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Preferential Groundwater Flow Pathways and Hydroperiod Alterations Indicated by Georectified Lineaments and Sinkholes at Proposed Karst Nuclear Power Plant and Mine Sites

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Abstract

Sustainable development of any type that utilizes water or involves excavations in karst aquifer systems, such as the regional Floridan aquifer system (FAS), requires knowledge of preferential groundwater flow pathways that can extend adverse impacts beyond the development site and alter natural hydroperiods. Such pathways include fractures and other types of karst conduits that are associated with modern and relict sinkholes. Developments, including power plants and mines, that have not accounted for these features have caused induced recharge, altered hydroperiods and saltwater intrusion in the FAS, resulting in destruction of wetlands and adverse impacts to other surface waters, wildlife habitat and threatened and endangered species. This study analyzed indicators of preferential groundwater flow by considering surface expressions of underlying geological conditions (lineaments and modern sinkholes) in the FAS, which coincide with the United States southeastern coastal plain. Lineament mapping by Vernon (1951) and the Florida Department of Transportation (FDOT, 1973), incorporating analog mapping techniques and hardcopy prints of satellite imagery, preceded extensive urbanization, groundwater extractions, and mining in the region. All of these alterations limit the ability to identify fractures using lineaments by reducing groundwater discharges and vegetation indicative of those discharges. In this study, established methods for georectification, including control-point identification and spatial matching of scanned maps and remotely sensed images, were applied to these previously mapped lineaments. These results were applied to the environmentally sensitive karst study area of Citrus and Levy Counties, Florida in the southern extent of the FAS. Geospatial analyses of lineament distribution and modern sinkhole locations from the state database showed a dense network of lineaments with associated sinkholes throughout the study area and seven surrounding counties, including the proposed sites for a nuclear power plant and two mines in Levy County. Proposed excavations and water use for construction and operation of the power plant and mines would result in irreversible adverse environmental impacts on extensive depressional wetlands beyond the surface-footprint impact of these developments via these preferential flow pathways that were not evaluated during the review process.

Keywords: dolines, fractures, geospatial analysis, GIS, induced recharge, induced saltwater intrusion, modern and relict sinkholes (paleosinks)

1. Introduction

1.1 Current Approach Resulting in Unsustainable Development

The entire state of Florida and southeastern coastal plain portions of Alabama, Georgia and South Carolina are underlain by the regional karst Floridan aquifer system (Krause & Randolph, 1989; Miller, 1986). This aquifer system consists of limestones that have been subjected to multiple karst cycles (Upchurch & Lawrence, 1984) and is the source of water, both directly and indirectly, for the majority of developments in Florida (Fernald & Purdum, 1998; Johnston & Miller, 1988; Miller, 1986). A standard practice in investigations of foundation stability, sinkhole probability, and groundwater availability involves delineation of photolinear features that may predispose affected areas to instability and high transmissivities (Lattman & Parizek, 1964; Littlefield, Culbreath, Upchurch, & Stewart, 1984; Parizek, 1976). Despite this standard, development currently is permitted in Florida by local, district, state and federal governments without these investigations or evaluations of groundwater impacts or groundwater models that evaluate impacts to or from preferential groundwater flow via fractures and karst conduits. These features are associated with modern and relict sinkholes (synonymous with paleosinks for our study), as described by Bacchus, Masour, Madden, Jordan and Meng (2011). This problem occurs, in part, because there is no interactive database available to these regulatory entities and local governments where these features are represented accurately. Instead, these regulatory entities routinely rely on information provided by those applying for development permits. This failure to consider preferential groundwater flow pathways has resulted in unsustainable development practices, with adverse impacts that include water pirated from neighboring cities, counties and states, as well as from adjacent watersheds and across groundwater divides. This pirated water causes induced saltwater intrusion and induced recharge, which dewaters wetlands and other surface waters and alters natural hydroperiods (Bacchus et al., 2011; Krause & Randolph, 1989; Lewelling, Tihansky, & Kindinger, 1998; Metz & Lewelling, 2009; Stewart & Stedje, 1990; Watson, Stedje, Barcelo, & Stewart, 1990).

This study was initiated because review of environmental impacts from any type of proposed developments in Florida that utilize water or involve excavations, fail to consider adverse environmental impacts from this pirated water that would extend beyond the surface footprint of those developments from preferential flow through fractures and associated karst conduits. Those karst conduits include depressional wetlands that are relict sinkholes aligned along fractures. For example, the National Environmental Policy Act (NEPA) requires that federal agencies conduct a cumulative impacts analysis of the adverse environmental impacts of proposed projects reviewed by those agencies. In reality, based on Environmental Assessments (EA) and Environmental Impact Statements (EIS) for proposed projects in Florida reviewed during the past 30 years, agencies routinely do not consider environmental impacts associated with preferential groundwater flow pathways beyond the surface footprint of proposed projects in this regional karst aquifer system. The proposed nuclear power plant, Tarmac limestone mine and Knight Farm sand mine (Knight mine) in Levy County, Florida are examples of developments that should consider preferential groundwater flow pathways, such as associated fractures and sinkholes documented in published literature and available data, prior to licensing and permitting. Examples of typical deficiencies in the agency review processes are provided to facilitate improved evaluations in the future. The results of this study can be used as a primer to explain the crucial role of preferential groundwater flow pathways in predicting adverse environmental impacts and applied to other projects in the study area, with similar approaches applicable throughout Florida and the remaining FAS.

1.2 Objectives, Hypotheses and Implications

The first objective of this study was to select an environmentally sensitive area within the extent of the regional (FAS) where multiple large development projects were proposed, but adverse environmental impacts from preferential groundwater flow described above, and more fully below, were not evaluated or otherwise addressed. The proposed nuclear power plant, Tarmac limestone mine and Knight sand mine in Levy County, Florida met those criteria. The second objective was to apply established methods for georectification to previously mapped lineaments to build a spatial database using analog lineament data converted to digital format. The final objective was to evaluate the frequency and distribution of these lineaments and previously reported sinkholes in proximity to the proposed projects in the study area using ArcGIS™ 10 Geographic Information System (GIS) and describe the potential magnitude and extent of cumulative adverse environmental impacts from hydroperiod alterations and preferential groundwater flow pathways. Our alternative hypothesis, based on published literature described below, was fractures occur in the vicinity of the proposed development sites and that sinkholes would be associated with fractures. The theoretical and practical implications of this study, also based on published literature described below, include identifying areas of potential adverse environmental impacts from preferential flow through fractures in the FAS that may occur many kilometers beyond the proposed project sites. These are predicted to occur in response to groundwater extractions, excavations and other proposed actions that would alter natural hydroperiods, resulting in adverse impacts to wetlands and other surface waters, wildlife habitat and threatened and endangered species.

1.3 Terminology

Definitions of key terms are included in Table 1 to introduce the scientific foundation of our study and to facilitate an understanding of how this work relates to the goal of sustainable development in areas of the southeastern United States underlain by the FAS and in other areas with karst terrain. The Glossary of Geology definition of the term “sinkhole” confirms that it is synonymous with the term “doline” and the definition of doline indicates that in America “most dolines are referred to as sinks or sinkholes” (Neuendorf, Mehl Jr., &

Jackson, 2005). Paleo-sinkholes and relict sinkholes are considered synonymous in this paper. The state's database (http://fcit.usf.edu/florida/maps/galleries/sinkholes/) only addresses locations of modern sinkholes.

Terms such as lineaments, fracture traces and photolinears have been used in the literature without reference to definitions and implying synonymous applications. Definitions in Table 1 are applied to our study and the term lineament encompasses features referenced in the literature as photolinears and features referenced as fracture traces. When photolinears represent areas of increased fracture density, however, they are termed fracture traces. Fracture traces also represent vertical zones of generally higher hydraulic conductivity that function as vertical pathways for ground-water flow between the surficial and semi-confined aquifers (Stewart & Stedje, 1990). The lineaments mapped by Vernon (1951) have been confirmed as fractures, including faults, and were referenced as fracture traces (Faulkner, 1973). Therefore, those lineaments are presumed to represent areas of increased fracture density rather than single fractures. As defined in Table 1, faults are fractures where movement has occurred. Our references to fractures include faults and joints (fractures without movement), as well as lineaments mapped by FDOT (1973), without distinguishing faults as a type of fracture.

1.4 Fractures Evident in Aerial Photographs and Satellite Imagery

At least since the 1950s aerial photographs have been used by geologists and experts in other fields to identify features that indicate buried extensions of old faults in the subsurface even in cases where no movement has occurred since superficial deposits (Mollard, 1957; Vernon, 1951). High altitude imagery, such as from U-2 aircraft and satellites, filters recognition of the smaller-scale linear features while accentuating the regional linear features (Littlefield, Culbreath, Upchurch & Stewart, 1984). Parizek (1976) assumed a 1 km (0.62 mi) width for structurally controlled lineaments. Although fractures, including faults, may not be evident at the surface, a large number of surface features can be related to very old failures in deeper subsurface rocks and detecting these features is not difficult for experienced photo-interpreters (Norman, 1976). Techniques for examining aerial photographs to identify fractures are described by Lattman (1958) and Trainer (1967). Some authors, such as Norman (1976), confine the term fracture trace to an order ranging in length from a few tens of meters up to a few kilometers, suggesting that major lineaments of crustal dimensions generally are apparent only on satellite imagery covering large areas or large mosaics of small-scale aerial photographs. A recent study in the southeastern U.S. reconfirmed the ability of satellite imagery to detect lateral hydrologic connectivity based on vegetation (Hwang, Band, Vose, & Tague, 2012).

The appearance of lineaments on aerial photographs can be grouped within five broad categories: (1) landforms; (2) tonal lineations; (3) vegetal lineations; (4) drainage lineations; and (5) combinations of 1 through 4. Examples of vegetal and drainage lineations include boundaries of vegetation or plant communities and straight sections of normally irregularly curving streams, respectively. Dark tonal lines caused by old drainage channels on top of hidden bedrock exemplify a combination of categories particularly indicative of lineaments (Norman, 1976). In an investigation of 178 faults in coastal sections, 75% were detected as clear linear features before field work. An additional 13% were noted as indistinct lineations after the presence of the fault was known. The remaining 12% could not be detected on the aerial photographs. The appearance of those coastal faults on the aerial photographs primarily was rectilinear or slightly curvilinear in form and included straight sections of streams, the disruption of tree patterns and vegetation boundaries (Norman, 1968).

1.5 Influence of Fractures, Karst Conduits and Sinkholes on Preferential Groundwater Flow

As described above, photolinears in carbonate terrains often represent zones of increased fracture density in the underlying limestone (Lattman & Parizek, 1964; Parizek, 1976) and subsequently are termed fracture traces. Fracture traces are recognized as vertical zones of generally higher hydraulic conductivity that can be vertical pathways for groundwater flow between the surficial and semi-confined aquifers (Stewart & Stedje, 1990). Sinkholes and associated highly transmissive zones are related to differential solution along linear fractures, faults and/or joints in limestones (Lattman & Parizek, 1964). Modern, short-term sinkhole activity in west-central Florida also has been reported to occur principally along the longest linear alignments, exceeding 30 km (18.6 mi) and most easily detected at the scale of high altitude and/or satellite imagery. These are seen more frequently in areas of high water use, such as agriculture, mining or urban areas. Koch (1984) emphasized that the single most important factor for preventing or greatly reducing sinkhole development and subsidence is area-wide management and maintenance of the existing groundwater table.

Sinkhole development over geologic time can occur along linear features and conduits of any scale (Littlefield, Culbreath, Upchurch, & Stewart, 1984). The non-random distribution of solution features controlled by regional joint patterns also extends beyond the present-day shoreline, in the submarine platform of the Floridan aquifer, where dissolution of Eocene and Oligocene rocks follow fractures caused by deep collapse, and sinkholes propagate to the surface through the overlying Neogene section along these trends. In fact, the most pronounced deformation from solution follows the reef and back-reef edge of the Late Cretaceous Paleocene carbonate platform and collapse and filling of submarine sinkholes, a process that continues today (Popenoe, Kohout, & Manheim, 1984). Florida is one of eight states in the U.S. that consider sinkhole collapse an important water issue. Most sinkholes form by slow, preferential dissolution of rock along fractures or by slow subsidence due to piping of a surface cover, a process involving the movement of material such as sand through preferential flow pathways such as solution-enlarged fractures (Ogden, 1984). The distribution and shape of sinkholes in the FAS have been used to map fractures in the Ocala limestone (Brook & Allison, 1983). Examples of preferential flow paths in the FAS include not only fractures, but also relict sinkholes that underlie depressional wetlands, such as pond-cypress wetlands, and which are aligned along fractures. These relict sinkholes, including depressional wetlands and open-water areas ranging in size from ponds to lakes, are aligned along fractures throughout the FAS, as illustrated by Brook and Sun (1982). Metcalfe and Hall (1984) also have reported that new sinkholes are known to form from the loss of hydrostatic support following withdrawals of large quantities of water from the FAS.

Subsidence susceptibility models of future sinkhole development in the FAS suggested that the most important measures of susceptibility to future sinkhole development were the number of sinkholes and number of fractures in a cell, followed by the number of fracture intersections and length of fractures in a cell. Model results were supported by independent data, including areas where changes in the piezometric surface exceeded 3 meters (9.8 ft), suggesting that sinkhole and bedrock fracture data can be used to develop relatively accurate ground subsidence susceptibility maps in the FAS and similar karst areas (Brook & Allison, 1983). Application of double Fourier series analysis in the FAS also was effective in defining areas of increased susceptibility to ground subsidence (Thorpe & Brook, 1984). The correlation of sinkhole development with fractures, changes in piezometric surface and withdrawals of large quantities of water provides support for the existence of preferential groundwater flow through fractures.

Large conductive fractures dominate fluid flow in the subsurface (Ortega, Marrett, & Laubach, 2006). Research in the FAS has shown that when pumping wells are located in the vicinity of fracture networks, the capacity of those wells to supply water increases because water can flow more easily through fractures and associated relict sinkholes (Brook, 1985; Brook & Allison, 1983; Brook, Sun, & Carver, 1986; 1988). Similar responses occurred in pumping wells located near fractures in crystalline rocks of the Georgia Piedmont and the Blue Ridge area of North Carolina (Yin & Brook, 1992). Although increased well capacity and higher yield due to fractures may appear to be beneficial, fracture intensity, or the abundance of fractures potentially available for fluid flow, and the probability of encountering fractures in a borehole, in fact, may limit economic exploitation of the resource (Ortega, Marrett, & Laubach, 2006). For example, one of two submarine springs off-shore of Crescent Beach, Florida produced 2,250 kilograms (5,000 pounds) of red snapper (*Lutjanus aya*) to one fisherman in 1962 and 450 kg (1,000 lb) of red snapper to another fisherman in 1968. By the time a fluorescein dye sample was released in the sinkhole in 1970, fresh, highly mineralized groundwater discharge supporting these fish had ceased and the downward movement of the dye suggested saltwater intrusion into the FAS was occurring at the site of the former spring due to groundwater extractions (Popenoe, Kohout, & Manheim, 1984). The fact that groundwater discharges from Floridan aquifer springs are reduced or halted in response to groundwater withdrawals, including from mining, is well established. One of the most notable examples is Kissengen Springs in Polk County, Florida. In 1933, Kissengen Springs was one of the largest springs in the Florida peninsula, discharging 43.6 cubic feet per second (28.2 million gallons per day) to the Peace River. The spring ceased to flow in 1950, coincident with the appearance of numerous sinkholes and increased solution and collapse activity in response to groundwater alterations and the prevalence of mining, which resulted in far-reaching adverse impacts to the area's hydrology and flow of the Peace River (Patton & Klein, 1989; Peek, 1951).

Large and numerous submerged sinkholes and freshwater springs, similar to Red Snapper Sink and discharging from the FAS, also occur along the low-energy Gulf coast of Florida. Examples include the coastal portion of Citrus and Levy Counties, where rising Holocene seas flooded the exposed karstified limestone surface of the west-central Florida coast. The irregular rock surface and numerous freshwater springs are the primary factors controlling the regional, modern coastal geomorphology and sedimentation (Hutton, Hine, Evans, & Osking, 1984). Large-scale fracturing and faulting of Tertiary sediments occurred during the post-Oligocene or Lower Miocene, forming the Ocala uplift. With the crest located in Citrus County, the Ocala uplift created a regional northwest-southeast trending fracture system (Vernon, 1951) and subsequent vents for spring flow from the Floridan aquifer (Roseneau, Faulkner, Hendry Jr., & Hull, 1977). It also created loci or surficial karst topography through solution of the underlying limestone (Hutton, Hine, Evans, & Osking, 1984). In addition to halting ecologically critical groundwater discharges to coastal areas, as occurred with Red Snapper Sink, groundwater withdrawals also cause hydroperiod alterations in relict-sinkhole sinkholes wetlands that are associated with those fractures, as summarized in Bacchus et al. (2003). Cross-sections representative of the relict sinkholes underlying pond-cypress wetlands are shown in Figure 1 of Bacchus (1998). The upconing of saline water through a fracture and a conceptual model of other solution and collapse features characteristic of the FAS are shown in Bacchus (2000).

