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Nonmechanical dewatering of the regional Floridan aquifer system

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ABSTRACT

The regional Floridan aquifer system has been dewatered and otherwise altered extensively throughout much of Florida and coastal Georgia by groundwater pumpage (mining). An increasing threat to this karst aquifer system is structural mining of aquifer formations, primarily to produce fertilizers, titanium products, construction materials, and pet food supplements. These excavations often include mechanical dewatering to facilitate shallow and deep extraction of the aquifer formations. All include reduced aquifer levels, dewatering of the aquifer system, and altered hydroperiods at and surrounding the excavated pits, due to increased void space and evapotranspirative losses (nonmechanical dewatering). Only mechanical dewatering is considered by regulatory agencies during evaluations of applications for structural mining of the aquifer system. Despite refuting data, open pits resulting from these excavations increasingly are portrayed as subsurface "reservoirs" that create new or enhanced sources of water in areas where natural groundwater supplies have been depleted.

Four permits and sites were evaluated for excavated and proposed pits in SE, NW, SW, and east-central Florida's natural areas used for groundwater supply. The combined surface area for pits under those four permits will result in ~237,000 m^3/d (~62.7 million gallons per day [Mgd]) of induced discharge from the regional Floridan aquifer system due to nonmechanical dewatering. This volume is more than twice the reported pumpage from the combined three municipal supply wells at the Miami-Dade West Well Field. The ~123 ha (~308 ac) SW Florida mine, most recently excavated in an area designated as critical habitat for the federally listed Florida panther, will result in induced aquifer discharge of ~1505 m^3/d (0.4 Mgd) due to nonmechanical dewatering. This loss is equivalent to ~5% of all water used by domestic supply wells in that county in 1990. That recently initiated excavation in SW Florida revealed environmental damage extending beyond the mine boundaries, to surrounding private property, and is the first documented case of such damage solely from aquifer formation mining and nonmechanical dewatering of the aquifer system. A federal court ruled on 22 March 2006 that the U.S. Army Corps of Engineers and U.S. Fish and Wildlife Service had failed to carry out their duty to protect the federal wetlands and protected species by issuing permits for mining in the SE case-study area.

Keywords: hydroperiod alterations, karst aquifer system, groundwater mining, induced discharge/recharge, MODFLOW.

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INTRODUCTION, BACKGROUND, AND TERMINOLOGY

Floridan Aquifer System

The Floridan aquifer is a regional, karst (carbonate) groundwater system that underlies Florida and the Coastal Plain portions of Alabama, Georgia, and South Carolina (Johnston and Miller, 1988; Fig. 1). Extensive portions of the regional aquifer are submerged beneath the Gulf of Mexico and the Atlantic Ocean, extending to the margin of the continental shelf (platform/plateau, not shown in Fig. 1). Historically, the surficial aquifers overlying the Floridan aquifer have provided natural recharge to, and received natural discharge from, the regional aquifer system via diffuse flow through lower permeability layers and points of preferential flow connections. Preferential flow occurs vertically and laterally through dissolution and collapse features (e.g., relict sinkholes, springs, and subterranean caves and cavities), bedding planes, and fracture networks. These conduits in the aquifer system historically facilitated considerable submarine groundwater discharge of freshwater in coastal areas. The relict sinkholes, characteristic of the regional Floridan aquifer system, formed during the fluctuating sea levels of the Pleistocene Epoch. These relict sinkholes are aligned along fracture networks, support natural depressional wetlands, and exemplify the first of the three morphological components of karst systems described by Ford et al. (1988): (1) input landforms that direct waters underground, (2) subterranean conduit systems, and (3) discharge areas.

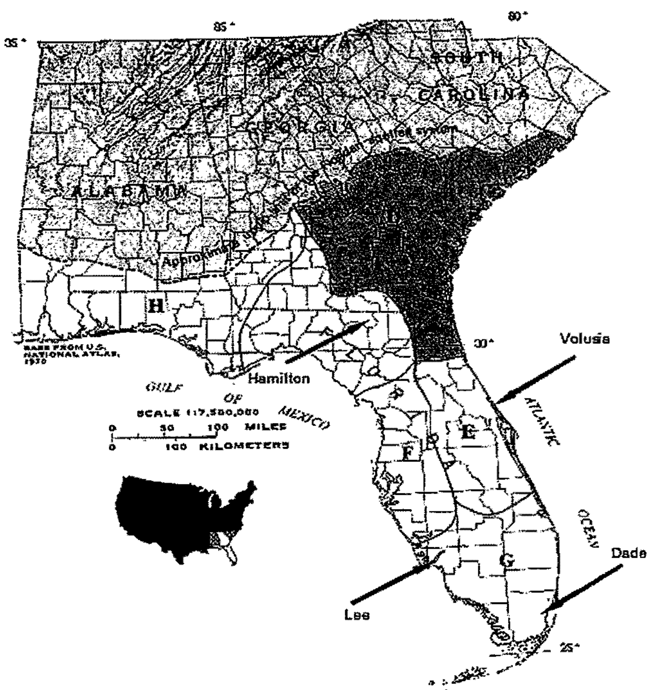

Figure 1. Extent of the regional Floridan aquifer system (submarine extent not shown); the six subregions designated for regional groundwater modeling (D, E, F, G, H, and unnamed subregions; from Krause and Randolph, 1989); and the four areas selected in Florida (SE—Dade County; NW—Hamilton County; SW—Lee County; east-central—Volusia County) for a case study of nonmechanical dewatering of the regional aquifer system due to mining of aquifer formations.

Forested wetlands, which characterize these natural depressional wetlands (infilled dolines), are dominated by pond-cypress (*Taxodium ascendens*) trees, endemic to the extent of the regional Floridan aquifer, while herbaceous depressional wetlands historically are dominated by native wet prairie species. The underlying structural characteristics (fractures and dissolution channels) of these natural depressional wetlands provide vertical groundwater connections between the surficial aquifer, where the natural wetlands are rooted, and the underlying Floridan aquifer, as well as subsurface connections between the depressional wetlands. During the rainy season, those natural depressional wetlands, without significantly altered hydroperiods, also are interconnected by surface waters and flow into streams and natural lakes (summarized in Bacchus, 2000a, 2000b; Bacchus et al., 2003; hydroperiod defined in Table 1).

Despite the important role of the surficial aquifers in providing natural recharge to the underlying Floridan aquifer, the surficial aquifers have been considered as separate from the Floridan aquifer. References in the literature to the "Floridan aquifer system" have not included the associated surficial aquifers. The natural interconnections between the surficial and underlying aquifer zones throughout the extent of the regional Floridan aquifer system provide sufficient scientific support for the conclusion that the associated surficial aquifers are an integral part of the underlying regional Floridan aquifer system. Therefore, all further reference to the regional Floridan aquifer system includes the overlying surficial aquifers.

Groundwater Mining

During the past century, groundwater pumpage from municipal, agricultural, and industrial supply wells throughout much of Florida and coastal Georgia has exceeded the sustainable yield of the Floridan aquifer system, as defined in Table 1, described by Bacchus et al. (2003), and described more fully below. Most recently, the U.S. Geological Survey (USGS) has summarized the extensive dewatering due to groundwater pumping of the regional Floridan aquifer system throughout much of Florida and coastal Georgia (Barlow, 2003). That review focused solely on the threat of saltwater intrusion to the continued exploitation of those groundwater resources. Groundwater pumpage for water supply and other purposes meets the common definition of mining: "To extract from the earth; to delve into and make use of: EXPLOIT" (Soukhanov and Ellis, 1984, p. 455). Dingman (1994) also recognized the removal of water from storage as groundwater mining (see Table 1). Therefore, groundwater pumpage from any portion of the Floridan aquifer system is considered as groundwater mining.

