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PRELIMINARY EVALUATION CRITERIA IN SUPPORT OF MINIMUM FLOWS AND LEVELS FOR SANDHILL LAKES

ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Technical Memorandum

Preliminary Evaluation Criteria in Support of Minimum Flows and Levels for Sandhill Lakes

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Contents

Introduction

Background and Purpose

Water management districts in Florida are mandated to establish minimum flows and levels (MFLs) for watercourses and minimum levels for surface water bodies (Section 373.042, Florida Statutes [*FS*]). MFLs are defined as the limit below which further surface and/or groundwater withdrawals would cause significant harm to the water resources and ecology of the area (Sections 373.042(1)(a) and (b), *FS*). In establishing MFLs, the water management districts provide for protection of nonconsumptive uses, including navigation, recreation, fish and wildlife habitat, and other natural resource values (Rule 62-40.473, Florida Administrative Code [*F.A.C.*]), and identify hydrologic conditions above which water is available for reasonable-beneficial uses (Section 373.019, *FS*).

Sandhill lakes often exhibit widely fluctuating water levels and may not demonstrate many of the histosol soils in large fringing wetlands used by SJRWMD to determine lake minimum levels. Relatively little is known about the hydrologic controls of sandhill lakes, and permanent lowering of water levels due to consumptive use could have unknown and harmful consequences. Sandhill lakes are typically sinkhole features in sandy landscapes that contain deep sandy soils. The Florida Natural Areas Inventory and the Florida Department of Natural Resources (FNAI and DNR 1990) describe sandhill lakes as shallow, rounded solution depressions found in sandy upland communities. The open water tends to be permanent, but levels may fluctuate dramatically with complete drying during extreme drought possible. Typically, these lakes are lentic with no significant surface inflows or outflows. The substrate is primarily sand with organic deposits that may increase with depth. In general, the water is clear, circumneutral to slightly acidic, and moderately soft, with a variable mineral content. These lakes are seldom eutrophic unless artificially fertilized through human activity (FNAI and DNR 1990).

The project's objectives are to develop a conceptual water resources model of sandhill lakes and based on this model:

- Identify significant water resource, environmental, and socioeconomic values of sandhill lakes.
- Evaluate whether the water resource, environmental, and socioeconomic values can be defined sufficiently to develop criteria under the relevant rules (40C-8 and 62-40, *F.A.C.).*

Criteria-Based Environmental and Socioeconomic Values for MFLs

Under Section 373.042, *FS*, the St. John's River Water Management District (SJRWMD) is required to use the best available information and methods to set minimum flows or levels to prevent significant harm to a given water resource and its dependent ecological system. In doing this, SJRWMD provides for the protection of nonconsumptive uses, including navigation, recreation, fish and wildlife habitat, and other natural resources. These and other nonconsumptive values are also recognized in a related rule (62-40.473, *F.A.C.)*, which states that in establishing MFLs consideration shall be given to protection of water resources, natural seasonal fluctuations in water flows or levels, and environmental values associated with coastal, estuarine, aquatic, and wetlands ecology. Rule 62-40.473 (1), *F.A.C.*, lists 10 water resource, environmental, or socioeconomic values to be considered for the relevant ecological system:

- Recreation in and on the water
- Fish and wildlife habitats and fish passage
- Estuarine resources
- Transfer of detrital material
- Maintenance of freshwater storage and supply
- Aesthetic and scenic attributes
- Filtration and absorption of nutrients and other pollutants
- Sediment loads
- Water quality
- Navigation

Of the 10 values, 8 are relevant to sandhill lakes. Navigation and estuarine resources are not relevant to sandhill lakes.

Methodolgy

This Technical Memorandum (TM) presents the results of a review of the scientific literature on sandhill lakes, and constructs a conceptual model of a typical sandhill lake ecosystem. The natural resource values of sandhill lakes were considered from an ecological and human-use perspective.