A geophysical investigation of a fracture trace more than 1 km (0.62 mi) long and 100 to 300 meters (328 to 984 ft) wide at the Cross Bar Ranch municipal wellfield in Pasco County and another fracture trace in Citrus County revealed different hydrogeologic responses to groundwater flow through the fractures. This research also determined that geophysical profiling methods using appropriate electrode spacing were effective in locating the center of a fracture zone (Stewart & Wood, 1984). Karst conduits also can be sinuous, with similar associated hydroperiod alterations and preferential flow resulting in adverse water quality and quantity impacts many kilometers from the source of the problem (Bacchus & Barile, 2005). Although pulsed or reversible drawdowns may result from mechanical withdrawals (supply-well pumping) that are reduced and increased, alternatively, or of limited volume and short duration, permanent hydroperiod and other environmental impacts can result from oxidation of organic soils in less than a year due to those withdrawals. Those environmental impacts cannot be reversed and dewatered organic soils trigger destructive wildfires in both wetlands and uplands (Bacchus, 2006; Southwest Florida Water Management District, 1996; Stewart & Stedje, 1990; Watson, Stedje, Barcelo, & Stewart, 1990).

Table 1. Definitions of key terms quoted from published sources

Term	Source	Definition
Doline		See Sinkhole
Fault	Neuendorf, Mehl Jr, & Jackson (2005)	(struc geol) A discrete surface or zone of discrete surfaces separating two rock masses across which one mass has slid past the other. Cf: shear zone; fault zone. Obsolete syn: paraclose
Fracture	Neuendorf, Mehl Jr, & Jackson (2005)	(struc geol) (a) A general term for any surface within a material across which there is no cohesion, e.g. a crack. Fracture includes cracks, joints, and faults. (b) A crack in a rock where the movement of rock separated by the crack is normal to the surface. See also: extension fracture; extension vein; stylolitic fracture.
Fracture trace	Stewart & Stedje (1990)	Fracture traces are vertical zones of generally higher hydraulic conductivity that can be vertical pathways for ground-water flow between the surficial and semi-confined aquifers.
Georectification	Esri GIS Dictionary (2012)	See Also : control point, georeferencing, orthorectification 1. [data editing] The digital alignment of a satellite or aerial image with a map of the same area. In georectification, a number of corresponding control points, such as street intersections, are marked on both the image and the map. These locations become reference points in the subsequent processing of the image.
Hydroperiod	Bacchus (1998)	Three important aspects of a wetland hydroperiod are (1) the depth or stage of fluctuating ground and surface water; (2) the duration of the water level at a given depth or stage; and (3) the periodicity or seasonality of the water level fluctuations. Disruption of any one of these three aspects can lead to the degradation and ultimate destruction of the wetland and the biota it supports.
Hydroperiod	Mitsch & Gosselink (2007)	The hydroperiod is the seasonal pattern of the water level of a wetland and is the wetland's hydrologic signature. It characterizes each type of wetland, and the constancy of its pattern from year to year ensures a reasonable stability for that wetland. It defines the rise and fall of a wetland's surface and subsurface water by integrating all of the inflows and outflows.
Lineament	Hobbs (1904)	Significant lines of landscape which reveal the hidden architecture of the rock basement – a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon. Many lineaments are identical with seismotectoinic [sic] lines and they therefore afford a means of to some extent determining in advance the lines of greatest danger from earthquake shock.
Lineament	O'Leary, Friedman, & Pohn (1976)	L. linea = line + L. mentum = akin to; hence, akin to or like a line. A lineament is a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon. At largest scale, lineaments may be identified with a single map unit; at smallest scale, they are expressions of a landscape and may be continental in extent. Hence actual length is relative to the scale of observation and cannot be arbitrarily limited. Lineaments (1) have geomorphic expression (in general, topographically negative), (2) are composite (either segmented or complex), (3) are characterized by alignment in a single direction (which may or may not conform to regional trend), (4) are straight or slightly curved, (5) are regional in extent, and (6) are scale related.
Paleo-	American Geological Institute (1976)	[<Gr. palaio-, palai-] A combining form meaning old, ancient, used to denote: (1) Remote in the past; (2) Early, primitive, archaic.
Photolinear	Stewart & Stedje (1990)	Photolinears are linear trends identified on aerial photographs that may represent zones of increased fracture density. Photolinears that are determined to represent ones of increased fracture density are termed fracture traces.
Relict	American Geological Institute (1976)	Geomorph: A residual topographic feature such as a beach ridge.
Sinkhole	Neuendorf, Mehl Jr, & Jackson (2005)	A closed depression in a karst or pseudokarst area, commonly with a circular or ellipsoidal pattern. It's [sic] drainage is subterranean; it's [sic] size is measured in meters or tens of meters; and it is commonly funnel shaped. Syn: doline; sink (karst); shakehole. Cf: collapse sinkhole; solution sinkhole.
Swallet	Jackson (1997)	The opening through which a sinking stream looses its water to the subsurface. Syn: insurgence.

2. The Study Area

The study area includes Citrus and Levy Counties, located on the Gulf Coast in rural west-central Florida, USA. That area was selected because of the highly ranked wildlife habitat (Endries, Gilbert, & Kautz, 2009) and multiple large proposed development projects under review in Levy County, which could, because of hydroperiod alterations, result in irreversible adverse environmental impacts in Citrus County to the south and other counties in the vicinity. This conclusion was based on published literature described in section 1.5, including the fact that fractures and other karst conduits that are pathways of preferential groundwater flow, are not constrained by governmental boundaries such as county and state boundaries (Krause & Randolph, 1989), or present-day shorelines (Popenoe, Kohout & Manheim, 1984). The proposed development projects include a two-unit Levy nuclear plant (LNP) by Progress Energy Florida, Inc. (PEF) to generate and export electricity to metropolitan areas of central Florida; a new limestone mine (Tarmac), referenced in the Draft LNP Environmental Impact Study (EIS) as the source of aggregate raw materials for concrete to construct the proposed nuclear plant (United States Nuclear Regulatory Commission, 2010a); and a new sand mine (Knight) also for the stated purpose of supplying raw materials to construct the nuclear plant. Figure 1 shows the location and extent of the study area over an image downloaded from Microsoft BING maps services. The 2010 data from the U.S. Department of Commerce Census Bureau (http://quickfacts.census.gov/qfd/states/12/12017.html) indicate that the areas of Citrus and Levy Counties are 1,512.42 square km (583.94 sq mi) and 2,907.35 sq km (1,122.53 sq mi), respectively, with a population density of 631 people per sq km (1,634 people per sq mi) and 95 people per sq km (246 people per sq mi), respectively.

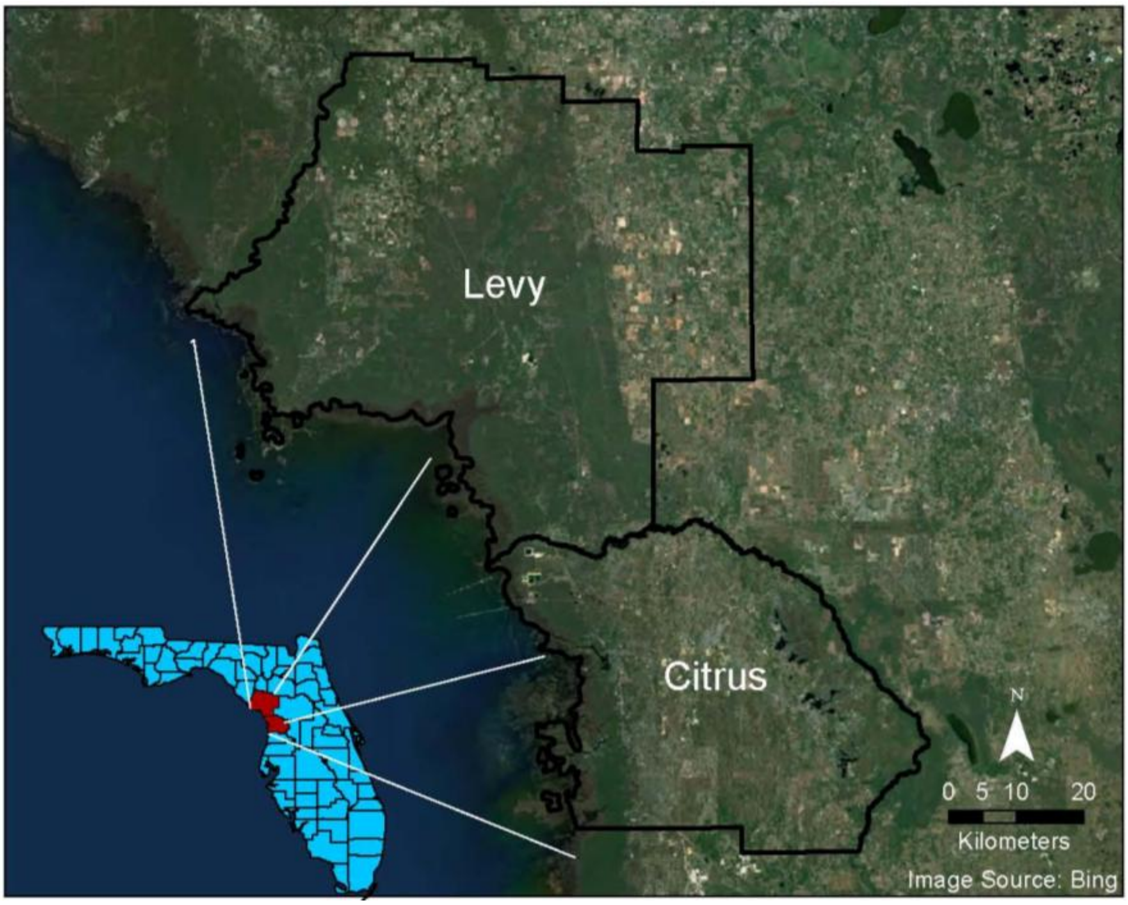


Figure 1. West-central Florida study area

3. Methods

3.1 Digital Data and Georectification

The analog format of lineament maps produced by Vernon (1951) and the Florida Department of Transportation (FDOT, 1973) were scanned and georectified to produce digital base maps. For the FDOT (1973) map, a high-quality large-format scanner was used to preserve the original map geometry and reduce distortions during analog to digital conversion of the 81 x 91-centimeter (32 x 36-inch) mylar sheet containing extracted lineaments and a copy of the Landsat image mosaic used by FDOT during map creation. The geometric rectification procedure of the digitized maps consisted of the identification of a number of well-distributed control points representing analog features on the raster maps and on reference vector layers (e.g., political boundaries, roads and hydrology) released by the U.S. Census Bureau as part of the 2011 TIGER/Line® Shapefiles dataset. Marks shared by the mylar sheet of mapped lineaments and the mosaic, with both layers in the same scale and projection, were used to align these products and to transfer control points acquired over the Landsat mosaic to the scanned lineament maps. The digital versions of the mylar and the mosaic were projected to the Web Mercator Auxiliary Sphere projection using the WGS84 datum. Physiographic features identified using the image mosaic also were used for control-point identification to improve the accuracy of the georectification process. The Vernon (1951) lineament map was georectified using a similar procedure, but with TIGER data as a reference. A total of 114 and 42 control points were acquired over the 1951 and 1973 maps, respectively. Because no information was available regarding the coordinate system used in the creation of the original lineament maps, the geometric rectification procedure was not based on coordinate system transformation alone. Instead, spline and second order polynomial transformations of the digitized maps were used to account for local discrepancies in positioning due to eventual geometric distortions of the original map media. The results of the geometric rectifications of the lineament maps were inspected visually and verified to conform adequately to the geometry and positional quality of the reference TIGER vector layers. The georectified lineament maps then were manually vectorized using heads-up digitizing and ArcGIS™ 10 GIS mapping software.

The base map showing wetlands extent in the analysis and figures described below was obtained from the U.S. Fish and Wildlife Service (USFWS) National Wetlands Inventory (NWI) web page (http://www.fws.gov/wetlands/Data/State-Downloads.html). The color infrared (CIR) aerial imagery used as base maps in the figures described below was acquired during December 2003 to March 2004 by the U.S. Geological Survey (USGS) and orthorectified as digital orthophoto quarter quadrangles (DOQQ). This CIR imagery, with a pixel ground resolution of 1 m (3.3 ft), was obtained online from the U.S. Department of Agriculture (USDA), Geospatial Data Gateway (http://datagateway.nrcs.usda.gov). The raster file for the ranked habitat from the Integrated Wildlife Habitat Ranking System developed for the Florida Fish and Wildlife Conservation Commission (FFWCC) in 2009 (Endries, Gilbert, & Kautz, 2009), used as a base map in the figure referenced below, was acquired from http://myfwc.com/research/gis/data-maps/terrestrial/wildlife-habitat-ranking-system/

The location data for modern sinkholes were coordinates obtained from the state database at the University of South Florida (http://fcit.usf.edu/florida/maps/galleries/sinkholes/), based on data gathered by the Florida Geological Survey (FGS) and the Florida Department of Environmental Protection (FDEP). The locations of mapped sinkholes matched the locations of sinkholes in the sinkhole shapefile provided by PEF. Because the data were not digitized, but entered as actual coordinates obtained from Florida's university data archive source, the accuracy of the sinkhole locations and any bias related to the collection of modern sinkhole location data are not evaluated or addressed in this study. Shapefiles of the proposed LNP units, supply wells, related boreholes, support facilities and the U.S. Army Corps of Engineers (USACE) jurisdictional wetland were provided by PEF. The locations of the proposed LNP supply and monitor wells that were permitted by the Southwest Florida Water Management District (SWFWMD) were determined by coordinates provided in SWFWMD Water Use Permit (WUP) 13262.0, issued August 26, 2009. The locations of the thermal infrared signatures indicative of groundwater discharge are based on USGS shapefiles (http://pubs.usgs.gov/of/2010/1120/). The boundaries of the 2011 Bad Land wildfire in Goethe State Forest (black outline) were determined by a shapefile provided by the Florida Division of Forestry. The approximate boundaries of the proposed Knight sand mine were georectified from maps included as figures in the SWFWMD Environmental Resource Management (ERP) application file for the stormwater management system of the proposed Knight sand mine.

3.2 Sampling and Analysis Procedures

3.2.1 Procedures for Collecting Water Quality Data and Documenting Groundwater Discharge Locations

Water quality data, including the salinity data in parts per thousand (ppt) displayed in figures described in the Results section, temperature in degrees Celsius (°C), conductivity in micro Siemens (µS) and total dissolved solids (TDS) in grams per liter (g/L) were collected using a YSI Model EC300. Calibration and operation of the YSI were as described in the requirements for that model (http://www.ysi.com/). The YSI probe was positioned within 25 cm (9.84 in) of the surface for surface samples and within 25 cm of the bottom for bottom samples. Water quality data were collected during periods of low tides, based on the tide tables for the Withlacoochee River entrance (http://www.tides4fishing.com/us/florida-gulf-coast/withlacoochee-river-entrance), to maximize the detection of low-salinity, low-flow groundwater discharge. Two categories of target areas for data collection were included in the study. The first category was the sides of the Withlacoochee canal, where: (a) spring discharges were visible during periods of low tide and (b) freshwater vegetation that would be killed by increased salinity levels from construction and operation of the proposed LNP (USNRC, 2012) occurred. Examples of potentially affected freshwater aquatic vegetation growing at or near the high-tide line included cabbage palms, cypress and oaks. The Withlacoochee canal is referenced erroneously as the “cross-Florida barge canal” in the LNP Draft and Final EIS (United States Nuclear Regulatory Commission, 2010a; 2012). The second category was the thermal infrared (TIR) areas indicative of groundwater discharges identified in Raabe and Bialkowska-Jelinska (2010) during a period of low ambient temperatures in March 2009. Spring discharge sites were located within the Withlacoochee canal on November 17, 2009. Water-quality data were collected at selected TIR bay and stream locations identified by Raabe and Bialkowska-Jelinska (2010) and related areas by co-author Bacchus on May 14, 2012 and May 17, 2012, and at selected Gulf Hammock TIR locations and related areas on May 14, 2012 and May 15, 2012. Coordinates for data collection and ground-observation locations were recorded with a hand-held Garmin HCx high-sensitivity color receiver global positioning system (GPS) with Wide Area Augmentation System (WAAS)-enabled differential corrections to approximate +/- 3 m positional accuracy.