TABLE 1. DEFINITIONS OF TERMS RELATED TO MECHANICAL (PERMITTED) AND NONMECHANICAL (UNPERMITTED) DEWATERING OF THE REGIONAL FLORIDAN AQUIFER SYSTEM ASSOCIATED WITH STRUCTURAL MINING OF AQUIFER FORMATIONS

Terms	Definitions
Baseline	The basic health, environmental and economic conditions that exist before any policy intervention. EXAMPLE: Successful lake ecosystem management requires long-term data so that baseline conditions and natural variations within the system can be determined. University of Ulster, Environmental Toxicology Research (Collin, 2001).
Conduit	A gross heterogeneity in the permeability distribution, characterized by non-Darcian flow. (Ford et al., 1988) In models, conduits are generally treated as one-dimensional pipes (Halihan et al., 1999).
Deep extraction	Structural mining that extends into one or more of the lower-permeability (semiconfining) zones associated with the water table (surficial) aquifer.
Extraction	As used here, synonymous with dredging, mining. Structural mining resulting in temporary (e.g., titanium mineral mining) or permanent (e.g., storm-water retention/detention; phosphate mining) pits that may be used to receive storm water, treated effluent, or other fluids. The removal, temporarily or permanently, of any solids (e.g., sand, shell, clay, peat, minerals, rock, ore) from a formation, that may be used for fill; raw materials for construction (e.g., cement, concrete, road beds, impervious surfaces); fertilizers; other agricultural or plant industry products (e.g., peat, sphagnum); titanium products; or other purposes.
Groundwater mining	Any time water is removed from aquifer storage (Dingman, 1994).
Hydroperiod	Natural fluctuations of the water table that maintain native plant and animal species and ecosystem functions; can be altered by aquifer withdrawals and injections; and includes three important aspects: (i) depth or stage of fluctuating ground water and surface water; (ii) duration of the water level at a given depth or stage; and (iii) periodicity or seasonality of the water-level fluctuations (from Bacchus, 1998).
Laboratory scale	Includes permeameter tests, fracture measurements, or conduit measurements that take place in the laboratory or outcrop; generally measurement of volumes ≥0.01–10 m^3; small scale, outcrop scale (modified from Halihan et al., 1999).
Non-Darcian	A situation that occurs when the flow through an aquifer no longer follows Darcy's law (i.e., the flux is not directly proportional to the gradient); generally predicted by Reynolds numbers greater than 10 (modified from Halihan et al., 1999).
Regional scale	The entire extent of the Floridan aquifer system; volumes greater than 1000 m^3 (modified from Halihan et al., 1999).
Semiconfined aquifer	Aquifers, whether artesian or water table, that lose or gain water through adjacent less-permeable layers (U.S. Geological Survey, 1989); leaky confined aquifer.
Shallow extraction	Structural mining that does not extend into the lower-permeability (semiconfining) zone(s) between the water table and the upper Floridan aquifer.
Subsidence	When used in relation to the materials that make up the surface layers of Earth, subsidence may mean sinking to a lower level, but it may also mean a sudden collapse of surface material into a subterranean void (Challinor, 1986). A progressive depression of Earth's crust ... a sinking or settling of the ground surface due to natural or anthropogenic causes. Surface material with no free side is displaced vertically downward with little or no horizontal movement (Allaby and Allaby, 1990). See Poland (1984) for extensive descriptions of subsidence associated with groundwater withdrawals.
Sustainable yield	Groundwater withdrawals that are equivalent to natural recharge on a seasonal basis, not averaged annually, and that result in no induced recharge to the supply zone (modified from Dingman, 1994); $\Sigma Q_w = \Delta R - \Delta Q_{GW} + \Delta S/\Delta t$, where ΣQ_w is the total pumping rate, ΔR and ΔQ_{GW} are the induced changes in recharge and discharge, respectively, and $\Delta S/\Delta t$ is the rate at which water is withdrawn from aquifer storage.
Well scale	Includes well or packer tests that occur on a scale of 100–1000 m^3, with wide variation, depending on well depth or packer size and configuration; local scale (modified from Halihan et al., 1999).

Induced Recharge

Historically, the layers of lower permeability within and between the surficial aquifers and underlying Floridan aquifer resulted in perched water table conditions in the overlying surficial aquifers. These conditions were essential in maintaining the natural hydroperiod of the depressional wetlands described in this case study. Continued pumping has resulted in subsidence (see Table 1) and an increase in the number and magnitude of natural breaches in lower-permeability (semiconfining) zones in the Floridan aquifer system, leading to considerable increases in induced recharge. The induced recharge comes from deeper (brackish to saline) zones of the Floridan aquifer and coastal waters, as well as from the overlying surficial aquifers. The result is the loss of integrity of the lower-permeability zones that perched the water table (summarized in Bacchus, 2000a, 2000b). Recent tracer studies using stable isotopes of water, radiocarbon, noble gases, and chloride have demonstrated that in areas of extensive long-term groundwater mining in southern Florida and SE Georgia, fossil water is not present

in samples from some wells in the Floridan aquifer zones (Clark, 2002; Clark et al., 1997). These findings suggest that induced recharge from the surficial aquifer is more significant than has been acknowledged.

Nonmechanical Dewatering

An additional and increasing threat to this regional karst aquifer system is structural mining of aquifer formations (deep and shallow extraction, as defined in Table 1). These excavations generally occur in rural, naturally vegetated areas, including the most ecologically sensitive depressional wetlands and other critical habitats for threatened and endangered species. Curtis (1989) provides a prime example of altered hydroperiod responses predicted in a nature preserve adjacent to a proposed sand mine in south-central Florida. The excavations also often include mechanical dewatering, via pumping, to facilitate extraction of the aquifer formations (defined in Table 1). The exchange of water between surficial and underlying aquifer zones at all depths is increased by both groundwater pumping and mining of the aquifer formations, as summarized by Bacchus (2000b), reported with site-specific examples by Wilcox et al. (2004), and discussed in more detail in the following. Despite the comparable adverse impacts of groundwater pumping and mining of the aquifer formations, mechanical dewatering is the sole consideration of federal, state, and local regulatory agencies during their evaluation of applications for structural mining of the aquifer system. No monitoring of subsidence with respect to a fixed datum is required. Consistent with regulatory terminology for mechanical dewatering, which requires a permit in Florida, induced aquifer losses that occur without pumping will be referenced herein as nonmechanical dewatering.

Unlike mechanical dewatering of the aquifer system, nonmechanical dewatering from excavated areas cannot be halted once the aquifer formations have been excavated and removed. In all but a few types of mining, such as the titanium (mineral) mines, the excavated pits remain as significant, permanent alterations of the natural land surface contours. In titanium mines, the mined areas are back-filled to approximate the pre-mined land surface contours as the floating mine barge moves forward from one mine area to the next. The mining process and the homogenized strata in the refilled pits, however, result in the destruction of surrounding wetlands and preclude reestablishment of forested wetlands on the refilled pits with native wetland trees such as pond-cypress (Bacchus, 1995). Titanium mines have been proposed adjacent to the Okeefenokee Swamp and Okeefenokee National Wildlife Refuge and have been permitted by the U.S. Army Corps of Engineers (USACE) in the upper reaches of the Satilla River in Georgia's Coastal Plain.

Both temporary (e.g., mobile titanium mines) pits and permanent (stationary) pits result in the irreversible and irrevocable commitment of natural resources, including water and forest resources. Such irreversible commitment of natural resources is required to be identified during the permit application process and to be evaluated during the Environmental Impact Statement (EIS) analysis (USACE, 2000, p. 81). For example, forests (trees) in the United States are significant sinks for sequestering carbon to ameliorate global warming (Schimel et al., 2002). The permanent direct and indirect loss of trees and forests caused by mining operations throughout the extent of the Floridan aquifer system eliminates that means of reducing global warming. Even mine sites lacking trees prior to initiation of mining contribute to global warming through land-use changes. Kalnay and Cai (2003) recently documented that land use change is a significant cause of global warming. The impact of mining on global warming is another example of its indirect and cumulative adverse effects. Despite refuting data, excavations of open pits increasingly are being portrayed as subsurface "reservoirs" that enhance or create sources of water in areas where excessive pumping has resulted in severe groundwater depletion (Wilsnack et al., 2001).

Case Study

No scientifically based studies have been conducted to compare the environmental conditions prior to (baseline), during, and following mining of the aquifer formations throughout the regional Floridan aquifer system. Determining the extent of adverse impacts due to mechanical versus nonmechanical dewatering at sites where pits have been excavated is difficult in cases where both processes have occurred at the same mine site. A case study was conducted and is presented here for four representative areas of the regional Floridan aquifer system (SE, NW, SW, and east-central Florida; Fig. 1). This case study provides a general comparison of environmental impacts associated with excavations that involve both mechanical and non-mechanical dewatering, and excavations involving nonmechanical dewatering only.

The mining activities in SE and NW Florida are large-scale limestone and phosphate mines, respectively. The limestone mines are referred to as "rock mines" or "limerock mines" by the regulatory agencies. The mining activities in SW and east-central Florida are relatively small-scale operations, primarily for the production of fill material. The latter was permitted by the St. Johns River Water Management District (SJRWMD, permit no. 4-172–86929-1) as a subsurface "reservoir" to increase available water. Each large-scale limestone pit evaluated in SE Florida in the case study also is being permitted by the South Florida Water Management District (SFWMD, 1997) and USACE (10 consolidated permits) as a "reservoir" that enhances or increases the amount of available water.

For evacuations selected in this case-study review for those representative areas of the aquifer system, a general quantification of the loss of ground water due to nonmechanical dewatering was determined using site-specific information available to agencies reviewing permit applications for these activities. The general adequacy of groundwater models commonly used for evaluating impacts of these excavated pits also was considered.

Adverse Impacts

Adverse impacts from structural mining of the surficial and underlying aquifer zones result from: (1) lateral flow of ground water into the excavated pit from surrounding areas, due to the large void space of the pit compared to smaller void spaces filled with water in the aquifer formations; (2) vertical flow of ground water into the excavated pit from underlying aquifer zones under pressure, via breaches in the semiconfining layer(s), as defined in Table 1; (3) increased evaporative loss of water over the surface area of the excavation, as ground water is converted to surface water; (4) increased evapotranspiration (ET) surrounding the excavation, as water-conserving native vegetation inevitably is replaced by water-depleting alien and nuisance native plant species; and (5) contamination of the surrounding aquifer from pollutants entering the newly created surface water in the excavations. The case-study areas exemplify these factors and the increased threat from contaminant transport of pollutants entering these excavated areas when pumping wells are present in the vicinity of these pits.