The conceptual model integrates hydrogeology and the living system with essential ecosystem processes. The model is based on well known ecological paradigms to explain the roles that fluctuating water levels play in sustaining healthy sandhill lake systems. It focuses on ecological values of periodic hydrologic fluctuation that should be protected under District MFLs rules. The water resource economics literature will be reviewed to quantify the importance that humans place on key aspects of sandhill lakes and lake water-level fluctuations. The development of this methodology was based on consideration of the following:

- The relationship of environmental and socioeconomic values provided by the sandhill lake system to different points in the water level fluctuation regime.

- Relevant criteria in Rules 40C-8 and 62-40, *F.A.C.*, and linkages between those criteria and key structural and functional values of sandhill lakes will be identified.

- Geology and hydrology of these lakes are presented together, because they are closely related and form the basis for the peculiar nature of these systems.

- As they do in nature, the limnology and ecology follow the hydrogeology of these lakes.

- Key characteristics of sandhill lakes are related to available resource economics research in order to assess the effects that these characteristics may have on the value placed on these systems by humans.

Characteristics of Sandhill Lakes

This section presents a summary of the scientific literature from several disciplines of study in order to elucidate the principal geological, hydrological, limnological, ecological, and biological characteristics of sandhill lakes. These characteristics are used to develop a description of a "typical" sandhill lake. In most cases, the description should provide sufficient information to differentiate sandhill lakes from other types of Florida lakes.

The terms "sandhill lakes" and "sandhill lakes regions" are not well defined in the literature. Different classification schemes provide different definitions (Berner and Pescador 1988, FNAI and FDNR 1990, Burgess and Walsh 1991, Frydenborg 1991, and EPA 1997, summarized in EPA 1997). SJRWMD has recently grouped lakes within their borders using a tree classification scheme (Mace 1999). For the purposes of this document the definitions offered in the Florida Natural Areas Inventory (FNAI) and Florida Department of Natural Resources (FDNR) (1990) are used. They defined "clastic upland lakes" and "sandhill upland lakes" within the ecoregions generally understood as sandhills. Clastic lakes are those with clay or organic substrates that retard vertical seepage, because they maintain water more consistently than do sandhill upland lakes, which may be found nearby. Kindinger et al. (1999) provides the geologic basis for upland clastic and sandhill lakes. A hydro-geologic characterization is used as the foundation for constructing hydrologic and ecologic characterization of sandhill lakes.

Geologic and Hydrologic Characteristics

Hydrogeology

The geology and hydrology of Florida sandhill lakes has been intensively investigated over the last 10 years. The U.S. Geological Survey (USGS), SJRWMD, and others have conducted research to characterize geologic conditions and groundwater hydrology of sandhill and seepage lakes, meaning those lakes without surficial inflows or outflows. As a result of this research, a considerable bibliography has been developed. The work has included investigations along the ridge of Florida from Lake Annie, near Sebring, to the sandhill lakes in Baker and Clay counties, as well as some in the Florida panhandle. The panhandle sandhill lakes region was not considered part of the work presented here because sandhill lakes in that region possess somewhat different limnological properties than those in the SJRWMD.

The specific geologic conditions that create a seepage lake can be generally defined, but the geology of each lake creates specific circumstances that influence the hydrologic behavior of that lake system. Seepage has a specific geologic meaning. Sandhill lakes may be seepage lakes, but not all seepage lakes are sandhill lakes.

Kindinger et al. (1999) summarized lake formation and characterization of lakes in north-central Florida recognizing nine geological structures that develop sinkholes as a result of chemical dissolution of limestone and associated mechanical processes. These structures were identified through seismic profiles near and within 33 lakes in the region. Three lake types were defined as progressive phases of sinkhole lake formation:

- **Young**–The active subsidence and collapse phase defines a young sinkhole lake. Young lakes are characterized by steep sides that gradually become shallower as the sinkhole plugs with surficial (sand) sediments. During this stage the plug may be flushed and active subsidence may occur repeatedly. The lake area expands as sediments slump from the sides to fill the hole or holes.