3.2.2 Procedures for Sampling and Analyzing Lineament and Sinkhole Data

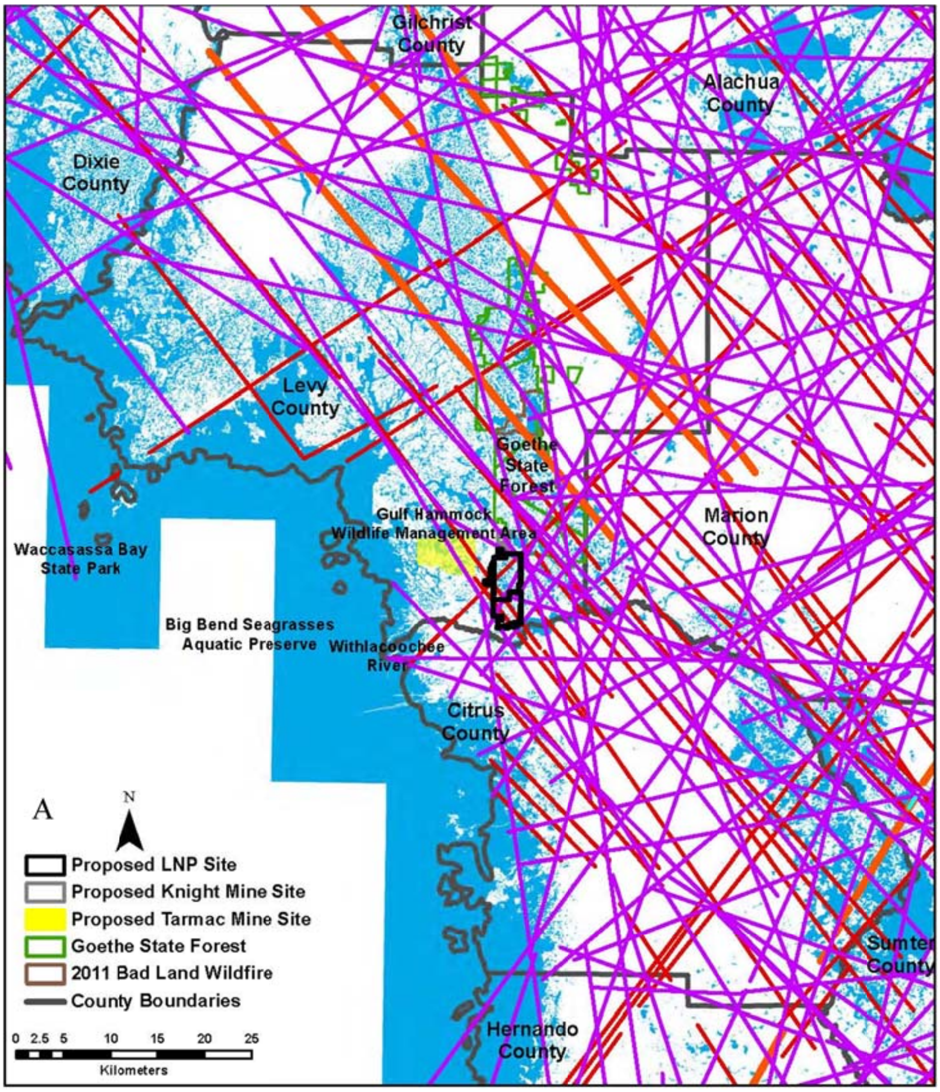
Our study evaluated the location and characteristics of previously mapped linear features indicative of fractures, including faults, extending to or in Citrus and Levy Counties, similar to the rose diagrams for spatial frequency analysis of lineaments by Harnett and Barnett (1977) and Brook and Allison (1986) and for a grid of cells by Norman (1976). The angle distribution of linear features over the area of study was analyzed for all geometrically rectified and vectorized lineaments mapped by Vernon (1951) and FDOT (1973) that are included in or extend to Citrus and Levy Counties. A multi-cell grid (cell size=0.12º x 0.12º) that encompassed lineament segments in the two counties was created to characterize the directional distribution of cumulative lengths of linear features over the entire study area. For each cell, the entire length of vectorized lineaments within or entering the cell was measured and the cumulative length of lineaments for individual 15º azimuth steps (north=0º) were calculated. The angular distribution of cumulative lengths also was computed considering the boundaries of Citrus and Levy Counties. Because one objective was to show the total lineament length as potential groundwater connectivity, length-weighted rose diagrams did not use lineaments clipped to cells or county boundaries, but calculated total lengths including the parts of lineaments that extend beyond the two-county study area. Multi-cell rose diagrams show one diagram per grid cell (center=0 km, outer circle=350 km, step=50 km) while individual rose diagrams (center=0 km, outer circle=700 km, step=100 km) were generated when considering boundaries of Citrus and Levy Counties. Rose diagrams were created using the description of length-weighted rose diagrams provided by Prost (2002).

Geospatial analysis to assess the proximity of sinkholes in Citrus and Levy Counties to fracture lineaments was conducted in ArcGIS Version 10, as GIS is an established aid in visualizing and mapping rock properties in regions of subtle topography (Belt & Paxton, 2005). The data layers for sinkholes and fractures were reconciled to a common, Robinson projection system. This pseudocylindrical projection has minimal distortions within areas approximately 45º north and south of the equator. Citrus and Levy Counties are located at 28.8946ºN and 29.3301ºN latitude, respectively. The Robinson Projection is known as a compromise projection that maintains all types of distortions to be relatively low over most of the globe (Usery, Finn, & Mugnier, 2009; Dean, 2012). Next the spatial join tool of ArcGIS was used to join the attributes of the two feature classes using the spatial relationship, “CLOSEST.” The result was a list of sinkholes and distances to fracture lineaments from which the shortest distances between sinkholes and lineaments were selected.

4. Results

4.1 Proximity of Fractures, Including Faults, to the Proposed Nuclear Plant, Proposed and Existing Mines and Environmentally Sensitive Areas

Figure 2A shows a GIS overlay of the extent of fractures, including faults, mapped as lineaments by Vernon (1951, as red and bold orange lines, respectively) and by the FDOT (1973, as purple lines) in Citrus and Levy Counties, over the location of wetlands (blue shading) mapped by the USFWS under its NWI program. Figure 2B is an enlargement of the vicinity of the proposed LNP Units 1 and 2 site, the proposed Tarmac mine site and the proposed Knight mine site, in proximity to Big Bend Seagrasses Aquatic Preserve, Waccasassa Bay State Park, Gulf Hammock Wildlife Management Area and Goethe State Forest, including the approximate boundaries of the destructive wildfire in the state forest, referenced as the Bad Land wildfire, that began on April 26, 2011 and continued burning until June 28, 2011, according to the Florida Department of Agriculture and Consumer Services, Florida Forest Service's Incident Report 2011-08-0370. The extent of wetlands on the proposed LNP site that are jurisdictional Waters of the United States, as determined by the USACE, was comparable to the wetlands shown on this NWI map. This figure also shows the proximity of the fractures, including faults, to the five proposed supply wells (red circles) and cluster of five proposed monitor wells (black circles) permitted on August 26, 2009 by the SWFWMD for the site of the proposed LNP.



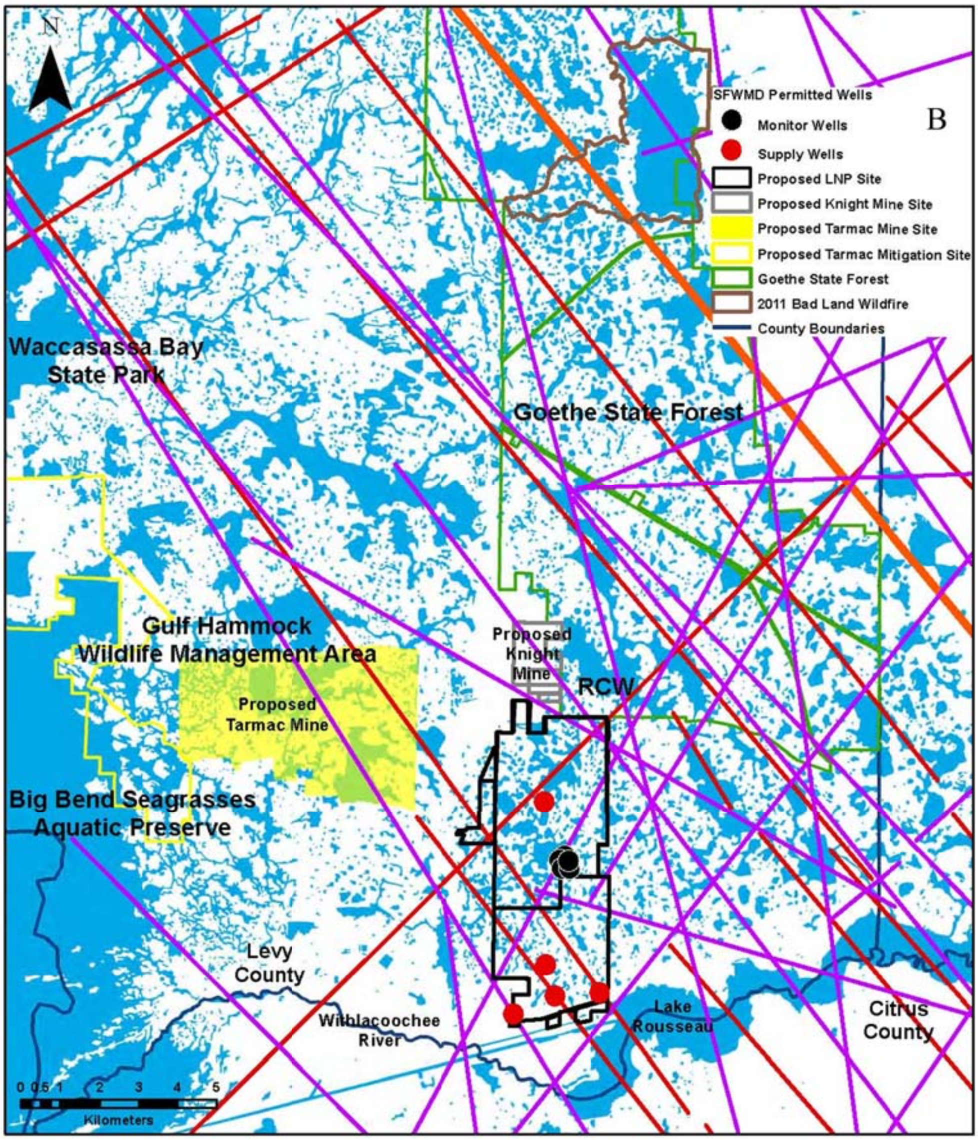


Figure 2. Locations of previously reported fractures, including faults (red, orange and purple lines), in Citrus and Levy Counties, Florida over the National Wetlands Inventory (NWI) map (blue shading):

A. in proximity to the Levy nuclear plant, Knight Farm sand mine and Tarmac limestone mine proposed sites, Goethe State Forest and the 2011 Bad Lands destructive wildfire and B. enlargement showing proximity to the permitted locations of five supply wells and five monitoring wells proposed for the Levy nuclear plant site and the Tarmac mine mitigation site.

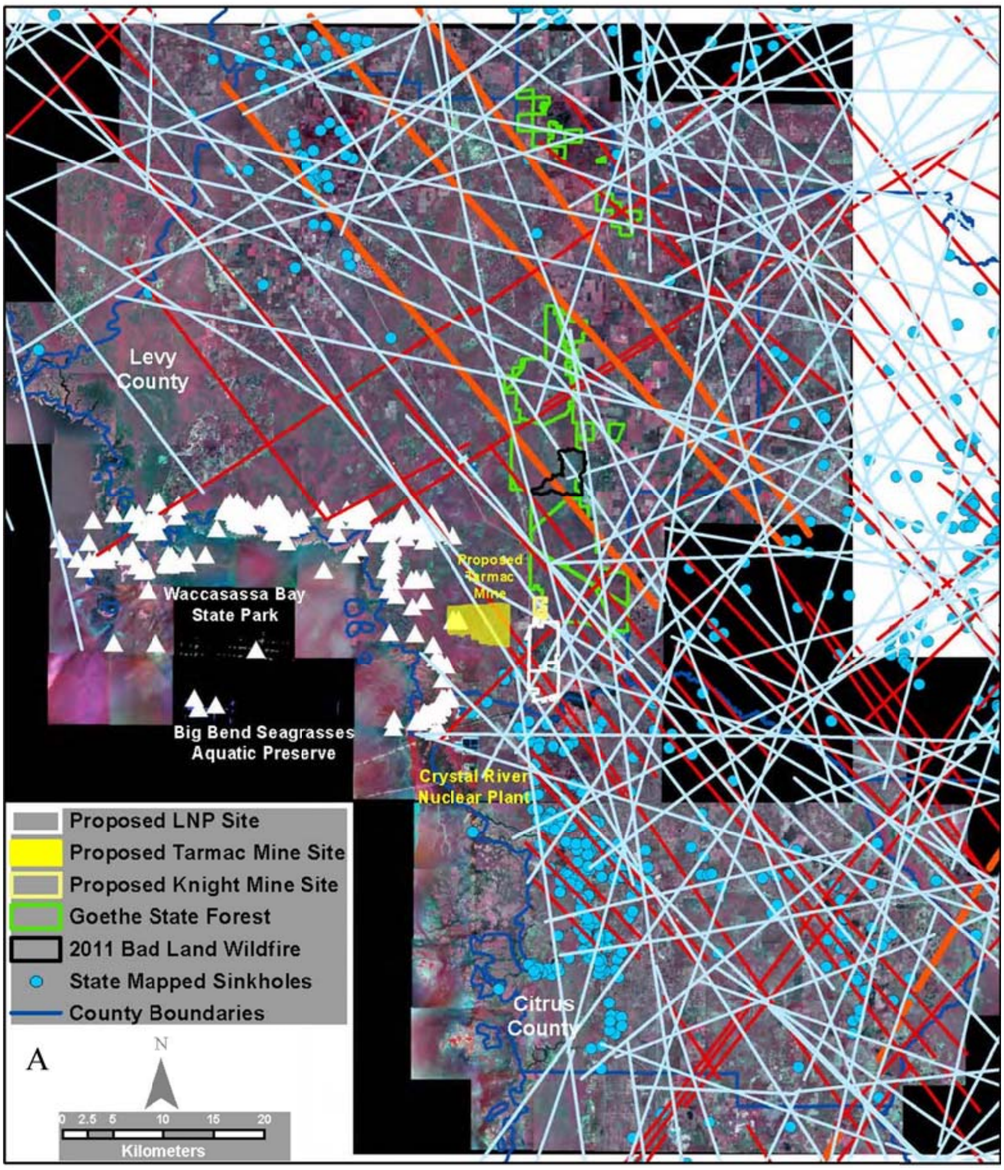
The locations of the same features mapped by Vernon (1951, red and bold orange) and FDOT (1973, light blue lines) in Citrus and Levy Counties, Florida, are shown in Figure 3A, over the winter 2003-04 CIR DOQQ aerial imagery and in proximity to the boundaries of the proposed site for PEF's LNP Units 1 and 2 and proposed mining shown in Figure 2. The additional information in Figure 3A includes the locations of modern sinkholes (blue circles), based on coordinates from the state database maintained by the University of South Florida and thermal infrared signatures (white triangles) indicative of groundwater discharges in the vicinity of the proposed LNP and mine sites as identified by Raabe and Bialkowska-Jelinska (2010) during a period of low ambient temperatures in March 2009.

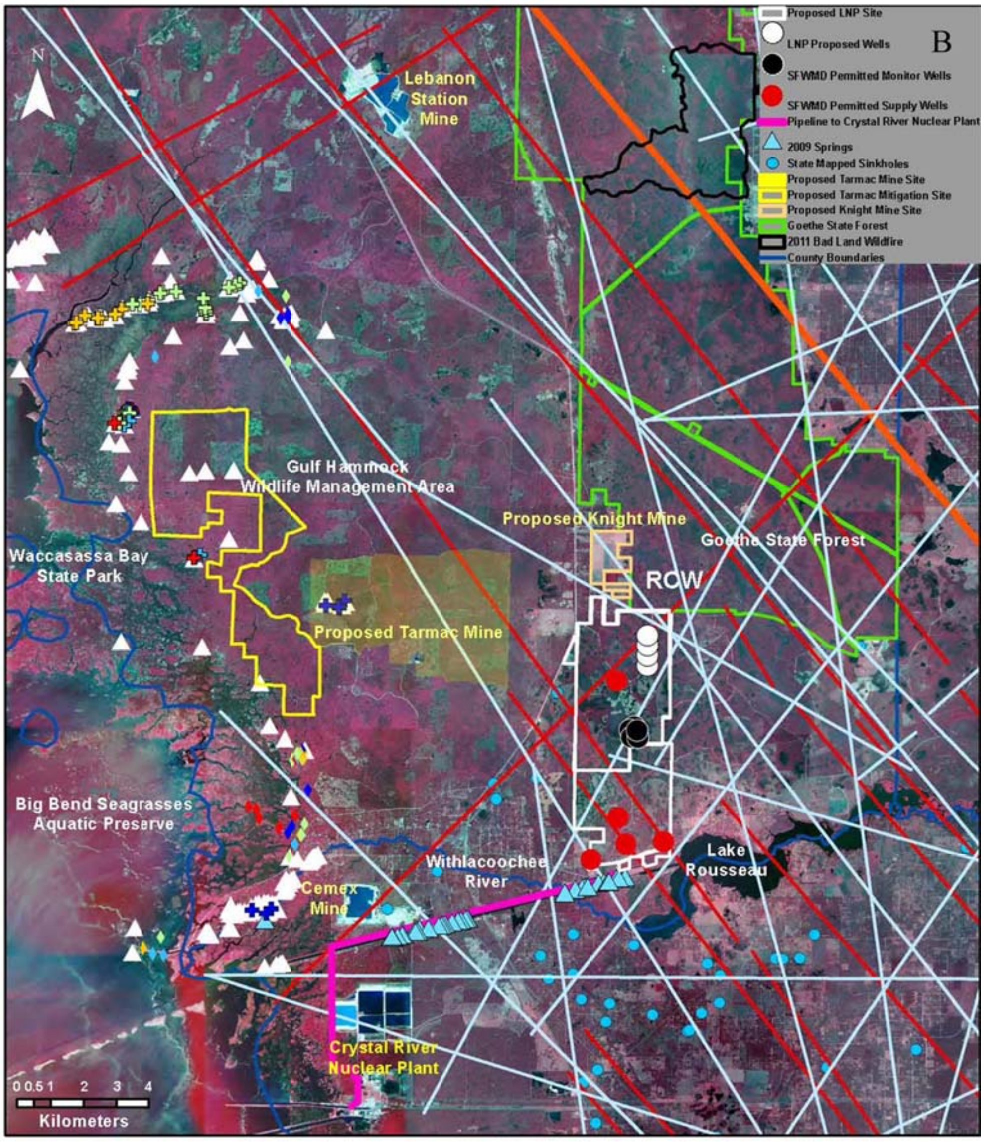
Figure 3B enlarges Figure 3A, using the same DOQQ CIR base map and symbols referenced previously and showing springs (blue triangles) documented in this study discharging along the Withlacoochee canal on November 17, 2009 and the proposed location of the LNP pipeline (pink lines) that coincides with those springs and extends from the proposed LNP project to the debilitated Crystal River nuclear plant in Citrus County. The proximity of the fractures, including faults, to the permitted locations of the same five proposed supply wells (red circles) and cluster of five proposed monitor wells (black circles) permitted by the SWFWMD also is shown in Figure 3B. Included in this figure, based on shapefiles provided by PEF, is LNP's proposed location of the five supply wells (white circles) in the northeast corner of the proposed LNP site and adjacent to the southwest boundary of Goethe State Forest. This location of the proposed wells is not consistent with the location of the proposed LNP supply wells permitted on June 2, 2008 by the SWFWMD (WUP 13262.000, red circles), with an expiration date of August 26, 2059. The Final EIS for the proposed LNP suggests that specific locations for the components of the proposed LNP have not been determined (USNRC, 2012), although this information is essential for determining the impacts of each proposed component, particularly the supply and monitor wells. The existing Cemex mine is shown in Figure 3B, north of the debilitated Crystal River nuclear plant and west of the proposed LNP site. The existing Lebanon Station mine also is shown in Figure 3B, west of the boundaries of the 2011 Bad Land destructive wildfire. Historic USGS topographic quadrangle maps and aerial photographs confirm that the dark-blue signature in the aerial imagery at those two existing mine sites previously was ground water, but now is exposed (daylighted) as the result of those mining operations.