REPRESENTATIVE AREAS IN THE REGIONAL FLORIDAN AQUIFER SYSTEM

SE Florida

The most significant, if not the first, claim that mining of the Floridan aquifer system formations creates a "reservoir" ("lake") that enhances or increases the amount of available water was made by the South Florida Water Management District (SFWMD, 1997) and USACE (2000, p. 3). These claims were made regarding the existing and proposed limestone mine pits in Miami-Dade County. The USACE Final EIS proposed the direct loss of ~8400 ha (reported as 21,000 ac) in the Everglades watershed, in SE Florida, by conversion of this area to mine pits and related facilities. This action would result in the direct loss of ~6320 ha (reported as 15,800 ac) of Everglades Pennsucco wetlands (USACE, 2000). Ten limestone mining operations were proposed to be authorized under a single, consolidated USACE Section 404, Clean Water Act dredge and fill permit, for which a public notice was published on 1 March 2001. The ten individual mining corporations included under that consolidated permit were: Continental Florida Materials, Inc.; CSR Rinker Materials Corp.; Florida Rock Industries; Kendall Properties and Investments; Lowell Dunn Company; Pan American Construction; Sawgrass Rock Quarry, Inc.; Sunshine Rock; Tarmac America, Inc.; and White Rock Quarries.

The 231 km^2 (reported as 89 mi^2) area designated to be converted into a coalescence of mine pits is referred to as the "Lake Belt" area, although no natural lakes occur there. The location is within one of the most environmentally sensitive areas of the state, in the Everglades watershed (approximate UTM boundaries: 25.95, 25.77, 80.40, 80.50). This area also is part of the historic headwaters of Shark River Slough (SFWMD, 1997).

These mining activities were included by the USACE as one of the primary components of the Comprehensive Everglades Restoration Plan (CERP), which USACE has proposed funding with tax revenue. A second key component of the UASCE's "restoration" plan is aquifer injections. More than 330 wells have been proposed to be drilled primarily into the upper Floridan aquifer for artificial recharge injections. These injection wells are referenced as "aquifer storage and recovery" (ASR) wells by the USACE and SFWMD. The original estimate for the Everglades restoration activities was ~$8.4 billion, when the estimated cost of the ASR wells was ~$1.5 million each. The estimate provided in the recent Final EIS for the pilot project for these initial injection wells at the Kissimmee River, Moore Haven, Hillsboro Canal, and Port Mayaca sites in the Everglades watershed was $5.5 million, $5.6 million, $5.4 million, and $8 million, respectively (USACE, 2004a; see also USACE, 2004b), which will increase the total cost of the proposed "restoration" considerably. Restoration of the Everglades' hydrology and hydropatterns is essential for the continued survival of several threatened and endangered species (SFWMD, 1997). Data collected by numerous sources from ASR wells previously tested in the Everglades watershed were evaluated later by the USGS (Reese, 2002). Those data were used to determine the volume of water withdrawn from the ASR wells as a mixture of low-chloride injected water and high chloride ground water, before the withdrawn water exceeded a designated level of 250 mg/L chlorides. The actual "recovery" from those ASR wells was not calculated by the USGS (Reese, 2002). Actual "recovery" values calculated for those wells were so low that those values suggest that ASR injections will result in additional adverse impacts to the hydroperiod of the Everglades, similar to the adverse impacts of the channelization of the Kissimmee River (Bacchus, 2005). The USACE and other public agencies are currently attempting to unchannelize the Kissimmee River using tax revenue.

The mining was described by the Florida Legislature in 1992, as the "Northwest Miami-Dade County Lake Plan" (Chapter 373.4149(4), Florida Statutes). Subsequently, the USACE initiated an EIS for the proposed "Rock-Mining-Freshwater Lakebelt Plan." An EIS is designed to evaluate all of the direct, indirect, and cumulative impacts on the human environment of a proposed agency action, such as the permitting of mining operations. The Final Programmatic EIS for the project included citations describing the net increase in water loss due to increased evaporation from the aquifer that would occur from the proposed mining operation. None of the indirect or cumulative impacts of that aquifer dewatering were considered in the EIS. The Final Programmatic EIS concluded, without supporting scientific data, that the project would "... vastly improve native plant communities and the habitat functions and values they supply within the Pennsucco wetlands" (USACE, 2000, p. 1).

Two of the mine pits that have been excavated in the central portion of the area designated as the belt of mine pits to be

excavated within wetlands in SE (Miami-Dade County) Florida are ~1 km (0.6 mi) west of the Miami-Dade County Northwest Well Field. The Northwest Well Field is the largest water-supply well field in the county and is composed of 15 wells. These wells collectively pumped an average of 340,650 m^3/d (reported as 90 million gallons per day [Mgd]) for municipal use in 1997. According to the SFWMD (1997), the installed capacity of that well field is 851,625 m^3/d (225 Mgd). The second major municipal well field constructed within the wetlands proposed to become the "belt" of mine pits, is the West Well Field. This well field, located in the SW portion of the designated "belt," is composed of three wells, with a total installed capacity of 113,550 m^3/d (30 Mgd), and a planned second phase that would double that capacity (SFWMD, 1997). Both well fields are relevant to the case study in this subregion of the Floridan aquifer system, but only the Northwest Well Field will be discussed in more detail.

The adverse impacts on natural wetlands from the surficial aquifer pumping at the municipal well field were illustrated in what appears to be the only scientific study of environmental conditions prior to and following mechanical dewatering by a municipal well field within the extent of the Floridan aquifer system (Hofstetter and Sonenshein, 1990; Sonenshein and Hofstetter, 1990). The results of that research are summarized below, because of the relevance of the findings to nonmechanical dewatering of the aquifer system.

The Miami-Dade County Northwest Well Field is located west of the Miami Canal, east of Levee 30 and the L-30 Canal, and north of the Tamiami Canal. This well field is constructed in the eastern portion of the wetland that has been designated Everglades National Park and "Wildlife Management Area/ Conservation Area No. 3." In May 1983, groundwater withdrawals from the unconfined Biscayne aquifer began at the Northwest Well Field (Sonenshein and Hofstetter, 1990). The highly permeable nature of the Biscayne aquifer, underlain by the Floridan, and its significant hydraulic connection between the aquifer and streams has been described by Hull and Beaven (1977), who indicated that the groundwater level declines in response to pumping of the wells. Water levels in seven observation wells were above land surface 25%–50% of the time prior to initiation of groundwater withdrawals from the Northwest Well Field, (Sonenshein and Hofstetter, 1990). Those high levels occurred despite a period of prolonged low rainfall that reportedly had occurred in the area for ~15 yr prior to initiation of pumping (Eugene Shinn, USGS, August 1999, personal commun.). After pumping was initiated, water levels in three wells were reported to have been above land surface <1% of the time, with details as follows:

"Water levels have declined in 30 percent of the 65-square mile study area since the well field began operating. In 15 percent of the area, water levels have been lowered below land surface. ... The area dewatered by pumping at the well field is about 10 mi^2 (15 percent of the study area) and is no longer considered a wetland." (Sonenshein and Hofstetter, 1990, p. 1).

At the time of the study, mean daily pumpage from this well field ranged from ~242,240 to 507,190 m^3/d (reported as 64–134 Mgd). Annually, withdrawals are slightly greater from March through August (Sonenshein and Hofstetter, 1990). In 1978, four study sites associated with the well field were dominated by native herbs and shrubs. By 1988, composition had shifted to woody, upland plants dominated by the invasive alien species, melaleuca (*Melaleuca quinquenervia*), with a respective loss of native herbaceous and wetland species at all four sites (Hofstetter and Sonenshein, 1990). The authors concluded that the adverse environmental impacts documented in the area surrounding this well field were a direct result of the groundwater mining (mechanical dewatering).

The rapid conversion from desirable native wetland and upland plant species to aggressive invasive alien and nuisance species is a common occurrence throughout the extent of the Floridan aquifer system, as natural hydroperiods (defined in Table 1) are altered. The cover photograph for Wildland Weeds (Brown, 2004), showing the mass invasion of an alien climbing fern (*Lygodium microphyllum*), is an example of a more recent problem comparable to the melaleuca invasions in areas evaluated by the author where groundwater extraction is occurring.

Hydroperiod alterations result from lowering water levels by induced recharge in response to the pumping of underlying formations or dewatering the water table directly through pumping from the surficial aquifer, as documented in the Northwest Well Field study. It also occurs as a result of abnormal pulsing of the surficial aquifer, in response to pumping cycles of supply wells. Scientific studies comparable to those conducted for the Northwest Well Field have not been conducted to document all of the adverse environmental impacts of nonmechanical dewatering of the aquifer system from excavations, such as the mine pits permitted and proposed in the pit belt and the other areas evaluated in this case study.

