02) of intersecting major subsurface channels (Worthington, 2009).

The inadequacies of the current approach used in Florida include: (1) lack of site-specific baseline groundwater data preceding excavations and significant groundwater withdrawals for mining and other activities such as processing plants for phosphate ore; (2) insensitivity of regional groundwater data to localized karst depressional wetlands; (3) inability of the groundwater flow models to identify the subsurface preferential flow paths where the impacts are occurring due to model assumptions of homogeneous, isotropic aquifer conditions; and (4) inability of groundwater data or model results to translate into impact on the biotic environment (Bacchus, 2006). The lack of site-specific baseline groundwater data particularly is problematic in south Florida, where the natural hydrology has been altered extensively (Florida Water Resources Research Center, 2000). Presumptions of constant-head and no-flow boundary conditions for vertical flow in the surficial aquifer and lateral flow in underlying aquifer also are unrealistic for karst aquifer systems (Harmon and Wicks, 2006; Metz and Lewelling, 2009).

Despite these inadequacies, attempts to assess cumulative impacts from other types of proposed and existing mining in Florida using MODFLOW model results have been conducted in Charlotte County, south of our Hardee County case study (e.g., applications 07-EX-12 South Washington Loop and 08-EX-06 [aka 08-EX-39] Washington Loop Fill

Pit Excavation Project; Johnson Engineering, Inc., 2009), in north-central Florida (Dufresne and Drake, 1999), and in northwest Florida panhandle (Richards et al., 1993).

Telescoping digital models using the USGS computer code MODFLOW have been developed for the karstic Floridan aquifer system region of the United States (Garza and West, 1995) and are being used throughout that region (Jones, 1997). The inadequacies described herein are not resolved by using variable cell areas or grid spacings to evaluate impacts of mining in Florida, such as those that have included "cell areas of 100-foot by 100-foot" in Charlotte County, considered as "fine grid spacing" (Charlotte County, 2009), 152-m (500-ft) grid spacing in Lee County (Rawl and Voorhees, 2005) and "250 ft by 195 ft" cells in Hendry County, all south of our study area. Those modeled results also produced a concentric cone of influence typical of MODFLOW models (Murray Consultants, Inc., 2007). The finest of those grid scales is 100 times less sensitive than the 1-m resolution of the CIR image used for analysis of depressional wetland impacts in this case study, but this is not atypical for MODFLOW simulations of impacts from mining in Florida.

The March 2009 CFI–Hardee Phosphate Complex Environmental Resource Permit (ERP) Application for the South Pasture Mine Extension (C. F. Industries, Inc., 2009) included "dewatering the surficial aquifer" in response to the agency's request for additional information. Comparable impacts should be expected by mining proposed in the 2009 Mosaic Four Corners Lonesome CRP Modification MOS-FCL-CPH application (Mosaic Phosphate Company, LLC, 2009). Both proposed phosphate mines are in the immediate vicinity of our study area and rely on MODFLOW models similar to those described previously to predict environmental impacts.

No published or unpublished data were identified to support the presumption that dewatering the surficial aquifer, independently or in conjunction with extraction of the aquifer matrix and groundwater from the Floridan aquifer system during phosphate mining, does not affect surrounding wetlands and other native habitat. The unpublished 1973 lineaments map of Florida prepared by the Florida Department of Transportation Remote Sensing Section supports the conclusion that impacts to depressional wetlands, such as those in our study area, would not be consistent with the concentric drawdowns predicted by the groundwater models described previously. Although the simulations of those groundwater models cannot determine impacts to the biotic environment, the results of our study support the conclusion that scientific analysis of remotely sensed NIR data for wet prairie wetlands can be used to evaluate cumulative impacts of groundwater alterations to depressional wetlands in this region *via* high-permeability features characteristic of karst such as the fracture networks suggested by these mapped linear features.