This figure also shows the location of the existing red-cockaded woodpecker (RCW) nesting colony in the southwest corner of Goethe State Forest, adjacent to the northeast corner of the LNP site and adjacent to the eastern boundary of the proposed Knight mine site. The USFWS declared the RCW an endangered species in 1970 (http://www.fws.gov/rcwrecovery/ and http://www.fws.gov/rcwrecovery/rcw.html). The location of the RCW colony shown in Figure 3B is proposed as one of the alleged mitigation locations for the proposed LNP and includes at least four fractures mapped by Vernon (1951) and FDOT (1973).

Figure 3B also provides related locations where surface water salinity measurements were collected as background for this study in January 2012 (diamonds) and March 2012 (crosses), including salinity data collected in locations of thermal infrared signatures (white triangles) indicative of groundwater discharges in the vicinity of the proposed LNP as identified by Raabe and Bialkowska-Jelinska (2010) during a period of low ambient temperatures in March 2009. Salinity levels ranged from fresh to saline (0.01-5 ppt = dark blue; 5.01-14 ppt = light blue; 14.01-21 ppt = green; 21.01-24 ppt = orange; 24.01-30 ppt = red, respectively). The multiple dark blue crosses located in the center of the Gulf Hammock Wildlife Management Area west of the location of the proposed Tarmac limestone mine represent several small mines where the excavation of limestone from the carbonate aquifer system has resulted in large areas of fresh groundwater discharge. The cluster of blue diamonds approximately 8 km (5 mi) north of those small mines and coinciding with the fracture (diagonal red line) extending from the proposed supply well in the southeast corner of the south LNP parcel represents additional small mines where limestone was excavated from the carbonate aquifer system.

Figure 3C is an enlargement of Figure 3B, using the same base map and symbols described for Figures 3A and 3B. The southwest corner of the RCW nesting colony in Goethe State Forest and the permitted locations of the five individual proposed monitor wells (black circles, #6 through #10) also are shown in Figure 3C. This Figure also shows the locations of the LNP exploratory boreholes (yellow circular outlines) that PEF used to characterize the subsurface conditions at the proposed LNP (USNRC, 2012). This figure also includes the proposed locations of the two LNP cooling towers (bold light green), three LNP stormwater ponds (blue outlines) that would be excavated if the proposed LNP is constructed, and the proposed LNP site access roads (brown).


Levy County
Waccasassa Bay State Park
Big Bend Seagrasses Aquatic Preserve
Proposed Tarmac Mine
Crystal River Nuclear Plant
Citrus County
Proposed LNP Site
Proposed Tarmac Mine Site
Proposed Knight Mine Site
Goethe State Forest
2011 Bad Land Wildfire
State Mapped Sinkholes
County Boundaries
A
N
0 2.5 5 10 15 20
Kilometers


Proposed LNP Site
LNP Proposed Wells
B
SFWMD Permitted Monitor Wells
SFWMD Permitted Supply Wells
Pipeline to Crystal River Nuclear Plant
2009 Springs
State Mapped Sinkholes
Proposed Tarmac Mine Site
Proposed Tarmac Mitigation Site
Proposed Knight Mine Site
Goethe State Forest
2011 Bad Land Wildfire
County Boundaries
N
Lebanon Station Mine
Gulf Hammock Wildlife Management Area
Waccasassa Bay State Park
Proposed Knight Mine
Goethe State Forest
RCW
Proposed Tarmac Mine
Big Bend Seagrasses Aquatic Preserve
Withlacoochee River
Lake Rousseau
Cemex Mine
Crystal River Nuclear Plant
0 0.5 1 2 3 4
Kilometers

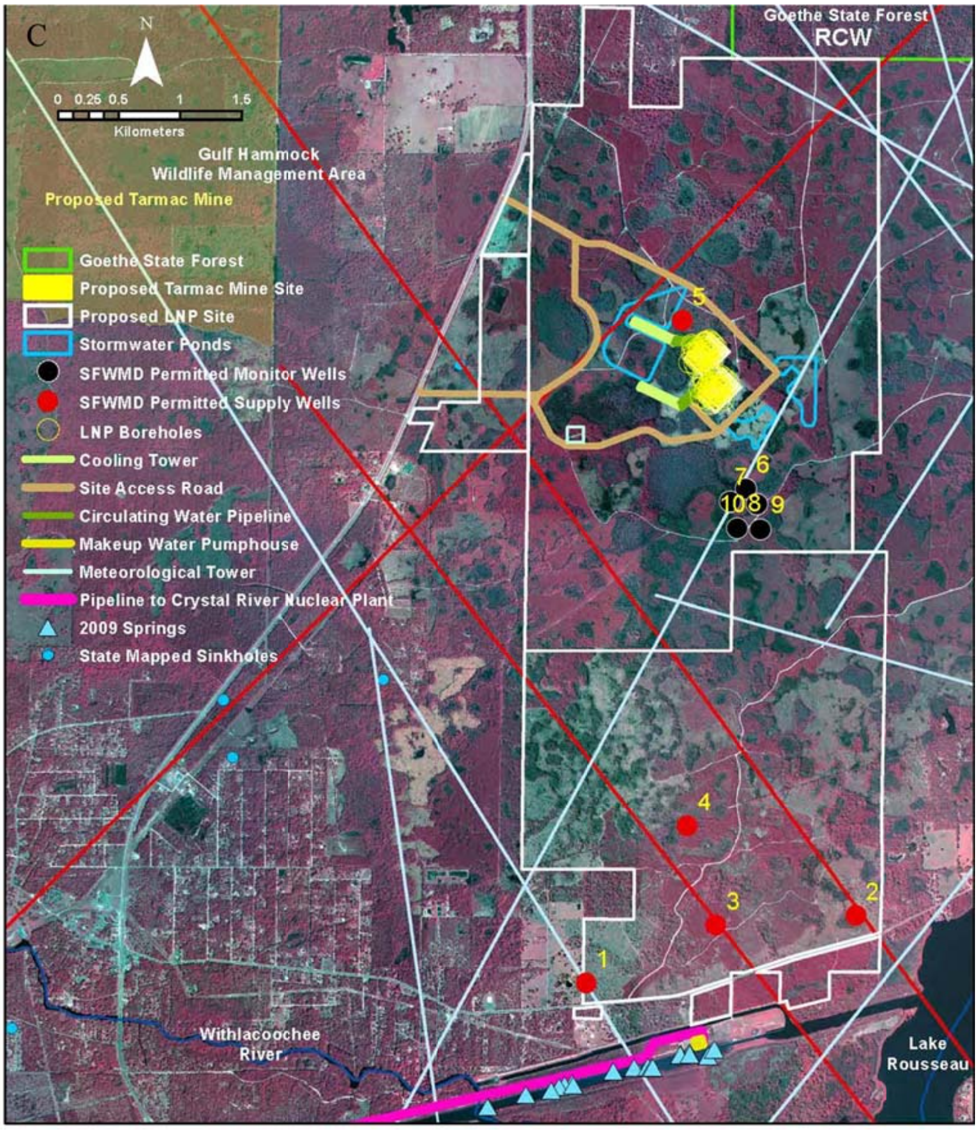


Figure 3. Locations of previously reported fractures, including faults (red, orange and light blue lines) and modern sinkholes over DOQQ CIR imagery, and the debilitated Crystal River nuclear plant, the Levy nuclear plant, Knight Farm mine and Tarmac mine proposed sites, and Goethe State Forest, with extent of the 2011 Bad Land destructive wildfire:

A. in Citrus and Levy Counties, Florida; B. in proximity to red-cockaded woodpecker (RCW) colony, permitted locations of proposed LNP supply wells and pipeline, and the springs discharging into the Withlacoochee canal, March 2009 thermal infrared hot spots (white triangles) indicative of groundwater discharge in the vicinity of the proposed LNP, and range in surface water salinities in January 2012 (diamonds) and March 2012 (crosses) throughout the vicinity of Gulf Hammock Wildlife Management Area, Big Bend Seagrasses Aquatic Preserve and Waccasassa Bay State Park; and C. in proximity to LNP exploratory boreholes and proposed LNP stormwater ponds, cooling towers, monitoring wells and selected associated construction.

The base map for Figure 4 incorporates the extent of wildlife habitat ranked from least important (1 – light gray) to most important (10 – red) by the Integrated Wildlife Habitat Ranking System developed under the Florida Fish and Wildlife Conservation Commission (FFWCC) in 2009 (Endries, Gilbert, & Kautz, 2009). The features in this figure are the same as for the previous maps, with Vernon's (1951) fractures, including faults, in white and bold orange, respectively, and those mapped by FDOT (1973) in light blue. Figure 4 also includes the boundaries of the proposed sites for the LNP, Knight sand mine, Tarmac limestone mine and Tarmac mitigation in proximity to the fractures, and to Goethe State Forest, the destructive Bad Land 2011 wildfire in the state forest and examples of proposed mitigation areas for the LNP, such as the RCW nesting colony.

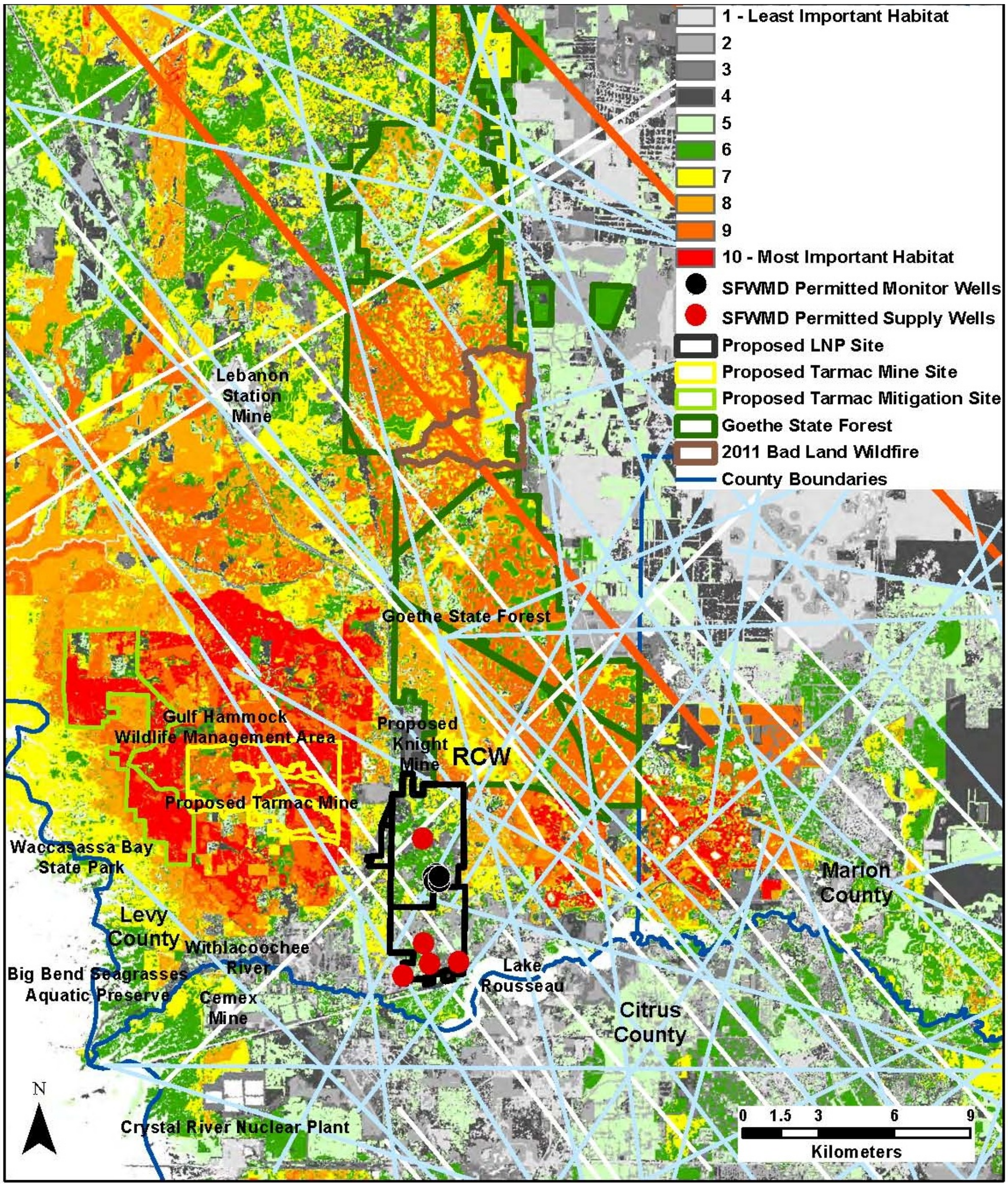


Figure 4. Locations of fractures, including faults, mapped by Vernon (1951, white lines and bold orange lines, respectively) and FDOT (1973, light blue lines) over state-ranked integrated wildlife habitat map, in proximity to the debilitated Crystal River nuclear plant, the existing Cemex and Lebanon Station mines, proposed Levy nuclear plant, Knight Farm, mine Tarmac mine and Tarmac mine mitigation sites, and Goethe State Forest, with extent of the 2011 destructive wildfire and the red-cockaded woodpecker (RCW) nesting colony as a proposed LNP mitigation site

The network of fractures and faults in the vicinity of the LNP and associated mines extends throughout Levy County and into neighboring Alachua, Citrus, Dixie, Gilchrist, Hernando, Marion and Sumter Counties (Figure 2A). Three of the fractures mapped by Vernon (1951, red lines) and six mapped by FDOT (1973, light-blue lines) dissect the proposed LNP site. Three fractures are located in the immediate vicinity of proposed LNP supply wells #1 through #4 (red circles) permitted in the south parcel by SWFWMD in conjunction with the State Site Certification of the LNP (Figures 2B, 3B and 4). Three of those proposed supply wells are in the immediate vicinity of the Withlacoochee canal and the permitted LNP supply well (supply well #1) in the southwest corner of the LNP site are in the immediate vicinity of the cluster of springs identified in this study in the Withlacoochee canal (Figure 3B). Those wells are associated with three fractures extending southeast through the dammed stretch of the lower Withlacoochee River, known as “Lake Rousseau” at the junction of the Withlacoochee canal. These fractures also extend into Citrus County, through a cluster of modern sinkholes (blue circles).