The rate and magnitude of water movement in the karst Biscayne aquifer in response to mechanical pumping initially were illustrated by the inadvertent contamination of the aquifer when saline water extracted during the drilling of a waste injection well was discharged into an unlined surface pit. The denser saline water percolated into the Biscayne aquifer and migrated, with little mixing, as a slug toward the municipal supply wells. In that case, the saltwater plume traveled laterally ~1.6 km (~1 mi) in 18 months (Pitt et al., 1977).

More recently, the USGS conducted a Rhodamine WT dye tracer test in the Biscayne aquifer, in the vicinity of the Everglades pits, to calibrate a dual-porosity geophysical conceptual groundwater-flow model. The apparent mean velocity of advective flow observed in that study (366 m/d) exceeded the simulated velocity (8 m/d) for that area by ~3 orders of magnitude (http://gsa.confex.com/gsa/2003AM/finalprogram/abstract_65197.htm). That observed velocity in the USGS tracer test was an order of magnitude less than the velocity (~3384 m/d) observed by Paul et al. (2000) for tracers introduced into shallow-aquifer sewage effluent injection wells in the Florida Keys (reported as 60 ft deep and 0.02 Mgd).

Stable-isotope data acquired from groundwater and surface waters in the SE case-study area prior to that USGS study (through 1998) were not published until 2004. The results of that study revealed that the mine pits east of the Everglades breached two semiconfining layers in the Biscayne aquifer, causing water to flow vertically upward into the pits excavated in the pit belt from a deep groundwater source. That breached flow resulted in the mixing of shallow and deep ground water from the Everglades, including Everglades National Park. Those data illustrate that Everglades surface waters infiltrate into the aquifer and flow laterally, eastward, into and through the pits (Wilcox et al., 2004). That study was not designed to determine the total amount of ground water and surface water diverted from the Everglades by the mined pits, but recommended that additional research be conducted to make that determination.

The Dade County Code that was in effect in 1997 generally prohibited mining within a 60 d travel time from the wellheads. Using MODFLOW-based simulations, that distance was determined to be ~0.8 km (reported as 0.5 mi by SFWMD, 1997). Based on the observed flow response in the USGS tracer test referenced above, the distance for the 60 d travel time was traveled in ~2 d by Everglades water flowing into and through the pits.

The EIS prepared for the proposed consolidated mining permit for the belt of mine pits described the increase in evaporative water loss that would occur due to the mining of ~8400 ha in the Everglades. The changes in evapotranspiration (ET) and evaporation (E) rates that would occur from unmined to mined conditions are depicted in Figures 2A and 2B, respectively, based on previously published data (Chin, 1996; Krulikas and Giese, 1995; Odum, 1984; and USACE, 2000). Dry-season conditions are shown in the before-mining illustration, because, historically, the water table would be at or above land surface during the wet season. This figure also illustrates the important point that the root systems of the key ecosystem tree species are associated with the natural fluctuation range (both low and high) of the water table.

The resulting nonmechanical dewatering of the aquifer for each 0.4 ha (1 ac) of surface area excavated includes the loss of the historic ~25 cm/yr (reported as ~10 in/yr) net recharge plus an additional loss of ~23 cm/yr (9 in/yr) of aquifer water (Fig. 2B). In areas surrounding each excavation, recharge is reduced from the historic ~25 cm/yr to only ~18 cm/yr (7 in/yr), as water-conserving native vegetation is replaced by water-depleting alien plant species, such as melaleuca (Fig. 2B, black/gray canopy), and similar nuisance native plant species. After pit excavation, the level of the water table (▼) is permanently lowered below the root zone of some key native species (e.g., pond cypress; Fig. 2A, gray canopy) and to levels that result in chronic water stress to other key native species with tap roots that still are within the lowered water table (e.g., pines, *Pinus* spp.; Fig. 2A, black canopy, and Fig. 2B, defoliated canopy). These conditions lead to the premature decline and death of those species. A federal court ruled on 22 March 2006 that the U.S. Army Corps of Engineers and U.S. Fish and Wildlife Service had failed to carry out their duty to protect the federal wetlands and protected species by issuing permits for mining in the SE case-study area (U.S. Southern District Case No. 03-23427-CIV-Hoeveler).

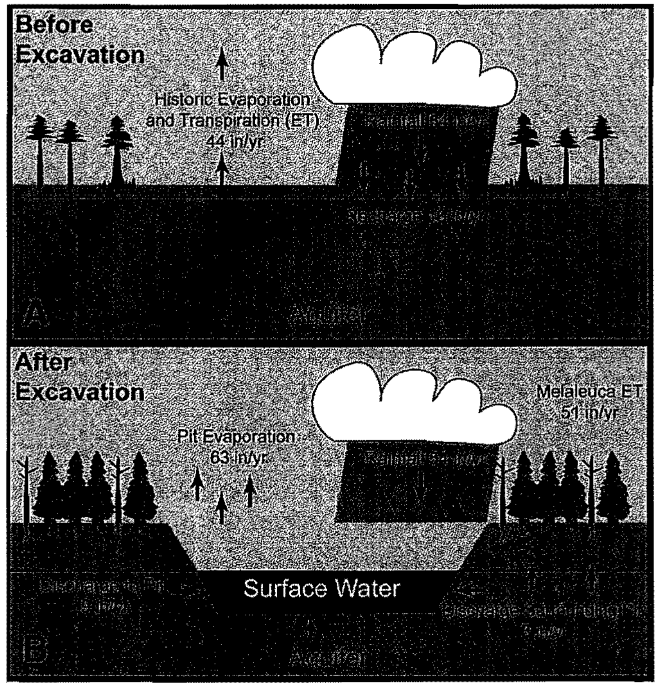

Figure 2. Permanent reduction of groundwater resources by excavations, based on historic rainfall, evapotranspiration (*ET*), and evaporation (*E*) rates for southern Florida (Chin, 1996; Krulikas and Giese, 1995; Odum, 1984; USACE, 2000; printed with permission). (A) Before excavation, historic rainfall and *ET* are ~137 cm/yr (reported as 54 in/yr) and ~112 cm/yr (reported as 44 in/yr), respectively, resulting in net recharge to the aquifer system of ~25 cm/yr (10 in/yr). (B) After excavation, historic rainfall is held constant, while *ET* over the excavated pit is converted to *E*, with an increase to ~160 cm/yr (reported as 63 in/yr), and *ET* surrounding the pit increases to ~130 cm/yr (reported as 51 in/yr), due to induced conversion from water-conserving to water-depleting vegetative cover, such as invasive and alien species, permanently lowering the water table (▼). See text for details.

The net loss of water from the aquifer system after excavation of the pits is ~48 cm/yr (19 in/yr) for each 0.4 ha (1 ac) of surface area excavated (Equations 1 and 2). Based on a minimum excavated area of ~8400 ha (reported as 21,000 ac) in the SE case-study area, the total loss of ground water, due to solely nonmechanical dewatering from that mining project, would be ~112,335 m^3/d (29.7 Mgd).

$$R_{nat} = P - ET_{nat} \tag{1}$$

and

$$R_{pit} = P - (E_{pit} + ET_{pit}), \tag{2}$$

where R_{nat} is the natural recharge before pit excavation (adjusted for overland flow, which is held constant for both equations), R_{pit} is the recharge after pit excavation (negative), P is the annual precipitation, ET_{nat} is the natural loss of water due to combined evaporation and transpiration, and $(E_{pit} + ET_{pit})$ is the combined loss of water due to evaporation from the pit and increased evaporation and transpiration from alien and/or invasive species surrounding the pit.

This loss is equivalent to the total volume of water mechanically pumped from the aquifer by the three municipal supply wells reported by SFWMD (1997) for the Miami-Dade West Well Field in 1997 (Table 2). This loss also is equivalent to ~50% of the base municipal withdrawals from the Miami-Dade Northwest Well Field, where surficial aquifer level drawdowns were documented by Sonenshein and Hofstetter (1990) in 30% of their ~169 km^2 (reported as 65 mi^2) study area. As in that study, the groundwater alterations associated with areas that already have been mined in SE Florida have resulted in conversion from water-conserving natural wetland and upland vegetation to impenetrable stands of melaleuca. The conversion of native wetland species to invasive alien species and nuisance native species is used as justification by the USACE and other regulatory agencies to expedite permits for additional losses of formerly natural wetlands, with no bona fide mitigation to replace those wetlands.

The USACE EIS did not consider the permanent lowering of surficial aquifer levels that results from the physical removal of the aquifer formations in the extensive structural mining proposed for the pit belt. In the absence of any additional indirect or cumulative impacts, the permanent lowering of the water table will result in altered hydroperiods in Everglades wetlands surrounding the excavated pits. The USACE EIS also neglected to consider the combined adverse impacts of the mechanical dewatering of the aquifer from the municipal, agricultural, and industrial wells, in conjunction with the permanent lowering of the water table resulting solely from the removal of the aquifer formations and conversion to open pits (a cumulative impact).