CONCLUSIONS AND RELATED APPLICATIONS

Analysis of remotely sensed NIR data from herbaceous depressional wetlands does not appear to have been used anywhere to evaluate groundwater impacts on the biotic environment related to mining operations. Likewise, literature searches failed to reveal any applications of remotely sensed NIR data used to assess the impacts of shallow ditches on depressional wetlands in conjunction with adjacent mining operations.

Based on the conservative assessment measures used in this case study, 567 wet prairie wetlands, with a total area of 1,367 ha (3,376 acres), were identified in the study area. The total number of wetlands per 2 $\times$ 2 km plots ranged from 0 to 43. The total area of the wet prairie wetlands in each plot ranged from 0 to 112 ha (0 to 276 acres). Wet prairie wetlands generally lacking invasive species and other signs of disturbance indicative of groundwater alterations had low mean NIR values ($\leq$80 DN), while wet prairie wetlands exhibiting invasive species and other signs of degradation had high mean NIR values ($\geq$100 DN). In total, 108 and 284 wetlands comprised the low and high DN categories, respectively. Low mean NIR values ($\leq$80 DN) of wet prairie wetlands within the 32 study-area plots were associated with wetlands generally lacking invasive species and other signs of disturbance indicative of groundwater alterations. High mean NIR values ($\geq$100 DN) were associated with wet prairie wetlands exhibiting invasive species and other signs of disturbance indicative of anthropogenic groundwater alterations.

The spatial distribution of depressional wetlands with high mean NIR values in the study area was not consistent with the typical "cone" of influence or concentric groundwater drawdown patterns commonly produced by standard MODFLOW modeling (Bacchus, 1998; Sepulveda, 2002; Rawl and Voorhees, 2005; and Murray Consultants, Inc., 2007). Instead, the spatial distribution of wetlands with high NIR values more closely resembled alignment with NW to SE and NE to SW trends of fractures in the bedrock (karst aquifer system) occurring throughout the peninsula of Florida. Study-area wetlands with the greatest number of high mean NIR values occurred in statistically significant clusters in the NW and SE

quadrants. These clusters may be indicative of cumulative impacts from other mines in Hardee County to the west and south of the study-area mines, respectively. Large standard deviation of NIR values within individual wetlands, combined with mean NIR values between 81 and 99 DN, also may be associated with disturbed wetlands indicative of groundwater alteration impacts. Determination of the full range of mean NIR values for depressional wetlands exhibiting signs of degradation associated with groundwater-related impacts requires additional analysis.

Depressional wetlands associated with shallow ditches in the study area surrounding the representative phosphate mines in Hardee County exhibited mean NIR DNs ranging from the lowest to highest values. Results of chi-square, Fisher's exact, and two-sample t-tests all supported the conclusion that the effect of ditches on vegetation NIR values in depressional wetlands was not statistically significant. Therefore, we concluded that ditches were not the controlling factor influencing mean NIR values in these natural depressional wetlands. Similarly, the spatial distribution of disturbed wetlands with high mean NIR DNs was not consistent with damage from previous hurricanes or fluctuations in rainfall.

The public-domain availability of the type of CIR imagery used in this case study facilitates widespread application of the methodology we have developed here. This methodology has direct applications for evaluating the condition of similar herbaceous depressional wetlands in Florida and the southeastern coastal plain. Our newly developed methodology also has potential application to forested depressional wetlands throughout Florida and the southeastern coastal plain, as well as to other depressional wetlands in karst landscapes. Finally, this approach also may be applicable to riparian wetlands in karst areas where significant groundwater impacts are occurring. Based on information from the selected CIR imagery and baseline maps, combined with field observations during ground-truthing and rapid ground assessments, depressional wetlands in the study area historically were consistent with natural depressional wet prairie wetlands in other areas of Florida and the southeastern coastal plain. Therefore, although the study area is located in Florida, the methodology developed in this case study is applicable throughout the U.S. southeastern coastal plain extent of the Floridan aquifer system and potentially in other areas underlain by regional karst aquifer systems. Further research could provide the full range of mean NIR values associated with wet prairies exhibiting signs of degradation associated with groundwater-related impacts in the study area.

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