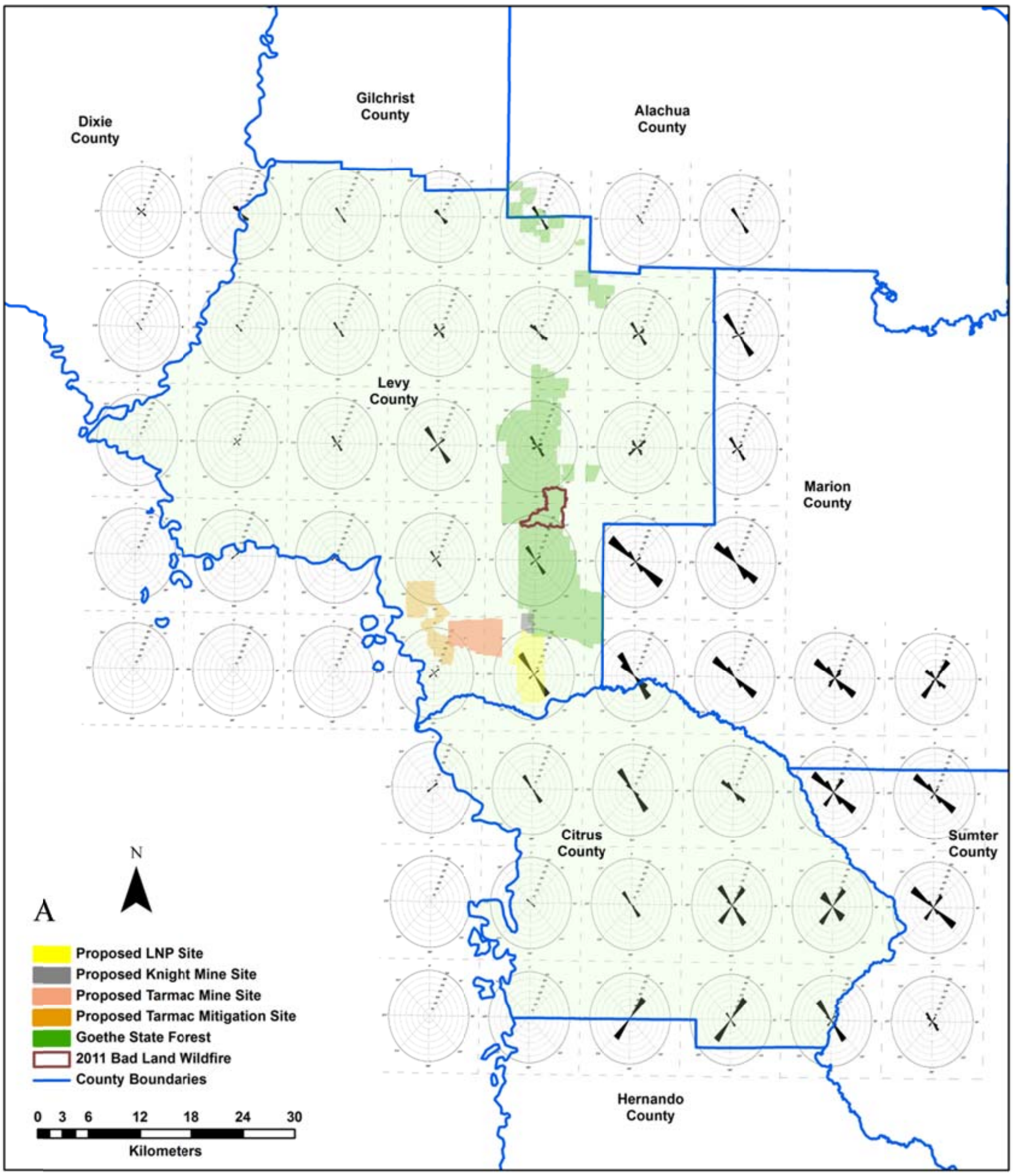
Two of these fractures also extend northwest through the Gulf Hammock Wildlife Management Area and the site of the proposed Tarmac mine, where they intersect with a northeast trending fracture that extends through the existing Lebanon Station Mine. That fracture intersects two additional fractures mapped by Vernon (1951) that are oriented northwest to southeast and extend through Goethe State Forest (Figure 3B). One of those fractures, identified by Faulkner (1973) as a fault (bold orange line), extends through the approximately 1,200-hectare (3,000-acre) area in Goethe State Forest that was burned by a destructive wildfire (outlined in black). That wildfire began in April 2011 and continued to smolder and burn for approximately two months, according to the Florida Forest Service’s Incident Report 2011-08-0370. As described in the Discussion section, organic soils in depressional wetlands with anthropogenically altered hydroperiods can ignite and burn for long periods of time because those soils no longer are protected by saturated or inundated soil conditions, resulting in severe and fatal damage to tree roots.

Of the six fractures mapped by FDOT (1973) that dissect the proposed LNP site, the fracture intersecting supply well #1 also intersects a second fracture northwest of supply well #1, which extends through the eastern stormwater pond (outlined in blue) that is proposed to be excavated in the north parcel of the LNP site (Figure 3C). That fracture also extends into Goethe State Forest, in the vicinity of the RCW nesting colony habitat, then intersects with a network of additional fractures and faults extending throughout Goethe State Forest. Southeast of the 2011 Bad Land wildfire area in Goethe State Forest, north of the LNP and east of the Lebanon Station mine, the fault described previously intersects with the fracture mapped by FDOT (1973) trending northeast to southwest. That fracture extends through the LNP site, in the immediate vicinity of proposed supply well #5 permitted by SWFWMD (red circle, Figure 3C). This fracture also is in the immediate vicinity of the proposed well locations identified by the shapefiles provided by PEF (white circles, Figure 3B). All of these proposed supply wells associated with this fracture are located in the northern half of the LNP site. That same fracture also extends southwest through another cluster of sinkholes in Levy and Citrus Counties and the existing Cemex mine in Citrus County (Figure 3A).

Fractures mapped by FDOT (1973) that are located in the northeast corner of the LNP north parcel intersect the proposed Knight Farm sand mine site and the vicinity of the proposed Tarmac limestone mine, extending into the Gulf Hammock Wildlife Management Area (Figures 3A and B). The southern fracture of that pair also intersects the fracture mapped by Vernon (1951, red line) that extends through the Tarmac mine site to the northwest, then through proposed supply well #2, located in the southeast corner of the south parcel of the LNP site, and through Lake Rousseau (Figures 3B and C).

4.2 Analyses of Fractures and Modern Sinkholes

Figures 5A and B illustrate the length-weighted results for distribution density analyses of fractures, including faults, mapped by Vernon (1951) and FDOT (1973) as 0.12º x 0.12º rose diagram grid cells throughout Citrus and Levy Counties and the LNP, Knight mine, Tarmac mine and Tarmac mine mitigation sites and the Goethe State Forest and 2011 Bad Land destructive wildfire sites. Diagram petals for the multi-cell grids indicate distance in kilometers, ranging from 0 to 350 km (0 to 217 mi) from the center of the diagram to the outer circle, respectively. The length step is 50 km (31 mi). Figures 6A through D are results for the length-weighted distribution density rose diagram analyses of fractures, mapped for the entire Citrus County, by Vernon (1951) and FDOT (1973), and for the entire Levy County by Vernon (1951) and FDOT (1973), respectively. Diagram petals for Figure 6 indicate distance in kilometers, ranging from 0 to 700 km (0 to 434 mi) from the center of the diagram to the outer circle, respectively. The length step is 100 km (62 mi). The proximity of modern sinkholes to the nearest fracture in Citrus and Levy Counties (in meters), based on fractures, including faults, mapped by Vernon (1951), by FDOT (1973) and as a combination of those two data sets, is provided in Figure 7. The frequencies of modern sinkholes and fractures, including faults, mapped by Vernon (1951) and FDOT (1973) are provided in Table 2, by county. Table 2 also includes the lengths of the longest and shortest fractures mapped by Vernon (1951) and FDOT (1973) for both counties and the mean fracture lengths. Figures 8A and B illustrate the number and lengths of fractures mapped by Vernon (1951) and FDOT (1973) in Citrus County and Levy County, respectively.



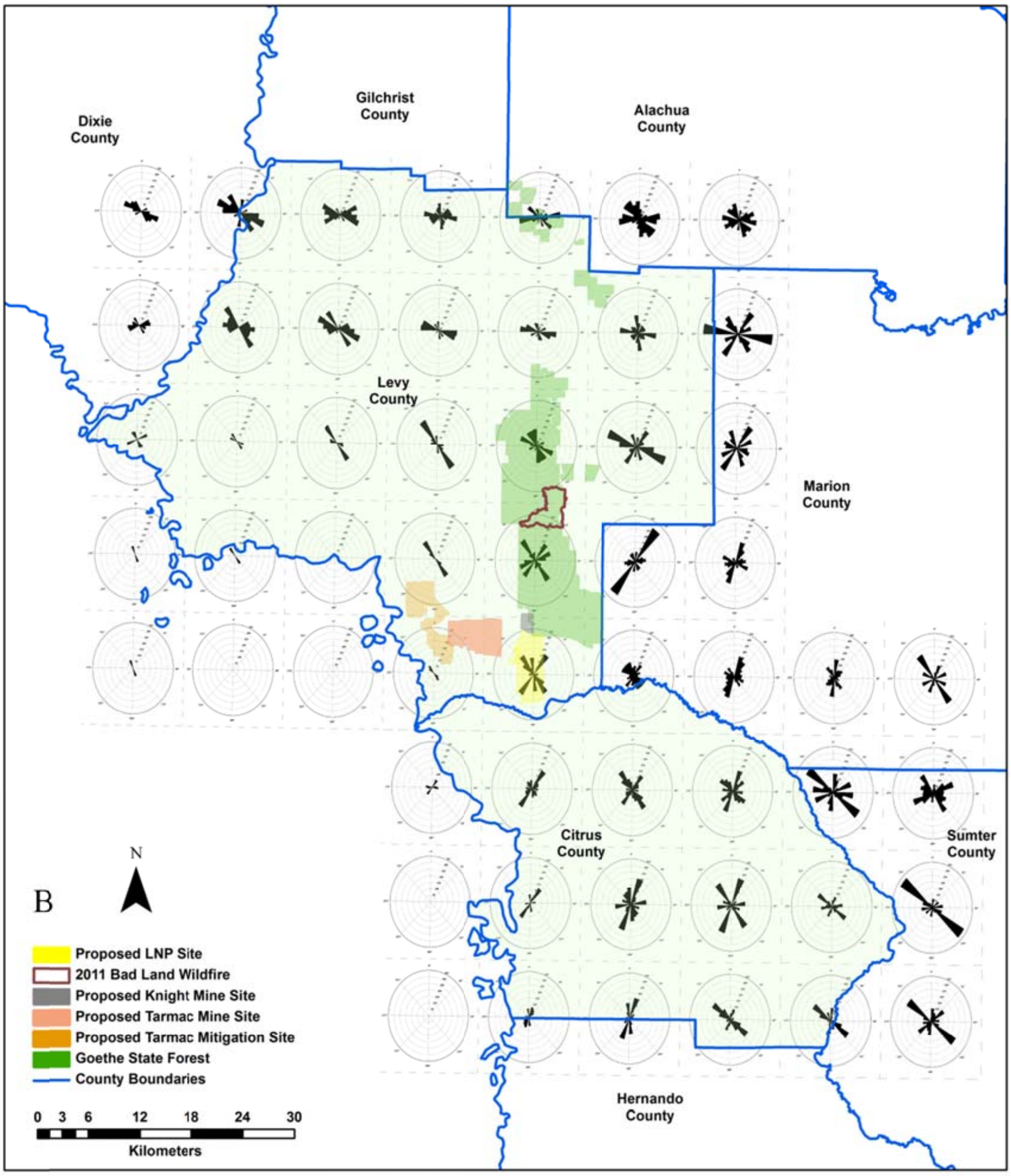


Figure 5. Length-weighted rose diagrams showing distribution density in 0.12º x 0.12º grid cells throughout Citrus and Levy Counties, Florida for fractures, including faults, mapped by: A. Vernon (1951) and B. FDOT (1973)

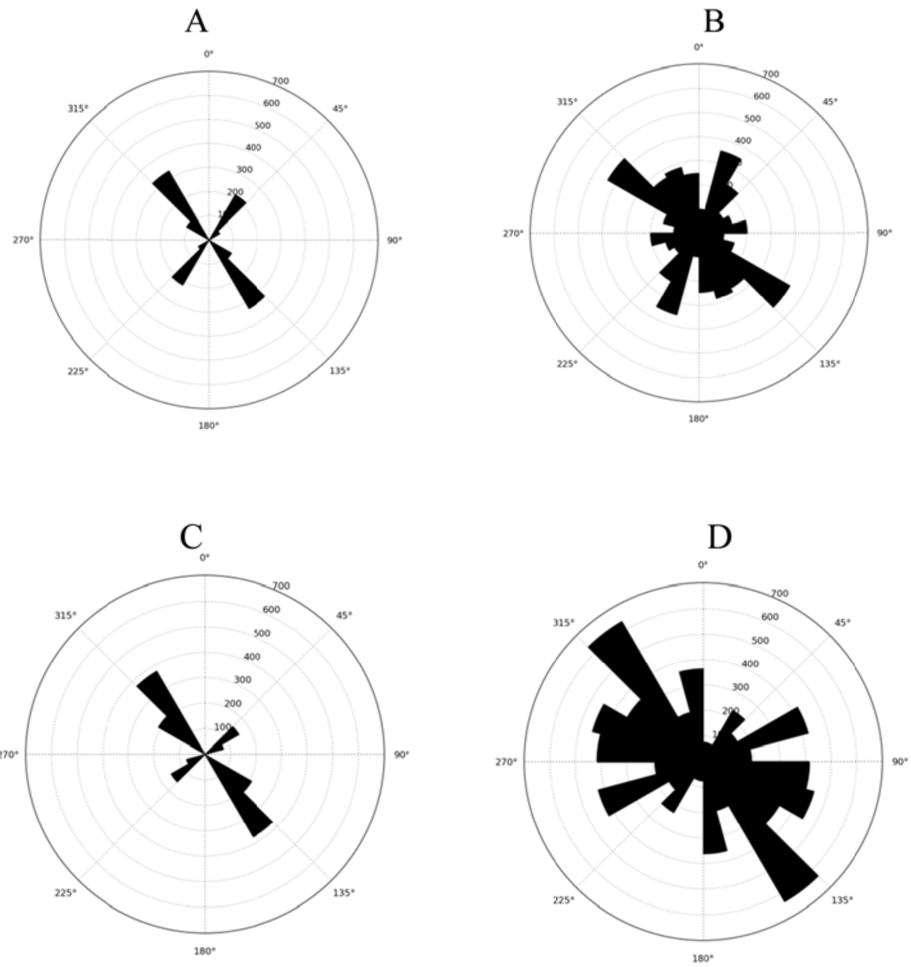


Figure 6. Length-weighted rose diagrams showing distribution density for fractures, including faults, throughout Citrus and Levy Counties, Florida mapped by: A. Vernon (1951) in Citrus County; B. FDOT (1973) in Citrus County; C. Vernon (1951) in Levy County; and D. FDOT (1973) in Levy County

Table 2. Frequency of modern sinkholes, fracture intersections, longest and shortest fractures and mean fracture lengths for Citrus and Levy Counties, Florida

County	**Modern Sinkholes**	**Fracture Intersections**	**Total Fractures**		**Total Combined Fractures**	**Shortest-Longest Fractures (km)**		**Mean Fracture Lengths (km)**	
			Vernon	**FDOT**		**Vernon**	**FDOT**	**Vernon**	**FDOT**
Citrus	314	210	25	51	76	2.9-67.7	6.3-168.8	32.5	53.8
Levy	63	200	25	63	88	0.7-82.8	2.2-110.3	28.4	56.5

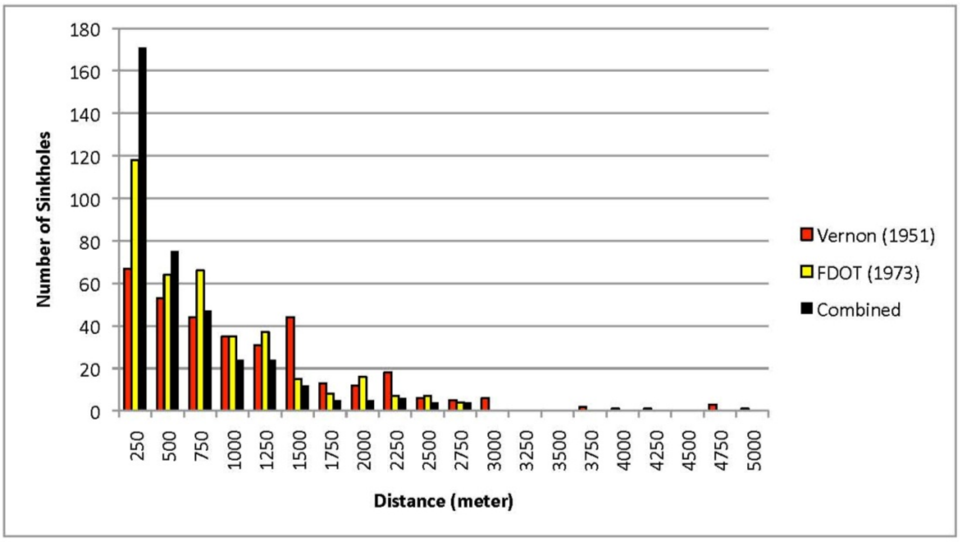


Figure 7. Proximity of modern sinkholes to fractures, including faults, in Citrus and Levy Counties, Florida, mapped by Vernon (1951) and FDOT (1973)