Finally, the USACE EIS did not consider the replacement of desirable native plant species in naturally vegetated Everglades areas surrounding the excavated pits by aggressive invasive species such as melaleuca. That conversion from native to alien species will result in an additional increase in groundwater loss of 7 cm/yr (3 in/yr) for each 0.4 ha (1 ac) within the actual cone of influence resulting from the nonmechanical dewatering of the excavated pits (Fig. 2). The lateral extent of the cone of influence surrounding the pits, due to the combined direct, indirect, and cumulative adverse impacts of mining the aquifer formations, and mechanical and nonmechanical dewatering of the aquifer system, has not been determined. That lateral extent, however, would be greater than the actual cone of influence from a combination of all pumping wells in that area.

As described previously, the mechanical dewatering of the aquifer system due to pumping from the Northwest Well Field resulted in a significant drawdown (cone of influence) in 30% of the ~169 km^2 (reported as 65 mi^2) study area. A realistic predicted cone of influence for the ~8400 ha of pits proposed to be excavated in the Everglades would be ~15% of that area, or ~26 km^2 (10 mi^2) surrounding the pits. Therefore, there is no scientific basis for the conclusion in the Final EIS that the negative impacts from the open pits, resulting from the permitted 8400 ha (reported as 21,000 ac) pit belt, would be confined primarily to the immediate area, and would not be expected to result in significant cumulative impacts to the Everglades ecosystem (USACE, 2000).

The reported "recovery" was <60% for ASR wells tested by consultants at two locations in Miami-Dade County in proximity to the pit belt and later evaluated by the USGS (Reese, 2002). After adjusting for the differences in chloride content for the injected and "recovered" water, actual recovery for all cycle tests at those wells was <15%. Clearly, ASR will not provide a mechanism for the continued production from the Miami-Dade municipal supply wells. As the municipal and other supply wells exhaust the groundwater resources, and open-ocean desalination becomes the primary source of potable water in the SE area of the case study, the direct adverse impacts of that pumping on the Everglades and coastal ecosystems will cease. The nonmechanical dewatering of the aquifer system supporting those ecosystems that results from the open mine pits, however, will continue irreversibly and irrevocably.

NW Florida

Comparable large-scale mining of the shallow and deep aquifer formations for phosphate deposits is occurring in the tributary wetlands of the upper Suwannee River, in rural NW Florida (Hamilton County, Fig. 1). Suwannee River tributaries

TABLE 2. MECHANICAL (PERMITTED) AND NONMECHANICAL (UNPERMITTED) DEWATERING ASSOCIATED WITH MINED PITS AT REPRESENTATIVE LOCATIONS THROUGHOUT THE REGIONAL FLORIDAN AQUIFER SYSTEM

Mine locations	Surface area of pits min/max		Mechanical dewatering permitted		Nonmechanical dewatering min/max		Comparable potable water supply
	(ha)	(ac)	(m^3 d^{-1})	(Mgd)	(m^3 d^{-1})	(Mgd)	(daily pumpage)
SE: Everglades, Dade County	8400	21,000	unspecified		112,335	29.7	West Well Field Miami-Dade municipal supply
NW: Suwannee River, Hamilton County	1136/9120	2841/22,800	984,100 -	260	15,192/121,964	4/32.3	West Well Field Miami-Dade municipal supply
SW: Corkscrew Swamp, Lee County	123/152	308/380	217,763	71.8	1505/1860	0.4/0.5	~5% of total 1990 domestic water use for Lee County
E-central: Spruce Creek, Volusia County	70	175	1893	0.5	857	0.2	~3% of total 1990 domestic water use for Lee County
Totals: four examples from regional aquifer	9729/17,742	24,324/44,355	985,993/1.6 × 10^6	260.5/332.3	129,889/237,016	34.3/62.7	>twice 1997 West Well Field Miami-Dade municipal supply

in the vicinity of the existing and proposed mining activities include Swift, Hunter, and Camp Branch. The predominant natural wetland and upland vegetation in the area of the NW Floridan aquifer system (depressional pond-cypress wetlands and pine flatwoods) is endemic to the extent of the regional Floridan aquifer system, and comparable to the native vegetation used to determine ET rates included in Figure 2.

The primary mining activities in this area are occurring at a mine site originally owned by Occidental Chemical and Petroleum Corporation (~UTM boundaries: 30.50, 30.40, 82.70, 82.83). After initiation of those mining activities, the mine was sold to Potash Company of Saskatchewan (PCS Phosphate–White Springs). A public notice published by the USACE on 17 May 2002 proposed to issue an additional 15 yr permit to mine ~3000 ha (reported as 7500 ac) of wetlands on a 40,232 ha (reported as 100,580 ac) project site. A second public notice, published on 13 June 2002, proposed mining another ~7432 ha (reported as 1858 ac) of jurisdictional wetlands within a 7631 ha (reported as 19,077 ac) mine application footprint over a 47 yr period. A substantial portion of the 40,232 ha project site contains natural, depressional wetlands, like those in the SE study area. The USACE presently does not consider those wetlands to be within their regulatory jurisdiction. As established above, these natural depressional wetlands occur throughout the Floridan aquifer system, have been shown to exist in relict sinkholes aligned along fracture systems, and are connected to surface waters (summarized by Bacchus, 2000b).

The site of the current and proposed White Springs mining activities originally was inspected in the late 1970s, prior to initiation of any mining activities in that area. Additional inspections were conducted at the mine site and surrounding watershed from 1991 to 2003, prior to the issuance of subsequent permits to expand the mine pits. Those inspections provided a basis for identifying landscape-scale changes in the rural watershed. Those evaluations were conducted using the field methods described by Bacchus et al. (2003). Groundwater alterations associated with the initially permitted White Springs mining operations have resulted in landscape-scale adverse impacts to both wetlands and uplands habitat extending more than 16 km (10 mi) beyond the boundaries of the mine site. Attributing the impacts to the White Springs mining operations is simplified by the lack of other significant industrial, agricultural, and municipal sources of groundwater alterations in the immediate vicinity of the White Springs mine site. One significant adverse impact of the White Springs mine is that it has caused White Springs to cease flowing. White Springs was a major source of water for the Suwannee River.

Such impacts are not unique to the White Springs mining operation or that subregion of the Floridan aquifer system. Lewelling et al. (1998) reported cessation of flow at several springs located near and within the Peace River channel, including Kissengen Spring. The flow at that spring was reported as "about 19 million gallons a day." Phosphate mines operate within the Peace River watershed, which is located ~80 km (~50 mi) north of the SW Florida case-study area. Lewelling et al. (1998) illustrated both the collapse of land surface (subsidence), due to mechanical and nonmechanical dewatering of the aquifer system by the mines in the Peace River watershed, and the structural characteristics of the aquifer system through seismic-reflection profiles.

The extent to which these adverse environmental impacts are associated with the nonmechanical dewatering aspects of the White Springs mine excavations is more difficult to determine. The mine has been operating under a Consumptive Use Permit (CUP) from the Suwannee River Water Management District (SRWMD) for the withdrawal (mechanical dewatering) of ~984,100 m^3/d (reported as 260 Mgd) of ground water for the mining operation. The mechanical dewatering permitted under that CUP permit represents more than 25% of the total water withdrawals permitted for the entire 14 county area regulated by the SRWMD, and approximately twice the groundwater withdrawals permitted for Miami-Dade County's Northwest Well Field, referenced above. Based on recent groundwater extraction information for that region (Barlow, 2003), the mechanical withdrawals permitted under that existing CUP also exceed the total groundwater withdrawals for the three northeasternmost coastal counties of Florida (reported as 217 Mgd), where long-term water-level declines in several areas have resulted. The nonmechanical dewatering that would occur solely from the permitted expansion of this mine also is comparable to the restricted additional pumpage (reported as 36 Mgd) permitted for all 24 coastal counties in the Georgia portion of the Floridan aquifer system (Barlow, 2003). The combined mechanical and nonmechanical dewatering of the Floridan aquifer system for the White Springs mine site also is comparable to the total 1997 groundwater withdrawals reported for the entire coastal Georgia area of the Floridan aquifer system (Barlow, 2003, p. 49).

Limited information was available to determine the amount of nonmechanical dewatering of the ~40,232 ha project site, in part because information confirming the total surface area mined under the initial permit was not readily available. The supplemental EIS prepared for the USACE for the expansion of the mine indicated mine pits for additional uplands to be mined would be excavated to depths of ~21–27 m (reported as 70–90 ft) under the following scenarios: ~1136 ha (reported as 2841 ac) to supply material for three years; and ~4000–5520 ha (reported as 10,000–13,800 ac) for the duration of the permit. The same document indicated that ~800 ha (reported as 2000 ac) of the jurisdictional wetlands and ~2800 ha (reported as 7000 ac) of additional wetlands on the site would be destroyed by the mining activities. A range for nonmechanical dewatering from the expanded mining operations for the limited three-year extractions in uplands would be ~15,192 m^3/d (~4 Mgd), with ~121,964 m^3/d (~32.3 Mgd) for the additional ~5520, 800, and 2800 ha (13,800, 2000, and 7000 ac) of uplands, jurisdictional wetlands, and non-jurisdictional wetlands, respectively. The total surface area of the mine expansion permitted by the USACE (excluding areas previously mined and permitted at this site) is greater than the total surface area of the 10 combined permits evaluated in the SE Florida area.

Table 2 provides a summary of the surface area of the pits evaluated in the four representative locations of the regional Floridan aquifer system. A second component of Table 2 is the volume of water authorized by the regulatory agency to be removed by pumping (mechanical dewatering). A third component of Table 2 is the unpermitted volume of water removed from the aquifer system due to the increased evaporative losses over the surface area extent of the pit and increased evapotranspirative losses in vegetated areas surrounding the excavated areas (nonmechanical dewatering). The information provided to and by the USACE for the ~8400 ha area that would be excavated within the concentration ("belt") of pits does not include the volume of water that would be removed from these pits by mechanical pumping. Therefore, the total mechanical dewatering values provided in Table 2 do not include any mechanical pumping for the SE Florida example.

Minimum and maximum values provided in Table 2 for the NW and SW case-study examples are based on multiple areas provided in regulatory documents for the extent of mined surface areas. Values for the SE location represent totals for 10 consolidated permits. Values for the NW location represent only the additional area to be mined under the expansion permits issued in 2003, and do not include the expansive existing mine pits. It is important to note that the permitted volume for mechanical dewatering of the aquifer system for the NW pits is approximately twice the maximum volume permitted for withdrawal for the Miami-Dade County's municipal Northwest Well Field, which was shown to dewater the aquifer for 30% of their ~169 km^2 (reported as 65 mi^2) study area.

A series of new sinkholes occurred west of Interstate 75 at Lake City, Florida, in proximity to County Road 252 (Pinemount Road, Columbia County) during the first days of March 2005. The largest of those sinkholes inspected by the author was ~80 m deep. The location of these sinkholes (~UTM coordinates 30.17, 82.71) was ~26 km south of the White Springs phosphate mine's southern boundary. That distance is about half the length of fracture traces measured in other areas of the carbonate platform underlying Florida (Popenoe et al., 1984). Those new sinkholes also were associated with natural depressional, pond-cypress wetlands, which are known to be aligned along fracture systems and connected to the underlying Floridan aquifer (summarized by Bacchus, 2000b). The degree to which nonmechanical and mechanical dewatering of the aquifer system by the White Springs mining operation may have contributed to those sinkholes has not been investigated.

Subsequently, new sinkholes appeared at three locations southeast of the Lake City sinkholes. The locations of those sinkholes are consistent with the NW-SE alignment of major fractures that occur throughout the Florida peninsula. The earliest (ca. 29 March 2005) was a large subsidence collapse feature (reportedly ~121 m deep) in the southbound lane of Interstate 75, ~40 km southeast of the Lake City sinkholes and ~3 km north of the Interstate 75 Alachua exit, in Alachua County (~UTM coordinates 29.83, 82.52). A second new sinkhole in Alachua County appeared in SW Gainesville on 28 April 2005 (~UTM coordinates 29.61, 82.37) and is associated with the depressional wetlands in the northeastern vicinity of Hogtown Prairie, west of Lake Alice. The location of that sinkhole is ~24 km southeast of the Alachua sinkhole and along the same general alignment as the newly formed sinkholes west of Lake City. Sanchez Prairie in San Felasco Hammock State Preserve also is located along that same NW-SE alignment, midway between the Alachua and Gainesville sinkholes. Paines Prairie State Preserve is located an equivalent distance southeast of the Gainesville sinkhole along the same NW-SE alignment. The wetlands in Florida, known as prairies (more accurately, wet prairies), are natural depressional wetlands equivalent to the forested, pond-cypress wetlands, but lacking a canopy dominated by trees.

In early May 2005, an additional sinkhole (reportedly 113 m deep) was discovered in the northbound lane of Interstate 75, near the 39th Avenue overpass, northwest of Gainesville (~UTM coordinates: 29.68, 82.46). Natural wetlands and lakes are located west and east of that sinkhole, along a SW-NE alignment, which is similar to the fracture networks that are perpendicular to and intersect with the NW-SE–trending fractures throughout Florida. The sinkholes described above, and associated ground subsidence are similar in nature to the new sinkholes and ground subsidence that are occurring off-site and in proximity to the sand mines in Putnam County, Florida (Florida Rock Industries' mines at Grandin and Keuka), and in Sumter County, Florida (Florida Crused Stone/Rinker Corporation's Center Hill Mine). The Putnam County sand mines, and a kaolin mine in the same vicinity, are located ~32 km east of Paines Prairie State Preserve. The degree to which nonmechanical and mechanical dewatering of the aquifer by those mining operations has contributed to the sinkholes, associated ground subsidence, and lowered lake levels in the vicinity of those mines, and the dewatering of Paines Prairie also has not been determined. Evaluations of that type are hampered by the paucity of site-specific geophysical, hydrogeological, and hydroecological background and monitoring data, because such data generally are not required in conjunction with the permitting of those mining operations.

SW Florida

Lee County, in SW Florida (Fig. 1), recently proposed extensive clusters of mines, patterned after those described in the SE Florida evaluation area. The SW Florida mines are proposed in an area designated by Lee County for groundwater supply, where development is restricted by the Lee County Plan. The application submitted by the miners to the SFWMD requested a 30 yr mechanical aquifer-dewatering permit for 217,763 m^3/d (reported as 71.8 Mgd) for expanded pit excavation. The maximum volume provided in Table 2 for total mechanical dewatering at all four subregional locations includes the 30 yr daily volume requested for the Westwind Corkscrew

Mine in Lee County (~UTM boundaries: 26.45, 26.49, 81.58, 81.62). No mechanical dewatering for the SE case-study area is included in Table 2 because that information was not provided. The minimum volume included only the values for mechanical dewatering in the NW and east-central areas.

The Westwind Corkscrew Mine is the most recently initiated of numerous such excavations proposed within the "Density Reduction/Groundwater Resources" (DR/GR) area designated by Lee County, Florida. It is located adjacent to the north side of Corkscrew Road (Sections 22 and 23, Township 46 S, Range 27 E), in eastern Lee County. The watershed containing the Corkscrew Mine has been designated as the Corkscrew Regional Ecosystem Watershed (CREW), and is designated as critical habitat for the federally listed endangered Florida panther.

This mine site contains numerous natural depressional wetlands characteristic of wetlands used by federally endangered wood storks for nesting and feeding. Those natural depressional wetlands are comparable to those occurring in the SE and NW case-study areas and throughout the regional Floridan aquifer system. In addition to being located within designated Critical Panther Habitat and Wood Stork Foraging Areas, the Corkscrew Mine is surrounded by Corkscrew Marsh (northeast of the mine site); Corkscrew Mitigation Bank, Florida Gulf Coast University (FGCU) Mitigation, and proposed Airport Mitigation (northwest of the mine site); Corkscrew Swamp Sanctuary (south of the mine site); and Flint Pen Strand and the Panther Island Mitigation Bank (southwest of the mine site).

The initial permit for the Westwind Corkscrew Mine was issued by the SFWMD on 9 September 1999, and mining operations began immediately. Activities which were referenced as "baseline" monitoring by the permittee's consultants were conducted and submitted after mining operations had been initiated. The Lee Plan 2003 Codification (Lee Plan) does not define the term baseline. The term "baseline," as used in the permit, is a scientific term, and is defined in Table 1. Baseline monitoring, as defined scientifically, was not conducted prior to initiation of excavations.

At the permittee's request, the original schedule for the annual monitoring required by the SFWMD permit conditions (which the Lee Plan authorizes Lee County to enforce) subsequently was modified, as was the schedule for submittal of the required reports. The modification provided for a significant delay in meeting the original requirements of monitoring and reporting. No requirements were included for the permittee to monitor, document, and report site-specific baseline (pre-mining) hydroperiod or groundwater-level conditions on and surrounding the mine site. A review of the County and SFWMD files for the Corkscrew Mine in 2003 revealed no data documenting seasonal or annual hydroperiods or groundwater levels on and surrounding the mine site.

The type of natural depressional wetlands characteristic of the regional Floridan aquifer system comprise ~50% of the Corkscrew mine site. As indicated above, these types of natural depressional wetlands have been identified as relict sinkholes (dissolution features) that are karst windows linking these surface systems to the underlying Floridan aquifer system through breaches in the semiconfining layers. The majority of the wetland areas on the site that had not been mined at the time of the case-study evaluations was historically dominated by pond-cypress trees. The historic extent of those wetlands can be seen in the soils map depicted in the U.S. Department of Agriculture Soil Conservation Service Soils Survey of Lee County, Florida. The historic extent of some of these wetlands also can be seen as the areas with patterned stipples and/or shading in the 1958 (photo revised 1973) Corkscrew USGS topographic quadrangle map. Some of the historic depressional wetlands already had been mined and incorporated into the pits at the time of the initial inspection for the case study in April 2003.