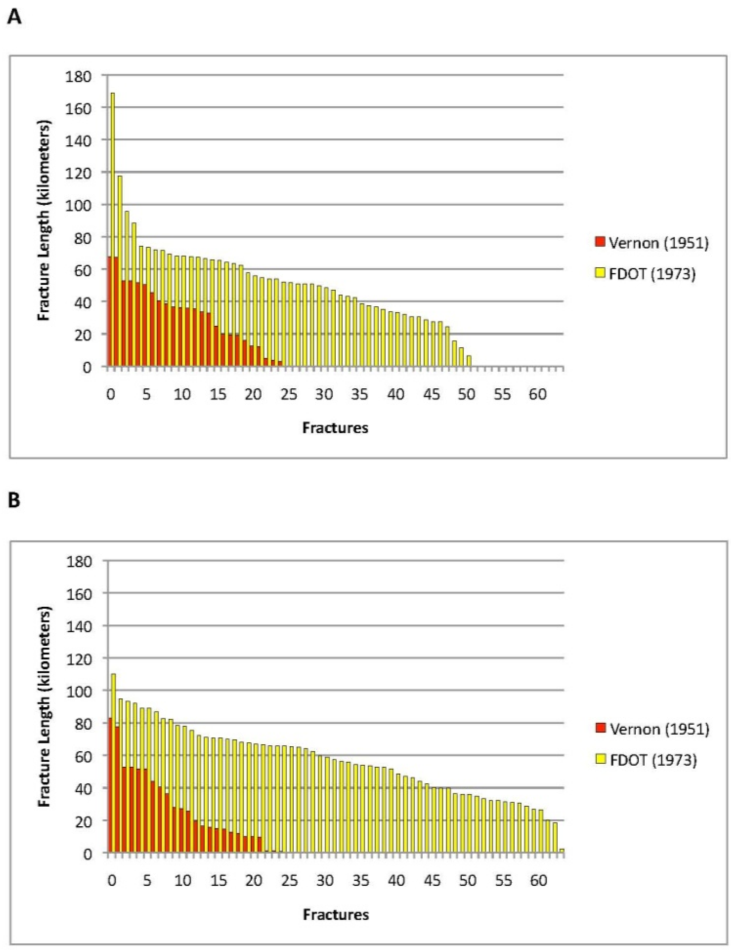


Figure 8. Length of fractures, including faults, mapped from aerial photographs (Vernon, 1951) and satellite images (FDOT, 1973) in: A. Citrus County, Florida and B. Levy County, Florida

5. Discussion

5.1 Fractures, Including Faults, and Sinkholes

5.1.1 Spatial Density of Fractures

Figures 2A, 3A and 4 illustrate how heavily fractured the bedrock is, particularly considering that only the most obvious fractures appear to have been mapped. This suggests that in all likelihood the karst aquifer is composed of interlinked cavities and is well integrated over the entire vicinity surrounding the study area. Therefore, any changes in ground water at one location are likely to affect large, hydrologically interlinked areas. This would include changes in water quality as well as changes in water levels, including hydroperiod, and possibly permanent lowering of the water level. The fact that the three fractures associated with the proposed LNP supply wells (Figure 3B) extend southeast through the dammed stretch of the lower Withlacoochee River and through a cluster of modern sinkholes in Citrus County is proof that the aquifer system is integrated over wide areas (George A. Brook, pers. com. November 12, 2012).

Figures 5A and B illustrate the differences in direction and frequency of fractures, including faults, mapped using aerial photographs (Vernon, 1951), and those mapped using satellite imagery (FDOT, 1973) as 0.12º x 0.12º length-weighted rose diagram grid cells throughout Citrus and Levy Counties. Rose diagrams are capable of revealing fracture trends in a buried bedrock surface that are visible only sporadically through overlying structures (Harnett & Barnett, 1978). The relevance of rose diagrams is described more fully by Norman (1976). Different results in this study for lineaments indicative of fractures mapped using aerial photographs and those mapped using satellite imagery are consistent with results from other studies using either aerial photographs or satellite images (Norman, 1976).

Figures 5A and B also show the length-weighted rose diagram results in proximity to the LNP, Knight mine, Tarmac mine and Tarmac mine mitigation sites and to the Goethe State Forest and boundaries of the 2011 Bad Land destructive wildfire in Levy County. For example, the prevailing direction for six fractures determined from the aerial photographs (Figure 5A) in the rose diagram cell that includes the LNP site, the majority of the Knight sand mine site, the eastern third of the Tarmac mine site, the southern boundary of Goethe State Forest, including the RCW nesting colony, and the lower Withlacoochee River and Lake Rousseau, is northwest to southeast. The northwest to southeast fracture pattern in the study area is related to the broad northwest-southeast trending upwarp associated with the Ocala Uplift (Faulkner, 1973). One fracture is oriented perpendicular to those fractures in the LNP cell. The prevailing directions are similar for fractures in the cells to the west of the LNP cell, with the western half of the proposed Tarmac mine and southern half of the proposed Tarmac mitigation site; to the northwest, with the northern half of the proposed Tarmac mitigation site; and for the two cells to the north, with the majority of the state forest and the area of the 2011 Bad Land destructive wildfire, but fewer fractures occur in those cells. Although the prevailing direction of fractures determined from the satellite imagery (Figure 5B) for those same cells also is northwest to southeast, other fractures in more heterogeneous directions were identified.

The fact that fractures dissect the Goethe State Forest site where the 2011 Bad Land destructive wildfire burned for at least two months in 2011, suggests that groundwater alterations from developments beyond the boundaries of the state forest and associated with those fractures or other groundwater flow pathways resulted in altered hydroperiods in the pond-cypress wetlands within the boundaries of the 2011 Bad Land fire. Figures 2B, 3B and 4 illustrate the locations of the fractures that dissect that burn site in Goethe State Forest. No evidence was found that the relevant state agencies or others have evaluated the role of those fractures in the 2011 Bad Land destructive wildfire. Figures 2B, 3B and 4 also illustrate that other fractures intersecting the fractures that dissect the 2011 Bad Land destructive wildfire site also dissect the LNP, Tarmac mine and Knight mine sites, the LNP RCW mitigation site in Goethe State Forest and other off-site wildlife habitat that is highly ranked by the state (Endries, Gilbert, & Kautz, 2009). The presence of those fracture networks should have resulted in the consideration of cumulative adverse environmental impacts to the mitigation sites by the USNRC, the USACE, the USFWS and the USEPA. For example, if the mitigation sites are being dewatered by preferential flow and induced recharge from these fractures and other karst conduits, those sites cannot be legitimate mitigation, but must be considered additional, off-site adverse impacts. The LNP Draft and Final EIS (USNRC, 2010a; 2012) and the Tarmac Draft EIS (USACE, 2012) all failed to consider the role of those fractures and preferential groundwater flow in the destructive 2011 Bad Land wildfire and the cumulative impacts that the proposed LNP and mine sites would have on increasing the frequency and magnitude of destructive wildfires in Levy County and surrounding counties in the future.

The increased heterogeneity of fracture directions on the satellite imagery compared with the results from the aerial photographs in proximity to the LNP site increases the potential for adverse environmental impacts from hydroperiod alterations in additional directions if the proposed LNP construction and groundwater withdrawals occur. Despite the differences in direction and frequency of fractures mapped using aerial photographs (Vernon, 1951) and regional fractures mapped using satellite imagery (FDOT, 1973), both sources show that groundwater and environmental monitoring proposed in the Final EIS do not consider the adverse environmental impacts that have been identified with the distribution and frequency of other fractures in the FAS that are similar to the fractures in Figures 5A and B or the sustainability of the LNP, Knight mine, Tarmac mine and mitigation sites.

The direction and frequency of fractures for rose diagram cells in Citrus County also vary throughout the county and for the same cells depending on whether aerial photographs or satellite imagery was used to map the fractures. For example, for fractures mapped using aerial photographs (Figure 5A), the prevailing direction of fractures in the coastal (western) half of Citrus County is northwest to southeast, with perpendicular fractures absent or rare. In the eastern half of Citrus County strong perpendicular fractures are evident. For fractures mapped using satellite imagery (Figure 5B), the prevailing direction of fractures along the Citrus County coast is northeast to southwest, with minimal perpendicular fractures. For the remaining, inland cells, perpendicular fractures are more evident than in Figure 5A.

The county-wide length-weighted rose diagrams depicted in Figures 6A and C show similar northwest to southeast and northeast to southwest trending fractures mapped by Vernon (1951) in Citrus and Levy Counties. Comparison of Figures 6A and B, however, shows the more expansive pattern in the fractures mapped by FDOT (1973) for Citrus County than those mapped by Vernon (1951) in the same county. Comparing the county-wide length-weighted rose diagrams for the fractures mapped by FDOT (1973) shows a more dispersed pattern of fractures and greater fracture lengths in Levy County than in Citrus County (Figures 6B and D). The differences between the fracture patterns mapped by Vernon (1951) and FDOT (1973) is presumed to be due to the regional fractures that are longer and more apparent in satellite imagery (Littlefield, Culbreath, Upchurch & Stewart, 1984; Norman, 1976).

5.1.2 Frequency of Modern Sinkholes, Fracture Intersections and Fracture Lengths

Fracture intersections are important because they are a factor associated with the increased probability of subsidence such as sinkholes (Brook & Sun, 1982; Littlefield, Culbreath, Upchurch, & Stewart, 1984). Therefore, consideration of the frequency and distribution of fracture intersections is an important factor in insuring that proposed developments will be sustainable. The LNP Draft and Final EIS (USNRC, 2010a; 2012) and the Tarmac Draft EIS (USACE, 2012) all failed to consider the role of preferential groundwater flow associated with fracture intersections in the destructive 2011 Bad Land wildfire and the cumulative impacts on hydroperiod alterations in other areas.

The total number of fracture intersections for Citrus and Levy Counties is similar, at 210 and 200, respectively (Table 2), but the state database for modern sinkholes reports approximately five times more modern sinkholes in Citrus County than in Levy County, with a combined total of 377 (Table 2). Table 2 shows that both counties included 25 fractures mapped by Vernon (1951), but the number of fractures mapped by FDOT (1973) was more than twice that for both Levy and Citrus County. The total number of fractures from the combined data sets was 76 for Citrus County and 88 for Levy County. Table 2 also provides the total lengths of the longest and shortest fractures for both counties, based on those mapped using aerial photographs and those mapped using satellite imagery. Fracture length is an important consideration because longer fractures can result in more far-reaching, off-site adverse environmental impacts. The LNP Draft and Final EIS (USNRC, 2010a; 2012) and the Tarmac Draft EIS (USACE, 2012) also failed to consider the role of fracture length in preferential groundwater flow associated with the destructive 2011 Bad Land wildfire and the cumulative impacts on hydroperiod alterations in other areas.

The LNP site evaluation conducted for the Final EIS used boreholes to conclude that no fractures occurred on the LNP site but those boreholes were concentrated at the surface footprint where the two nuclear units would be constructed, rather than distributed throughout the site or in the immediate vicinity of where the fractures are located (USNRC, 2010a; 2012; Bacchus and Rizzo live testimony, 10/31/12). Figure 3C provides the locations of those boreholes. Large fractures in the subsurface typically are widely spaced and have much larger dimensions than the diameter of a borehole. Therefore, the probability of encountering such fractures is small and even if such fractures are intersected, only fragmentary data are collected (Narr, 1991). In many cases, microfracture abundance is related directly to macrofracture abundance (Marrett, Ortega, & Kelsey, 1999;

Ortega & Marrett, 2000), but microfractures were not mapped by Vernon (1951) or FDOT (1973) or considered by the LNP Draft or Final EIS (USNRC, 2010a; 2012) or the Tarmac Draft EIS (USACE, 2012).

It is important to note that no claims were made that the fractures mapped by Vernon (1951) and FDOT (1973) were the only fractures that occur in those counties (Faulkner, 1973). In fact, numerous drainage lineations indicative of fractures are evident in areas where no fractures were mapped by Vernon (1951) or FDOT (1973), based on personal communications with George A. Brook, University of Georgia (November 2012). The presence of these unmapped fractures is supported by Hutton, Hines, Evans and Osking (1984), who note that tidal creeks in this west-central Florida area form by following fracture lines and by connecting geographically isolated ponds together, and by Littlefield, Culbreath, Upchurch and Stewart (1984), who report that linear features such as joints, fracture zones or faults widespread throughout west-central Florida can be detected at all scales by the presence of ancient sinks. It is important to note that the state's sinkhole database does not include these ancient, relict sinkholes, evidenced by the depressional wetlands, such as those that occur throughout the proposed LNP and surrounding Levy County vicinity. Littlefield, Culbreath, Upchurch and Stewart (1984) identified 2,303 relict sinkholes compared to 138 modern sinkholes in one county of that west-central Florida study area using USGS quadrangle maps to identify topography and closed depressions. Other remote imagery used in that study included 1:20,000 aerial photographs for location of fracture traces and 1:500,000 LANDSAT images for recognition of lineaments. Geophysical methods used in that study included horizontal electrical profiles, vertical electrical soundings, tri-potential profiles, and microgravity and triple-track gravity profiles.

There also may be additional modern sinkholes in the study area other than those shown in Figures 3A through C. First, the state's database that includes numerous counties, including Citrus County (http://fcit.usf.edu/florida/maps/pages/11100/f11119/f11119.htm) and Levy County (http://fcit.usf.edu/florida/maps/pages/11100/f11140/f11140.htm) was compiled in 2008 and other sinkholes may have occurred in the study area since 2008. Additionally, there is a tendency for more sinkholes to be reported in highly urbanized areas, either because sinkholes are discovered more readily where populations are denser and the sinkholes affect more people or because urbanized areas actually create more sinkholes (Littlefield, Culbreath, Upchurch, & Stewart, 1984). For example, the occurrence of 533 modern sinkholes along state highways in Florida since 1958 has been documented by FDOT. Those data also reveal a greater frequency for sinkhole occurrence as the depth to the underlying limestone decreases (Beggs & Ruth, 1984). To the northeast, there were no reports of modern sinkholes until approximately 1981 when grading for a highway project was initiated and a limestone mine began operations adjacent to the highway project in 1983, resulting in formation of sinkholes in the highway and swallets in the roadside ditches due to changes in the water table and flow gradient (Koch, 1984).

Similarly, approximately 4,000 human-induced sinkholes have formed in Alabama since 1900, compared to an estimated 50 natural collapses. The induced sinkholes result from construction or a decline in the water table due to: (a) loss of buoyant support; (b) increase in the velocity of movement of ground water; (c) water table fluctuations at the base of unconsolidated deposits; and (d) induced recharge (Newton, 1977). The FAS extends through the coastal plain of Alabama (Krause & Randolph, 1989). Consequently, the fact that the study area is less urbanized than other areas of Florida may have resulted in fewer sinkholes being reported in those counties and the proposed LNP and associated development may induce the formation of additional sinkholes. Finally, reporting only the number and location of sinkholes also ignores the fact that individual sinkholes coalesce with lateral increase in size (Brook & Allison, 1983). Some of the procedural steps recommended by Ogden (1984) for sinkhole analysis include: (a) delineation from topographic maps and aerial photographs; (b) depth, width and elongation analysis including statistical comparison to fractures (joints and faults) and photo-lineament trends; (c) topographic analysis; (d) water-table monitoring; (e) identification of deformation of man-made structures, ponding of rainwater and vegetation stress; (f) shallow geophysical analysis (e.g., resistivity, seismic reflection); and (g) identification of mining, impoundments, water diversions and groundwater pumping. The proposed LNP and mines would result in all of the sinkhole-inducing factors described in (g). A comparison of relict and modern sinkholes also may reveal that in Levy County, relict sinkholes are more abundant than modern sinkholes.

5.1.3 Proximity of Modern Sinkholes to Fractures

Fractures, including faults, are important controls for orientation of solution channels and development of groundwater circulation patterns (Faulkner, 1973). This is the reason that fractures are important factors associated with the increased probability of subsidence such as sinkholes (Brook & Sun, 1982; Littlefield, Culbreath, Upchurch, & Stewart, 1984). Figure 7 reveals that more modern sinkholes (approximately 120) in the two counties are within 250 meters (820 ft) of a fracture mapped using satellite imagery than fractures mapped using aerial photographs (approximately 70). When the fractures from both data sets were combined, 45% of the 377 total number of sinkholes in the two counties, or approximately 170 modern sinkholes, were within 250 meters of a fracture. Figure 7 also reveals that for the combined fractures from the two data sets, approximately 70 additional sinkholes are within 500 meters (1640 ft) of a fracture. Therefore, approximately 64% of the modern sinkholes in the state's database are within 500 meters of a fracture mapped by Vernon (1951) or FDOT (1973), supporting the established position that fractures are important controls for orientation of solution channels and development of groundwater circulation patterns (Faulkner, 1973) and are associated with the increased probability of subsidence such as sinkholes (Brook & Sun, 1982; Littlefield, Culbreath, Upchurch, & Stewart, 1984). Figure 7 also illustrates that the modern sinkholes mapped for Citrus and Levy Counties are more closely associated with the fractures mapped by FDOT using satellite imagery because all of the mapped sinkholes are located within 2,750 meters (1.7 mi) of a fracture from that data set. Although the histogram is terminated at 5,000 meters, while still recording sinkholes associated with fractures mapped by Vernon using aerial photographs, that distance does not account for all 377 of the sinkholes in the two-county study area. By combining the two data sets for fractures, all sinkholes are located within 250 meters of a fracture. A more comprehensive analysis of sinkhole proximity to fractures would include relict sinkholes and additional fractures that were not mapped at the scales used by Vernon (1951) and FDOT (1973).