Prior to initiation of the mining operation, the depressional wetlands were connected by surface water flowing generally from NE to SW, through the mine site (Peg Apgar-Schmidt, April 2003, personal commun.). The depressional wetlands system extends through the adjacent residential property, where the historic flow continued south. Other private residential properties are located within the extent of this depressional wetland slough system. Prior to initiation of the mining activities, part of the flow was channelized along the east portion of the site. Both surface and groundwater flow is toward the privately owned Corkscrew Swamp Sanctuary. Based on the more conservative of the two permitted surface areas for excavated pits reported for the Corkscrew Mine (~123 ha, ~308 ac), nonmechanical dewatering will result in induced discharge of ~1505 m^3/d (0.4 Mgd) from this single permitted activity in the SW area of the regional Floridan aquifer system. That loss is equivalent to ~5% of all water used by domestic supply wells in Lee County, Florida in 1990 (Lee County Regional Water Supply Authority, 1993). A 30 yr mechanical aquifer-dewatering permit for 217,763 m^3/d (reported as 71.8 Mgd) was requested to expand excavations at this site. That permit had not been issued at the time of the April 2003 site evaluation.

At the time of the April 2003 site evaluation, the mining activities already had resulted in adverse impacts on and surrounding the mine site that were inconsistent with requirements of the Lee Plan. These adverse impacts include the physical dewatering of the regional Floridan aquifer system, and associated depressional wetlands and other native habitat on and surrounding the Westwind Corkscrew Mine site. This nonmechanical dewatering has resulted in both adverse physical and ecological impacts to "preserved" wetlands on the mine site and in wetlands and uplands on private property associated with the mine site. Adverse physical impacts include both subsidence of subsurface formations and subsidence of organic surface material (defined in Table 1). Ecological impacts include chronic stress of native tree species, culminating in tree death, and the invasion of alien plant species. Melaleuca and Brazilian pepper (alien species) are the predominant woody species invading the mine site and surrounding areas. Dense stands of melaleuca, comparable to those surrounding the Miami-Dade

pits, were observed in proximity to older mines in other areas of Lee County. During the time of the initial site evaluation, private property west (King property) and south (Schmidt property) of the mine site provided examples of significant dewatering beyond the perimeter of the permitted mine site. These areas appear to be the first documented case of such adverse impacts occurring solely due to nonmechanical dewatering of the aquifer system.

The conversion of ground water to surface water by the excavated Westwind Corkscrew mine pits also facilitates contamination of the potable water supply by airborne contaminants, such as agricultural pesticides, herbicides, and fertilizers. The significance of contamination of surface waters by aerial deposition is described by Zamora et al. (2003). The Westwind Corkscrew Mine is surrounded by agricultural land and rural home sites with private wells.

East-Central Florida

On 10 February 2004 the SJRWMD issued a permit (4–172–86929–1) to the City of Port Orange, in east-central (Volusia County) Florida. That permit authorized the mining of two pits, with a total combined surface area of ~70 ha (reported as 175 ac). The permit describes impacts to ~12.8 ha (reported as 32.1 ac) of wetlands and "preservation" of ~84.2 ha (reported as 210.5 ac). The mine pits would be excavated within the extensive natural areas of Rima Ridge and Bennett Swamp, which are tributaries to the Spruce Creek and Tomoka River. Spruce Creek and Tomoka River are designated as "Outstanding Florida Waters" (~UTM boundaries: 29.08, 29.15, 81.12, 81.08). Municipal well fields, as well as state forests and other protected areas are located within this watershed. Most of the wetlands on and surrounding the proposed mine site are the natural depressional wetlands previously described and occurring throughout the other areas of the case study. The pits are referenced in permitting documents as reclaimed water recharge/storage reservoirs that enhance/increase the amount of available water. A companion CUP permit (51218) issued by SJRWMD to the city on the same date authorizes mechanical pumping of ~1893 m^3/d (reported as 0.5 Mgd). Also authorized is the diversion of both storm water and treated sewage effluent/waste water (collectively referenced as "recharge") into the excavated areas.

At the time the adverse impacts were documented at that mine site, the proposed pits were comparable in surface area to those at the SW Florida Corkscrew Mine site (Table 2). The Corkscrew Mine included no mechanical dewatering. Therefore, comparable adverse impacts to the remaining ~84.2 ha of onsite wetlands (including those designated as "preserved") and offsite wetlands and uplands surrounding the east-central Florida pits are predicted to occur. In the proposed east-central Florida pits, however, the introduction of contaminants into the potable water source will be urban, rather than agricultural (as in the SW Florida pits). Murphy et al. (2003) describes the myriad contaminants that remain in treated sewage effluent. Rapid flow to the public supply wells on the site, similar to that described in the SE Florida area, is predicted for the contaminants contained in the treated effluent and storm water. The contaminated effluent and storm water would be used to replace natural recharge to the aquifer system. Despite the clear danger of discharging treated effluent and storm water into these types of excavations (J.M. Sharp, October 2004, personal commun.), no EIS was conducted in conjunction with the regulatory review and permitting of these pits.

The SJRWMD drafted an application for $27,227,000 in federal funding (State and Tribal Assistance Grants, STAG) and an equivalent amount in local funding (from cities and county, via a state revolving fund loan), for a total of $54,454,000 to finance activities related to the excavation of these pits, reportedly to increase water availability in this area. Ultimately, a private entity (the Water Authority of Volusia County, Florida) in conjunction with the City of Port Orange, submitted an application to the USEPA to receive federal STAG funds for the $9.1 million project. That project, which would result in construction of an elaborate interconnection of pipes to transport water from the excavated pits to municipal supply customers, also involved a proposed $5 million loan from the State of Florida for excavation of these pits into the aquifer system, as a water supply source. The city's population increased from 3781 in 1970, to 45,823 in 2000. The aquifer system is the sole source of water for the city and surrounding area. On 2 July 2004, the USEPA issued a "Finding of No Significant Impact for the Finished Water Interconnect Project: Water Authority of Volusia County, Florida" to fund the project, without any Federal Register Notice, or EIS.

INADEQUACIES OF MODFLOW-TYPE MODELS

The SFWMD used MODFLOW, as described in the following, to evaluate impacts from the pits and related actions proposed as part of the Everglades "restoration" plan:

> ... to evaluate the effectiveness of the proposed system of improvements identified by the CERP for the management of environmental and public water supplies. The specific model features that are of primary interest include proposed improvements such as subsurface reservoirs and surface impoundments used for the detention and treatment of surface water flows. (Wilsnack et al., 2001, p. 1)

> ... It is evident in these results that maintaining quarry stages will require the control of very large seepage rates either through the use of large pumping stations or deep horizontal flow barriers. ... Such losses are significant for the two quarries located adjacent to the well field. This would require the return seepage flows to be supplemented by flows derived from sources outside of the lakebelt area. Potential sources of water have been investigated previously (CH2M Hill, 1993). (Wilsnack, 1995, p. 211).

As indicated in the SE case-study discussion, actual "recovery" was extremely low from the ASR wells, including those tested by CH2M Hill in the vicinity of the proposed con-

centration ("belt") of pits (Bacchus, 2005; Reese, 2002). Therefore, a "deep horizontal flow barrier" (e.g., aquifer injections, ASR) to prevent loss of water from the pits, as suggested by Wilsnack (1995) in the statements above, is not likely to be successful. The surface impoundments intended to be environmental improvements for the Everglades (Wilsnack et al., 2001) that are being proposed by SFWMD and permitted by USACE also include extensive shallow extraction/mining (dredging). Examples include those proposed in Public Notices dated 13 December 2004 at the location of the Hillsboro ASR pilot project site and Loxahatchee National Wildlife Refuge (USACE Permit Application No. SAJ-1994–4532[IP-TKW]) and the Everglades Agricultural Area (EAA) associated with the Rotenburger Wildlife Management Area (USACE Permit Application No. SAJ-2004–7442[IP-TKW]). The following descriptions of those two projects were provided in the public notices. Based on the documented adverse impacts of pits, it is difficult to determine how the dredging of another 1470 ha (3675 ac) of pits in the Everglades will improve hydroperiods and hydropatterns, as stated in the following for those two projects, respectively:

> PROPOSED WORK: The proposed project includes excavating 425,000 cubic yards of material for construction of a 1,660-acre impoundment ... Approximately 769.33 acres of wetlands and 1,025.49 acres of uplands will be impacted as a result of the project. ... The specific objectives of the project include the following: improving hydroperiods and hydropatterns in WCA1 ... and in WCA 2A ... (Hillsboro ASR pilot project/Loxahatchee National Wildlife Refuge site)

> PROPOSED WORK: The applicant proposes to construct additional treatment areas for STA 2 and STA 5. A 2,015-acre area identified as Cell 4 will be constructed for STA 4 and a 2,560-acre area identified as Flow-way 3 will be constructed for STA 5. Areas within the proposed treatment cells will be dredged. The dredged material will be used to fill in low lying areas within the project footprint as well as for the construction of berms and levees ... (EAA/Rotenburger Wildlife Management Area project site)

Currently, MODFLOW and MODFLOW-type models are considered the best available technology for predicting groundwater-flow responses throughout the United States. MODFLOW is a regional-scale model that may be suitable for water balance at that scale; however, it is not suited for making localized site-scale evaluations in a karst environment, such as the Floridan aquifer system. This is due to the fact that the numerical grid cells used to construct the groundwater model and to represent the geologic layers (hydrostratigraphy) generally are too large to represent small features, which may be significant hydraulically.

A site-specific example in the SE case-study area documented results for vertical seepage rates in the Everglades wetlands area west of Levee 31N and indicated substantial differences from the computer model that appeared to be the result of local variations in the hydraulic properties of the uppermost zone of the Biscayne aquifer (Nemeth et al., 2000). The importance of such localized groundwater discharges to native wetland and aquatic species is not confined to the Floridan aquifer system (see Rosenberry et al., 2000). Therefore, a simple averaging of these localized flows for model purposes will not provide results capable of accurately assessing or predicting the environmental impacts of those and related actions.

The validity and accuracy of a model, as just described, relies on the conceptual model and accuracy of the data. Site-specific model data of flow characteristics for regulatory decisions, such as those described in the case-study areas above, typically consist of stratigraphic borehole data and laboratory analysis of extracted material. This approach of using laboratory-scale point data provides no information on the secondary permeability of preferential flow paths. Tracer studies, such as those recently conducted in the SE case-study area (Wilcox et al., 2004) and in NW Florida (http://gsa.confex.com/gsa/2004NE/finalprogram/abstract_70965.htm), and geophysical investigations, such those recently conducted in the SW case-study area (Cunningham et al., 2001), provide more accurate data for model development and calibration.

Another problem inherent in MODFLOW-type models is the reliance on a finite difference method (FDM) numerical solution technique. The FDM is incapable of explicitly including karst features, such as those throughout the Floridan aquifer system, in a realistic manner. Therefore, reducing grid sizes to address the scale constraints will result in limited model improvement, due to the numerical solution constraints. When the presence of karst features are known, MODFLOW users may incorporate "work-arounds" that fail to meet underlying numerical assumptions and provide unreasonable approximations of the physical system (see Palmer, this volume). One example is when boundaries of project sites, springs, wetlands, or the water table are set as constant head boundaries in the model. This does not allow the discharges from these features to vary, despite the fact that the alterations being evaluated may result in significant drawdowns, the total cessation of spring discharge, and the dewatering of the wetlands and surficial aquifer far beyond the mine site. As in the case-study areas, the significant drawdowns occur because no such barriers exist in the aquifer system. This was the scenario for the MODFLOW model used in the SW case-study area in an attempt to demonstrate to regulatory agencies that the mine pits would not cause adverse impacts.

Another common example is where significant solution cavities are known to exist in the aquifer system. These solution features are represented in the MODFLOW-type model as areally broad zones of very high transmissivity. This approach may be adequate for gross representations of the regional flow field. These underground flow paths, however, greatly diminish the ability to predict localized phenomena, such as interactions of these solution cavities or fractures with wetlands and other surface-water systems. This approach also constrains the ability to predict the speed at which contaminants in ground water are conveyed through these underground flow paths.

As shown in the SE case-study example, predictions by MODFLOW-type models often are many orders of magnitude smaller than actual conditions. Significant adverse impacts to wetlands and other surface waters, as well as the regional Floridan aquifer system, occurred in these case-study areas where none were predicted by the MODFLOW-type models. The most compelling example was in the SW case-study area. Adverse impacts to "preserved" depressional wetlands on the mine site and surrounding private property were consistent with groundwater mining soon after the mine pits were excavated, despite the absence of any mechanical withdrawal of ground water from that site. Those results are consistent with preferential aquifer discharge points identified in the SE case-study area (Nemeth et al., 2000), and those associated with native hydroecological indicator species in other subregions of the Floridan aquifer system (Bacchus et al., 2003) and other aquifer systems in the United States (Rosenberry et al., 2000).

Although there are many different variants of the original MODFLOW code in common use today, such as those used for the mine projects evaluated in this case study, none have the ability to incorporate realistic karst features into the model and identify possible localized adverse impacts to ground water. Following is a summary of some of the problems associated with the use of MODFLOW-type models to evaluate projects such as the pits described in the case-study examples above: (1) hydrogeologic model parameters are based on laboratory-scale and short-term, well-scale data, rather than on actual flow velocities determined from tracer studies; (2) boundary conditions are used that prevent model results from showing significant water-table drawdown beyond project site boundaries and in associated wetlands; (3) "Limit of Domain" conditions fail to encompass the entire areal extent of the groundwater impact; and (4) there is a failure or inability to model existing and induced preferential, conduit, or non-Darcian flow (vertical and horizontal) to accurately predict aquifer and surface-water responses that already have occurred or will occur, such as those associated with mechanical and nonmechanical dewatering of the aquifer system (see definitions in Table 1).

Finite element models (FEM), such as FEFLOW, FEMWATER, and MODFE, are better suited for modeling the complex conditions present in karst systems such as the Floridan aquifer system (see: http://water.usgs.gov/ogw/karst/kigconference/elk_traveltimes.htm and http://www.wasy.de). These models are not required by agencies with regulatory authority over mining. Throughout the Floridan aquifer system, there is a strong relationship between groundwater withdrawals (both mechanical and nonmechanical) and subsidence. This dictates that selected models should be capable of representing the following feedback loop in that system: mechanical/nonmechanical aquifer dewatering → lower groundwater levels → induced subsidence and increased soil loss → increased water table exposure → decreased aquifer recharge → lower groundwater levels (back to beginning). Modeling any single component of this system, on a stand-alone basis, will not capture the inherent complexity of the system. As a result, localized, feature-specific outcomes cannot be predicted. An integrated approach for modeling ground water and surface water as inseparable components is required to resolve this problem.

SUMMARY AND CONCLUSIONS

This case study evaluated excavation and removal of the aquifer formations authorized by a single permit in each of four geographical areas (SE, NW, SW, and east-central) representative of the regional karst Floridan aquifer system. Permit documents describe the excavations as subsurface "reservoirs" that will enhance or create new sources of water in areas where the regional aquifer system has been depleted by groundwater mining, despite the absence of supportive scientific documentation. Excavated pits also are described as "impoundments." Whether described as "reservoirs" or "impoundments," both types designated to receive treated sewage effluent, municipal wastewater, and/or storm-water runoff, similar to excavated storm-water retention/detention pits. Extraction of the aquifer formations (e.g., sand, shell, clay, peat, minerals, rock, ore) results in two forms of permanent, irreversible nonmechanical dewatering of the aquifer system and decline in water level. The first is dependent on the volume of solids extracted, and was not quantified in this case study. The second is due to increased losses via evaporation and evapotranspiration throughout and surrounding the excavated pits. Neither form of nonmechanical dewatering is considered by federal, state, or local regulatory agencies during evaluations of applications for structural mining of the aquifer system.

Collectively, the excavations authorized by the four permitted mine areas evaluated in this case study represent the conversion of ~17,700 ha (~44,400 ac) of ground surface (ground water) to surface water. The conversion of ground water to surface water authorized under those four permits will result in nonmechanical dewatering of the regional Floridan aquifer system totaling ~237,000 m^3/d (~63 Mgd). Mining activities also generally include mechanical dewatering of the aquifer system to facilitate extraction of the aquifer formations. MODFLOW-type models, accepted by regulatory agencies as the best available technology to predict the impacts of the mechanical dewatering, are unsuited for making localized, site-scale evaluations in a karst environment such as the Floridan aquifer system.

In one representative area of the case study (SW Florida), mechanical dewatering had not been initiated at the time of the initial mine site evaluation, ~3.5 yr after initiation of mining activities. Adverse impacts (e.g., subsidence, invasion of alien species, tree decline and death) on the mine property and surrounding property were consistent with nonmechanical dewatering associated with the onset of excavations by the Westwind Corkscrew Mine, the only significant new activity in the sparsely populated rural area. Based on the more conservative of the two permitted surface areas for excavated pits reported for the Corkscrew Mine (~123 ha, ~308 ac), nonmechanical

dewatering will result in induced discharge of ~1505 m^3/d (0.4 Mgd) from this single permitted mining activity in the SW area of the regional Floridan aquifer system. That loss is equivalent to ~5% of all water used by domestic supply wells in Lee County, Florida, in 1990, and appears to be the first documented case of such adverse impacts occurring solely from nonmechanical dewatering of the aquifer system. At the time the initial damage was documented, only a portion of the permitted area had been mined. The adverse impacts associated with nonmechanical dewatering of the regional karst Floridan aquifer system represent an irreversible and irrevocable loss of resources that are not evaluated or accounted for by the regulatory processes. These impacts result in significant harm to the human environment and federally endangered species with habitat dependent on the integrity of the regional aquifer system.

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