5.2 Hydroperiod Alterations

5.2.1 Causes of Hydroperiod Alterations

Natural hydroperiods are critical in maintaining wetlands and other wildlife habitat throughout the FAS, including habitat critical for the survival and recovery of threatened and endangered species (Bacchus, 1998; 2006). As the definitions indicate (Table 1), alteration of a single component of natural hydroperiods can result in the degradation and ultimate destruction of wetlands and the biota those wetlands support. The natural hydroperiods of wetlands and uplands associated with the FAS, which coincides with the extent of the southeastern coastal plain, are altered by mechanical groundwater withdrawals (pumping) from supply wells and from pumping to dewater excavations into the surficial aquifer (water table), as well as by excavations into the surficial aquifer that do not involve mechanical dewatering, as summarized in Bacchus (2006). Examples include LNP Units 1 and 2 and support facilities, and the Tarmac limestone mine and the Knight sand mine site that would provide the raw materials for construction of the LNP and support facilities. In addition to the limestone mining west of the LNP and the sand mining north of the LNP, excavations into the surficial aquifer also would occur for the LNP nuclear reactor foundations, stormwater ponds, pipelines and swales in Levy County.

These types of excavations into the surficial aquifer also result in three additional categories of alterations of the natural hydroperiod: (a) nonmechanical (passive) groundwater withdrawals, (b) physical displacement of water in the surficial aquifer and (c) capture and impoundment of overland flow (Bacchus, 2006). Nonmechanical dewatering occurs from mines, stormwater ponds and other excavations into the surficial aquifer due to evaporative loss following conversion of groundwater areas to surface waters. Physical displacement of ground water occurs from the ground water in surrounding areas flowing into the large void space created in the surficial aquifer when the excavated material is removed. Although the water table eventually reaches a new equilibrium, usually more than a year following an excavation, that new equilibrium will be lower and result in less ground water available to surrounding areas. Frequently excavations also are surrounded by berms or raised dikes, which are constructed from mined material and which capture and impound water that previously would have flowed to down-gradient wetlands, streams or coastal areas.

A more detailed description of nonmechanical alteration of natural hydroperiods is provided by Bacchus (2006), while Swancar, Lee, and O'Hare (2000) describe how groundwater flow from the surrounding basin in the FAS plays an important role in maintaining surfacewater levels when net precipitation is negative (less than evaporative loss) over the long term. In their study of natural lakes from August 1996 to July 1998, evaporative loss from the 53.6-hectare (132-acre) Lake Starr was 144.98 cm (57.08 in) per year and evaporative loss from Lake Lucerne was 146.98 cm (57.87 in) per year. Evaporative losses at both locations exceeded the 30-year average for precipitation 122.43 cm (48.2 in) per year and the approximated long-term average precipitation (51.99 in per year) for that area. Additionally, Swancar et al. (2000) documented that evaporative loss from large bodies of water, approximately 40 hectares (100 acres) or larger, exceeded the pan evaporation of 121.92 cm (48 in) per year for central Florida that is used routinely in water models to estimate impacts of proposed developments.

Drawdowns of the surficial aquifer may be pulsed or reversible if mechanical withdrawals (pumping) from supply wells are reduced and increased, alternatively, or of limited volume and short duration. Even if aquifer levels recover after pumping is reduced or halted, permanent hydroperiod and other environmental impacts can result from oxidation of organic soils in less than a year due to those withdrawals. Those environmental impacts cannot be reversed after pumping is reduced or halted. Mechanical and nonmechanical groundwater withdrawals and physical displacement of ground water independently and cumulatively have significant adverse impacts throughout the FAS, including the triggering of destructive wildfires (Bacchus, 2006; Southwest Florida Water Management District, 1996; Stewart & Stedje, 1990; Watson, Stedje, Barcelo, & Stewart, 1990). The distribution of pond-cypress wetlands surrounding pumping wells in the study by Stewart and Stedje (1990), shown in Figures 2 and 3, is similar to the distribution of pond-cypress on the proposed LNP site and surrounding vicinity.

5.2.2 Passive Groundwater Withdrawals Proposed for LNP

Examples of passive groundwater withdrawals that were not considered for the LNP included stormwater ponds, the excavations for the LNP nuclear islands, and ditches that would be excavated. Details on these passive dewatering components of the LNP that were not included or considered by the LNP Draft or Final EIS (USNRC, 2010a; 2012) are provided by PEF's engineer (Griffin affidavit, http://www.nirs.org/nukerelapse/levy/levyhome.htm), including some conflicting information. For example, PEF claims the large stormwater ponds for the proposed LNP would be "above ground" and would "have raised dikes surrounding them to keep the collected stormwater staged above ground level," but also states they are called "'wet ponds' in Florida because the pond bottoms will be below the natural seasonal high groundwater level; so there will be some open water in the ponds most of the year" (Griffin affidavit). More specifically, those proposed stormwater ponds would "occupy approximately 105 acres" (42 ha), be excavated "6-8 feet" (1.8-2.4 m) below ground and would divert and capture "more than 88 acre-feet" (108,546 cubic meters) of natural overland flow (Griffin affidavit). The Final Safety Analysis Report (FSAR), prepared by the USNRC (2010), states that the water table "lies less than 1 foot below ground surface" in rainy periods and approximately "5 feet below ground surface" during drier periods. Observations before and after excavation of hundreds of "wet ponds" throughout Florida, including those surrounded by "raised dikes," as proposed for the LNP site, confirmed that despite being permitted to comply with state, regional and federal regulatory requirements to preserve those associated wetlands, all resulted in the invasion by nuisance species and death of surrounding native vegetation that remained around the excavated "wet ponds." This occurs due to passive dewatering because water from the exposed aquifer system evaporates, particularly during periods without rain, depleting the aquifer (Bacchus, 2006). Reliance on an unidentified 1996 study by Knowles of the Rainbow Springs and Silver Springs basins for a period between 1965 and 1994 to conclude that "evaporation is about the same as direct precipitation on the ponds at 53.2 inches per year, plus or minus 7 percent" (Griffin affidavit) provides additional evidence that the proposed stormwater ponds would dewater the aquifer. Even if that rate of evaporation were not artificially low, Levy County rainfall data provided by SWFWMD reveals that annual rainfall was less than 135 cm (53 in) per year for 45 years and less than 127 cm (50 in) per year for 34 years during the period of record. These data provide additional evidence that the proposed LNP "wet ponds," contrary to additional statements by PEF (Griffin's affidavit), will not "be a source of recharge for the near-surface aquifer" but will dewater the aquifer system even during the rainy season and even if the historic rainfall levels do not decline in response to global climate disruption. The Final EIS (USNRC, 2012) confirms that "projected changes in the climate for the region during the life of the LNP Units 1 and 2 site include an increase in average temperature of 2 to 4º F" and a decrease in precipitation in the winter, spring, and summer. More precisely, the FEIS (USNRC, 2012) states that the "projected changes in precipitation patterns for southwest Florida over the next 70 to 80 years, as reported by the U.S. Global Change Research Program (GCRP 2009), are for a decline in rainfall of between 20 to 25 percent in the spring." Those seasons are the most critical for adequate water to avoid chronic water stress, and premature decline and death in pond-cypress wetlands (Bacchus et al., 2003). Aquifer levels in the northern portion of the LNP site also have been declining due to groundwater use and alternative water sources have been recommended (USNRC, 2012). Although the Draft EIS (USNRC, 2010a) also stated, "Declines in aquifer water levels may continue throughout Florida, as the aquifers are relied on in response to changes in precipitation and the growth in demand for freshwater (GCRP 2009)," the Final EIS failed to acknowledge those declining aquifer levels. Additional hydroperiod alterations would occur from the excavations for the LNP reactor foundations and the pipelines that would be constructed in the immediate vicinity of the springs along the Withlacoochee canal, because those "pipelines will need moderately deep (about 15 feet deep) excavations to be dewatered, and the foundations of the reactors will be the deepest areas to be dewatered (about 140 feet deep)," as described in Griffin's affidavit.

5.2.3 Active Groundwater Withdrawals Proposed for LNP

Although active groundwater withdrawals from the LNP supply wells were considered in the Final EIS, the cumulative impacts of those withdrawals were not considered. A cumulative impacts analysis not only is necessary to ensure sustainable development, it is required by federal law, as described in section 5.4.1. The hydroperiod alterations from the passive-dewatering described above from the proposed excavations would be combined with the LNP groundwater withdrawals as one type of cumulative impact. The SWFWMD permit for groundwater withdrawals (WUP 13262.0) indicates that the LNP project area is "5,373,000 acres" (2,174,375 hectares). The information in Table 3 for the five proposed LNP supply wells, including the average withdrawals and peak withdrawals, was included in the SWFWMD permit. The permit, which does not expire until August 26, 2059, includes no constraints on maximum groundwater withdrawals or groundwater withdrawals during periods of drought. Those constraints are reserved for certain types of irrigation uses, according to SWFWMD staff (Zachary Whitmore, pers. com. May 17, 2012). The fact that there are no permit requirements to halt or reduce groundwater withdrawals during times of drought ensures that both on-site and off-site adverse environmental impacts from groundwater withdrawals will be intensified and presumably irreversible during times of drought. Without restrictions on groundwater withdrawals during times of drought, LNP could withdraw the maximum amount of water allowed during those times when both plants and animals in the surrounding ecosystems are most reliant on natural groundwater contributions.

The units for the well-casing diameters and depths were not provided in the permit, but were confirmed by SWFWMD staff as inches and feet, respectively (Mike Phillippi, pers. com. May 29, 2012). The permit also does not specify the casing diameter, casing depth or well depth for supply wells #2 through #5 or for the five monitor wells (#6 through #10). The unavailable information for wells #2 through #5 is important because diameter of the well casing influences the volume of water that can be withdrawn during a period of time, while the depth of the casing and well influences the magnitude and extent of the adverse environmental impacts that will occur from the groundwater withdrawals. For example, adverse impacts from groundwater withdrawals from wells approximately 152 meters (500 ft) deep in the FAS, as described for well #1, could have a far-greater lateral extent due to preferential flow through fractures and other karst conduits than comparable withdrawals from wells approximately 6 to 12 meters (20 to 40 ft) deep, such as the private residential wells in the area. New sinkholes are known to form from the loss of hydrostatic support following withdrawals of large quantities of water from the artesian Floridan aquifer (Metcalfe & Hall, 1984).

Table 3. Groundwater use permitted by the Southwest Florida water management district in water use permit 13262.0 for the proposed Levy nuclear plant and related facilities

Well	Casing Diameter	Casing Depth	Well Depth	WD Ave GPD	WD Peak GPD	WD Max GPD
#1	16*	150**	500**	395,000	1,462,500	N/A
#2	NS	NS	NS	395,000	1,462,500	N/A
#3	NS	NS	NS	395,000	1,462,500	N/A
#4	NS	NS	NS	395,000	1,462,500	N/A
#5	NS	NS	NS	90,000	333,000	N/A
Totals				1,580,000	5,850,000	NS

GPD – gallons per day (gallons x 3.79 = liters; 1 cubic meter per day = 2.64 x 10^{-4} million gallons per day (MGD))

* in - inches (1 centimeter =0.39 inches)

**ft - feet (1 meter = 3.28 feet)

N/A - not applicable

NS - not specified

The average and peak groundwater withdrawals specified for the proposed LNP in WUP 13262.0, issued on August 26, 2009, also conflict with the LNP Conditions of Certification (COC) issued by the State of Florida in 2011. Page 49 of those conditions state: "The Licensee may make adjustments in pumpage distribution as necessary up to 125 percent on an average basis, up to 125 percent on a peak monthly basis, so long as adverse environmental impacts do not result and other conditions of this certification are complied with. In all cases, the total average annual daily withdrawal and the total peak monthly daily withdrawal are limited to the quantities set forth above.” Neither the WUP, nor the state’s COC or even the final EIS for the proposed LNP included any detailed monitoring requirements that would be capable of detecting adverse environmental impacts from the proposed groundwater withdrawals, particularly monitoring that could detect adverse environmental impacts before those impacts became irreversible.

As a comparison, the volume of ground water permitted by SWFWMD for withdrawal from each of the proposed LNP supply wells #1 through #4 exceeds the current quantities permitted for withdrawal for the municipal supply wells for the Cedar Key Water and Sewer District and the Suwannee Water and Sewer District. Those municipal supply wells are located northwest of the proposed LNP. Therefore, the conservative quantities permitted by the WUP for withdrawals from proposed LNP supply wells #1 through #4 would be equivalent to groundwater withdrawals for four new municipalities located on and withdrawing ground water from the proposed LNP site. Additionally, the conservative quantities permitted by the WUP for withdrawals from proposed LNP supply well #5 are greater than the permitted municipal groundwater withdrawals for Horseshoe Beach Utilities and Steinhatchee Water Association, Inc. and more than half of the permitted municipal groundwater withdrawals for Taylor Beach Water System, which includes both Dekle Beach and Keaton Beach. Those municipalities are located northwest of the proposed LNP site. Table 4 includes the volume of ground water permitted for withdrawal for these municipalities, the permit issuance and expiration date and the permit numbers. All of the municipal water use permits included in Table 4 were issued by the Suwannee River Water Management District (SRWMD). The SRWMD regulates water use in the northern watershed that would be affected by the LNP, while the SWFWMD regulates water use in the southern watershed that would be affected by the proposed LNP.

All of these municipal groundwater withdrawals are from the same FAS that would supply water to the LNP, yet PEF’s groundwater models for the SWFWMD permit, the COC and the EIS did not consider effects of proposed LNP withdrawals on municipal wells or private residential wells in the zone of impact for the LNP. In fact, PEF’s groundwater models did not even include the effects of drawdown from proposed LNP supply well #5 in the north LNP parcel. That omission is tantamount to failing to consider the impact of withdrawals from municipal supply wells for Horseshoe Beach Utilities and Steinhatchee Water Association, Inc.

It is important to note that at least two different coastal communities northwest of the LNP site, Cedar Key and Taylor Beach, already have encountered saltwater contamination in the permitted municipal withdrawals referenced in Table 4, with lower withdrawal volumes than any single supply well permitted in the south parcel of the LNP site. Contamination of the municipal supply wells occurred despite the fact that some of these wells already have been relocated further inland. On June 20, 2012, Cedar Key residents were ordered not to drink tap water until further notice because of the saltwater intrusion. Both municipalities have been forced to relocate supply wells further inland or implement reverse osmosis to remove the salts, at considerable expense to the residents. Other coastal communities, Horseshoe Beach and Suwannee, already have been forced to initiate reverse osmosis because of contamination of those municipal supply wells, as did Cedar Key (David Still, former SRWMD Executive Director, LNP direct testimony dated July 6, 2012). Private residential wells immediately west of the proposed LNP project and in the combined vicinity of the proposed LNP and proposed mines also have been contaminated with salt water or have gone dry (Sydney Bacchus, LNP direct testimony dated July 6, 2012). That information and additional details from testimony related to the proposed LNP are provided at http://www.nirs.org/nukerelapse/levy/levyhome.htm

None of the proposed projects evaluated in our study involved any type of tracer study to predict the magnitude and extent of impacts on saltwater contamination of ground water and surface waters (USACE, 2012; USNRC, 2010a; 2012). The site-specific data collected at the proposed LNP site to characterize the subsurface conditions were 118 borings (USNRC, 2012), clustered in a single area where no fractures were mapped (Figure 3C). The constraints and alternatives of using borehole data and MODFLOW models that assume porous-media flow to characterize groundwater flow in karstic carbonate aquifers are addressed by Quinlan (1991), Worthington (2003) and Worthington, Smart and Ruland (2002). Using borings to characterize subsurface conditions in a karst aquifer system is similar to using pump tests in wells. Worthington (2009) emphasized that using wells to assess flow through karst aquifers is inadequate because individual wells have a very low probability (typically 0.01-0.02) of intersecting major subsurface channels. Fractures are major subsurface channels. Physical and chemical tracers are alternatives for characterizing subsurface conditions. Physical tracers include water temperature differences, such as those used in the thermal infrared evaluation in the study area by Raabe and

Bialkowska-Jelinska (2010). More common tracing agents are those added to water at specific locations in an attempt to identify discharge points and velocity. An example of such a tracer is non-toxic, water-soluble fluorescent dyes. One view is that one well-designed tracer test, properly done and correctly interpreted is worth 100 computer simulations (Quinlan, 1991).

Table 4. Groundwater use from permits issued to municipalities in the zone of impact and aquifer system for the Levy nuclear plant

Municipality	Permit Issued	Permit Expiration	Permit Number	WD Ave GPD
Cedar Key	1/17/85	1/17/95	2-84-00831	229,000
Cedar Key	5/13/03	5/13/23	2-84-00831R	302,600
Horseshoe Beach	1/16/86	1/16/01	2-85-00293	44,000
Horseshoe Beach	11/1/02	11/1/22	2-85-00293R	162,000
Steinhatchee	2/21/85	2/21/05	2-84-00851	189,000
Steinhatchee	6/14/99	6/14/09	2-84-00851M	272,000
Steinhatchee	3/26/10	3/26/30	09-0029	370,000
Suwannee	3/6/03	3/6/23	2-84-00835R	365,900
Taylor Beach	4/20/90	4/20/10	2-83-00183	77,700
Taylor Beach	9/1/95	9/1/15	2-83-00183	128,500

GPD – gallons per day (gallons x 3.79 = liters; 1 cubic meter per day = 2.64 x 10^{-4} million gallons per day (MGD))

5.3 Changes in Salinity

Saltwater intrusion not only contaminates municipal and private residential wells, it also kills native vegetation that relies on fresh water in the aquifer for survival, particularly during the annual dry seasons and periodic droughts. Native vegetation comprises the highly ranked habitat that occurs throughout the zone of impact for the LNP and mines and is illustrated in Figure 4. Reverse osmosis (RO) is not an alternative source of essential fresh water for this native vegetation and associated wildlife. In fact, continued pumping of ground water already contaminated with saltwater for municipal use following RO treatment will increase the saltwater intrusion that has been documented in the zone of impact of the LNP and mines and subsequently increase the environmental impacts associated with saltwater intrusion.

The permitted groundwater withdrawals for the proposed LNP shown in Table 3, equivalent to more than four new municipalities, alone and without any of the new cumulative impacts such as the proposed excavations on the LNP, Tarmac and Knight mine sites, would increase saltwater intrusion in an area where critical wildlife habitat already is being destroyed by saltwater intrusion. The unsustainable groundwater use and artificial reservoir water impoundment of the LNP and mines also would result in increased saltwater intrusion by increasing sea-level rise, based on the recent findings of Pokhrel et al. (2012). They calculated that approximately 42% of the observed sea-level rise between 1961 and 2003 was caused by unsustainable groundwater use, artificial reservoir water impoundment, climate-driven changes in terrestrial water storage and the loss of water from closed basins.

The thermal infrared signatures indicative of groundwater discharges identified by Raabe & Bialkowska-Jelinska (2010) are aligned along the coastal interface and near-shore areas of the Gulf of Mexico (Figure 3A). These thermal infrared signatures also form an “S” shape that coincides with the boundary between the coastal forested hammock habitat and coastal marshes (Figure 3B), suggesting that groundwater discharges play an important role in maintaining both habitats.

Several inferences can be made from the pattern of salinity ranges shown in Figure 3B and the distribution of the individual thermal infrared signatures (white triangles) shown in Figures 3A and B. First, the pattern of salinity results displayed in Figure 3B confirms that there is no linear saltwater intrusion “front” that would be indicative of a non-karst coastal terrain. Instead, the pattern reflects preferential movement of saltwater through karst groundwater flow pathways such as fractures or sinuous karst conduits in response to alterations such as excavations and mechanical pumping in the vicinity of the LNP and Tarmac and King mines. This interpretation is supported by a similar pattern of dead and declining native trees in the vicinity where salinity data were recorded. One of the natural ponds in the Gulf Hammock Wildlife Area and Tarmac mine vicinity, where saltwater contamination has killed pine trees and cabbage palms, is shown in Figure 8A. The Gulf Hammock vicinity of the proposed LNP and mines also is characterized by swallets where, during the rainy season, surface water flows rapidly into the aquifer system through these karst conduits. Impoundments of that overland flow by the LNP and mines would reduce or entirely eliminate that source of aquifer recharge and down-gradient discharge of ground water, resulting in additional increases in saltwater intrusion. Another characteristic of the karst aquifer system in the Gulf Hammock vicinity is shown in the exposed karst in Figure 8B, with dead trees and co-author J. Patrick Lines included for scale. This lack of cover in the study area is a result of erosion on the crest and flank of the Ocala Uplift (Faulkner, 1973).

Additionally, in areas where limestone was excavated, resulting in pits extending into the surficial aquifer, a larger volume of ground water is diverted into these pits, resulting in ground water permanently exposed to high evaporation rates described above. These factors result in irreversible adverse impacts to the natural hydroperiods. In these areas the water in the pits exhibited low salinity and characteristics of groundwater discharges such as the macrophytic green alga, *Chara* spp. (Figure 8C), while natural surfacewater areas in the vicinity exhibited higher salinities. *Chara* harvest the calcareous deposits in its cells from calcium carbonate contained water from the FAS. The common name for *Chara* spp. is musk-grass, because of the unpleasant, musky odor (Tarver, Rodgers, Mahler, & Lazor, 1979). The most obvious explanation for these results is that these relatively small excavations, compared to the proposed Tarmac and Knight mines, diverted fresh ground water into those pits, where that water is depleted continually via evaporation, resulting in preferential saltwater intrusion in some of the natural ponds closer to the coast.

One example of these excavated areas shown in Figure 3B as the cluster of dark blue crosses over the white triangles indicates groundwater discharges in the western area of the proposed Tarmac mine site. A second example is the cluster of dark blue triangles over the white triangles north of the Tarmac mine site and aligned on the fracture mapped by Vernon (1951, red line) that extends southeast through the sinkhole at the proposed LNP entrance, through permitted LNP supply well #2 in the southeast corner of the LNP site and through Lake Rousseau, into Citrus County. Clearly the cumulative impacts of these existing excavations into the surficial aquifer, combined with the additional impacts from proposed excavations and groundwater pumping from the LNP site and induced flow through these fractures and other karst conduits should have been evaluated by the regulatory agencies.

5.4 Environmental Impacts Due to Hydroperiod Alterations

5.4.1 Cumulative Impacts

The U.S. Clean Water Act (CWA) of 1972 (33 U.S.C. §1251 et seq.) requires an assessment of all direct, indirect and cumulative impacts of developments that would result in the discharge of material into wetlands, such as the LNP and the mines that would provide the raw materials (e.g., aggregate) for construction of the LNP. A summary of the CWA is provided at http://www.epa.gov/lawsregs/laws/cwa.html. Cumulative impacts (effects) were defined by 40 CFR § 1508.7 as “the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions.”


A
B

Figure 8. Photographs of the Gulf Hammock Wildlife Area and proposed Tarmac mine vicinity, depicting:

A. one of many natural ponds where saltwater contamination has killed pine trees and cabbage palms; B. exposed karstic limestone charateristic of the aquifer system in that vicinity, with dead trees and co-author J. Patrick Lines; C. one of many shallow mined pits with low-salinity water and macrophytic green alga, *Chara* spp., indicative of calcium carbonate groundwater discharges

The U. S. Council on Environmental Quality, Executive Office of the President published a report in January 1997 entitled, “Considering Cumulative Effects Under The National Environmental Policy Act” (Cumulative Effects Report), to address the “incremental loss of wetlands under the national permit to dredge and fill and from land subsidence.” Table 1-2 of the Cumulative Effects Report indicates that “Cumulative effects may last for many years beyond the life of the action that caused the effects..... (e.g., acid mine drainage, radioactive waste contamination, species extinctions). Cumulative effects analysis needs to apply the best science and forecasting techniques to assess potential catastrophic consequences in the future.” The following eight scenarios of accumulating effects are described in Table 1-3 of the Cumulative Effects Report to ensure sustainable development:

Type 1 frequent and repetitive effects on an environmental system (e.g., extensive destruction of forested wetlands increasing global climate disruption);

Type 2 delayed effects (e.g., collapse of karst aquifer structure, sinkholes from groundwater mining, and exposure of coastal organisms and human communities to slow-acting contaminants like endocrine disruptors from aquifer-injected effluent and other wastes);

Type 3 high spatial density of effects on an environmental system (e.g., pollution discharges into the aquifer from nonpoint sources);

Type 4 effects occurring away from the source (e.g., breached groundwater "divides" causing diversions from one watershed as a result of groundwater pumping in another watershed);

Type 5 change in landscape pattern (e.g., fragmentation of critical wildlife migration corridors);

Type 6 effects arising from multiple sources or pathways (e.g., water stress combined with salt stress from salt drift from cooling towers);

Type 7 secondary effects (e.g., any and all types of development following highway construction);

Type 8 fundamental changes in system behavior of structure (e.g., large-scale karst aquifer system changes, with historic discharges of ground water to springs, streams, wetlands, and coastal areas ceasing or reversing).

Neither the EIS analyses conducted for the LNP (USNRC, 2012) nor the EIS prepared for the Tarmac mine (USACE, 2012) considered the cumulative environmental impacts that would occur due to the fracture network through and surrounding those proposed development sites. Bacchus (2001) provided examples of cumulative adverse environmental effects of hydroperiod alterations, like those that would occur from the LNP and mines in Levy County, on marine and estuarine habitat and organisms. A brief discussion and examples of other environmental impacts are included below.

5.4.2 Premature Decline and Death of Trees and Destructive Fires from Hydroperiod Alterations

The premature decline and death of trees from chronic water stress, particularly in the southeastern coastal plain of the U.S., has been documented in the scientific literature and summarized by Bacchus et al. (2003) and Bacchus, Archibald, Britton and Haines (2005). Attributing premature decline and death of native species of trees in the southeastern coastal plain to "drought" rather than alteration of natural hydroperiods is unfounded because tree roots have access to the shallow surficial aquifer, which buffers the effects of drought in this region. Signs of premature decline and death of native species of trees from chronic water stress in this region include proliferation of Spanish moss (*Tillandsia usneoides*), fungal infections, infestations of boring beetles and root damage from destructive wildfires. In reality, both bark beetle infestations and fungal infections have been shown to occur in the absence of, or to precede destructive wildfires that further injure or destroy stem, crown, or root tissues in areas where the natural defenses of trees have been compromised by hydroperiod alterations (Bacchus, 2007; Bacchus et al., 2003; Bacchus, Archibald, Britton, & Haines, 2005). Some authors have considered bark beetle infestations (Dixon, Corneil, Wilkinson, & Foltz, 1984; McHugh, Kolb, & Wilson, 2003; Menges & Deyrup, 200l) and fungal infections (Ostrosina, Bannwart, & Roncadori, 1999; Ostronsina, Hess, Zamoch, Perry, & Jones, 1997) as responses to fire, or second-order fire effects resulting in post-fire tree decline and mortality. None of those authors, however, evaluated hydroperiod alterations as the triggering mechanism for destructive fire in their research.

5.4.3 Adverse Impacts to Endangered and Threatened Species and Other Wildlife from Hydroperiod Alterations

Hydroperiod alterations that would occur from the construction and operation of the LNP, even in the absence of the Knight sand mine and Tarmac limestone mine, would result in the destruction of the most important wildlife habitats (ranked 6 through 10, Endries, Gilbert, & Kautz, 2009) shown in Figure 4. These inevitable hydroperiod alterations also would disrupt the life cycle of frogs, which are amphibians at the base of the wildlife food chain. Frogs require surface water of specific depth, during a specific time of year, for a specific duration, to allow eggs to hatch into tadpoles and tadpoles to mature into frogs. If any of these components of the natural hydroperiod is disrupted during the period from mating to emergence of a new generation of frogs, that entire year of reproduction will be lost and higher levels of the food chain will be deprived of food (Moler & Franz, 1987) Therefore, while the lifecycles of wetland plants and animals are adapted to fluctuating water levels, if the duration, extent, or seasonality of those natural fluctuations are altered, those fluctuations can be fatal for an entire generation or all future generations of those frogs. As with the example of frogs, the reproduction and survival of other animals such as federally endangered wood storks (*Mycteria americana*) and red-cockaded woodpeckers (*Picoides borealis*), as well as plants such as the pond-cypress would not be possible if wet and dry periods did not occur during the normal seasons or last for different durations, or were more drastic than those for which the living organisms have adapted. Pond-cypress wetlands, which occur throughout the LNP and surrounding vicinity, are nesting habitat for wood storks. The active nesting colony of red-cockaded woodpeckers, proposed as an alleged mitigation site for the LNP, occurs in the southern extent of Goethe State Forest, adjacent to the LNP site and the Knight mine site. Habitat for both of these federally endangered species would be destroyed if the LNP is constructed. Red-cockaded woodpeckers require live mature pine trees for nesting and wood storks also require shallow freshwater wetlands for feeding. Both the pine trees and those freshwater wetland-feeding sites also would be destroyed if the LNP is constructed.

The LNP, even without the mines, also would result in changing freshwater vegetation to brackish water vegetation in the lower Withlacoochee River, Withlacoochee canal and near-shore coastal areas. The population of federally listed manatees in that area feed on freshwater vegetation and rely on freshwater discharges in that vicinity, which also is an established birthing and nursery area. These are only a few examples of the species listed as federally endangered, threatened or pending that would be subjected to unpermitted "taking" from the destruction of habitat if the LNP project is construction. For example, Table 2-13 in the Final EIS for the proposed LNP lists 15 federally endangered and threatened species in the "affected environment" of the LNP. That table does not include red-cockaded woodpeckers or wood storks, despite clear evidence that habitat critical for the survival and recovery of these two species would be destroyed by the adverse impacts of the LNP and associated mines, particularly from hydroperiod alterations. Additionally, a letter from the Center for Biological

Diversity dated June 15, 2012 regarding the proposed LNP and entered into the EIS record for the LNP listed an additional 28 sensitive species potentially affected by the LNP that are awaiting listing as federally endangered or threatened species. That letter also noted that the U.S. Department of the Interior (USFWS) did not concur with the findings in the Draft EIS (USNRC, 2010a) regarding federally listed species because "no on-the-ground or targeted surveys were conducted for 12 federally protected species" (http://www.nirs.org/nukerelapse/levy/levyhome.htm).

6. Conclusions

Citrus and Levy Counties included a total of 314 and 63 modern sinkholes, respectively, reported in the state's 2008 database and 76 and 88 fractures, respectively, previously reported but not digitally georectified by Vernon (1951) and FDOT (1973). Those fractures, mapped from aerial photographs and satellite imagery, respectively, encompassed eight counties and presumably reflect fractures at different scales that range in length from approximately 0.7 to 168.8 km (0.4 to 104.7 mi). Those fractures also appear to be a conservative representation of the total number of fractures that are present in the study area. One of those fractures in Citrus County and three in Levy County were determined to be faults (Vernon, 1951; Faulkner, 1973).

The proposed LNP site includes a total of nine fractures, with two of those fractures extending through the proposed Knight mine site, two extending through the proposed Tarmac mine site, four extending through the Gulf hammock Wildlife Management Area, four extending through Goethe State Forest and three extending through the red-cockaded woodpecker nesting colony proposed as a mitigation site for the proposed LNP. Those fractures also intersect other fractures that extend through the Lebanon Station mine and a fault that extends through Goethe State Forest and an approximately -1200-hectare (3,000-acre) wetland area in the state forest where a destructive wildfire burned for approximately two months in 2011. Additionally, five of those fractures extend through the Withlacoochee River, including Lake Rousseau, the Withlacoochee canal and the eastern cluster of springs identified in the canal during our study, and one of the fractures crossing the proposed LNP also intersects the existing Cemex mine. Four of those fractures are associated with the five proposed LNP supply wells, but none of the proposed LNP monitor wells is associated with the supply-well fractures.

Groundwater pumping is known to result in preferential flow through fractures and sinkholes in the FAS. No groundwater models that considered induced preferential flow through karst conduits, including through the fractures on those proposed sites and surrounding vicinity, were prepared for the proposed LNP or the proposed Tarmac and Knight mines. In fact, neither the Draft EIS nor the Final EIS for the LNP even referenced fractures (USACE, 2012; USNRC, 2010; 2012). Induced preferential flow and mining in the FAS also are known to alter natural hydroperiods, resulting in adverse environmental impacts and unsustainable use of the natural resources. Those proposed projects also would result in cumulative adverse impacts, such as increasing saltwater intrusion that already has occurred and resulted in the death of trees and natural habitat in the Gulf Hammock Wildlife Management Area, an area ranked as most important habitat by the state, by combining with the adverse impacts that already have occurred from the existing Cemex and Lebanon Station mines. Adverse cumulative environmental impacts from the proposed projects also would occur in Bend Bend Seagrasses Aquatic Preserve, Waccasassa Bay State Park, Goethe State Forest and Withlacoochee Gulf Preserve, which was purchased with state "preservation" funds under the "Florida Forever" program, as well as in other habitat currently supporting populations of federally endangered and threatened species, including but not limited to the manatee and red-cockaded woodpecker.

This study reinforces the importance of evaluating historic geospatial information on lineaments indicative of fractures and associated sinkholes that may predispose affected areas to instability and high transmissivities when planning developments such as the proposed LNP and mines because those features are known to alter natural hydroperiods and water quality critical for the survival and recovery of threatened and endangered species, other wildlife and wildlife habitat. The network of fractures, including faults, associated with the proposed LNP and associated mine sites extends throughout Levy County and into neighboring Alachua, Citrus, Dixie, Gilchrist, Hernando, Marion and Sumter Counties, intersecting the most important wildlife habitat ranked by the state. This suggests that the zone of impact due to cumulative adverse environmental impacts from the proposed project encompasses at least these counties. The presence of these lineaments requires more detailed analysis of the proposed development sites and surrounding vicinity using geophysical methods such as horizontal electrical profiles, vertical electrical soundings, tri-potential profiles, and microgravity and triple-track gravity profiles, in addition to tracer studies to determine groundwater flow pathways and velocities.

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