- **Middle Age**–Transitional-phase (or middle-aged) lakes develop from the young lakes as the sinkhole plug becomes permanent and the lake develops a flatter and shallower bottom. The plug may also flush during this period, but the sediment gradually accumulates at a greater rate than the dissolution of the underlying limestone.
- **Mature**–The base-level phase (or mature lakes) occurs once the plug stabilizes and the lake becomes shallower. Continued erosion of material will eventually fill the basin if no reactivation of the sinkhole occurs.

A fourth lake type in the region, a polje, was also defined. A polje (drowned prairie) is another less-common type of lake formed when a rising groundwater table floods a lowland or depression. The lake floor is cut entirely across karst rock (sometimes covered with unconsolidated sediments) but is within the epiphreatic zone (that area just below the typical water level). Poljes are inundated at high stages of the groundwater table. These lakes may contain a variety of sinkhole lake types. Orange Lake in Marion and Alachua counties is an example of a polje. Polje lakes will not be considered further in this evaluation of sandhill lakes because they typically develop and sustain biological communities typical of lakes with more stable elevations, such as cypress fringes, areas of extensive organic soils, and wetland communities.

As a lake enters the young phase and the sinkhole is plugged, the lake bottom develops an organic layer that also reduces vertical seepage (Swancar et al. 2000, also see Lee and Swancar 1997, who report that bottom sediments may not reduce vertical leakage from Lake Lucerne). The water level fluctuates less widely and the lake gradually fills unless additional sinkholes develop.

In broad geologic terms, Florida "sandhill lakes" have the following characteristics:

- They exist within a karst landscape (Jennings 1985).
- They are usually terminal systems (that is, with little or no inflow or outflow) (Palmer 1984).
- Their formation is solution- or sinkhole-based (Kindinger et al. 1999).
- Karst overburden consists of deep marine sands (Kindinger et al. 1999).
- An incomplete confining layer or lack of a confining layer is typical (Kindinger et al. 1999).
- The Upper Floridan aquifer system (UFAS) potentiometric surface is below the ground surface (Kindinger et al. 1999).
- The lakes are within aquifer recharge areas. Lakes within aquifer recharge areas generally fluctuate more than those in discharge areas and the leakage rate from the lake generally increases with increasing soil permeability (Hughes 1974).

Of the criteria listed above, the first three offer little in the way of distinguishing between sandhill lakes and other Florida lakes. Almost all of the lakes in Florida meet the first general criterion because Florida is underlain with limestone. Approximately 70 percent of the lakes in Florida are without inflow or outflow (Brenner et al. 1990). Lakes formed by solution, or sinkhole collapse, occur in many geologic subregions of Florida's karst area. The presence of deep marine sand overburden, combined with a discontinuous, patchy, or absent confining layer underlying the surficial aquifer, and a UFAS potentiometric surface elevation below ground level, are conditions for recharge areas. The UFAS does not influence the water level of a seepage lake, but may influence vertical outflow from the lake. Vertical outflow is controlled by the head difference between the lake surface and deeper aquifers, and by the physical characteristics of the sublake geology (Sacks et al. 1998). Water elevations fluctuate widely in sandhill lakes because of the seasonal and climatic dynamics of the interplay between surficial aquifer system (SAS) levels, seepage inflows and outflows, and rainfall amounts and distribution (Metz and Sacks 2002). Water levels can also be strongly influenced by human activities such as groundwater withdrawals and altering surface water flow patterns.

McDiffit (1980) provided a relatively clear description of the physical conditions and general hydrological characteristics of the Lake Wales Ridge seepage lakes, summarized as follows:

- Relatively small, typically not in the top 1,000 Florida lakes in size
- Shallow with one or more deep zones reflecting old limestone collapse
- Filled in with sand sediments
- Thin layers of organic sediments in deep areas of the lake
- Large, sandy littoral zones
- Round to irregular in shape
- Often isolated or connected to other lakes only during high lake stages or periods of heavy rainfall
- Generally not sources of perennial streams

The FNAI defines two distinct lake types in upland sand ridge areas—"upland clastic lakes" and "upland sandhill lakes." More detailed descriptions of these lakes follow:

- **Upland Clastic Lakes**: irregular-shaped depressions or basins found in uplands. The substrates are generally clay with some organics. The water is circumneutral to slightly acidic and soft, with a low mineral content. These bodies of water are lentic without significant surficial outflows. Water is usually dissipated through evaporation and transpiration and, sometimes, through direct leakance to deeper aquifers.
- **Upland Sandhill Lakes**: shallow, rounded solution depressions found in sandy upland communities. The open water tends to be permanent, but levels may fluctuate dramatically with complete drying during extreme drought. These lakes are lentic with no significant surface inflows or outflows. The substrate is sand with organic deposits that increase with water depth. The water is clear, circumneutral to slightly acidic, and moderately soft, with a variable mineral content. These lakes are seldom eutrophic unless artificially fertilized through human activity (FNAI and FDNR 1990).

The primary difference between the two lake types is the presence of clayey substrates in the clastic lakes and its general absence in sandhill lakes. The clay layer reduces seepage losses from clastic lakes, resulting in more stable water levels.

If McDiffit's list of characteristics is slightly modified to include those of Kindinger et al. (1999), adding the presence of an incomplete or absent clay layer *in and under the lake bottom,* a geologic description of a sandhill lake emerges as follows:

- Florida sandhill lakes exist in the uplands of Florida's karst landscape. They exist within an overburden of deep marine sand surficial sediments, where an incomplete, or absent, confining layer is typical (Kindinger et al. 1999). Of particular importance is the lack of a confining (clay) layer in or under the lake bottom.
- The UFAS potentiometric surface is below the ground surface (Kindinger et al. 1999) around sandhill lakes and the lakes are within aquifer recharge areas. Lakes within aquifer recharge areas generally have water levels that fluctuate more than those in discharge areas and the seepage rate from the lake generally increases with increasing soil permeability (Hughes 1974).
- Geologically, sandhill lake formation is by sinkhole formation (Kindinger et al. 1999) with the sinkhole formations filling in with the sand overburden. They tend to be shallow with one or more deep zones reflecting locations of old limestone collapse.
- Sandhill lakes can be characterized as round to irregular in shape with large, sandy littoral zones.
- Sandhill lakes are usually terminal systems, with little or no surface water inflow or outflow (i.e., they are seepage lakes) (Palmer 1984). Sandhill lakes are most often isolated or connected to other lakes only during high lake stages or periods of heavy rainfall. They are not generally sources of perennial streams.
- Sandhill lakes tend to be relatively small.
- Typically, thin layers of organic sediments are found in deep areas of a sandhill lake.

Sandhill lakes exhibit large water-level fluctuations on a multi-decadal time scale(Robert Epting, personal communication 2004). Many, however, in the same geologic region and local area may have relatively stable water levels over shorter time scales (Robison 1992). This difference is a function of the stability of water inputs to the lakes. Sandhill lakes are thus of particular interest and pose a greater challenge in setting a minimum-level regime.

Hydrology

Investigations of sandhill seepage lakes in the upland sand ridge of north-central Florida have shown that the hydrologic budget of seepage lakes is dominated not by the inflows to and outflows from the surficial aquifer and aquifer elevation, but rather by the surficial aquifer system levels, which were correlated to annual cumulative rainfall (Sacks et al. 1998). Monthly seepage outflow is relatively consistent, while monthly groundwater inflow may vary by more than 100 percent (Grubs 1995 and Lee 1996). Lakes with a permanent outflow stream tend to have more positive net groundwater flow than seepage lakes because the source of the water in the stream is, in large part, groundwater. These lakes also typically display less stage fluctuation because surface water outflow moderates stage changes (Sacks et al. 1998). Sandhill lakes are not generally sources of perennial streams because the discharge depends on rainfall elevating lake levels to the point where positive net groundwater flow to the lake from direct rainfall overcomes vertical and horizontal groundwater seepage losses from the lake.

Rainfall, surficial aquifer levels, and site-specific geology control the hydrology of sandhill lakes. Sacks et al. (1998) list a number of factors that affect lateral and vertical groundwater flow for a particular lake, including recharge, artificial lowering of lake stage, pumping stresses from the deeper UFAS, and physical features such as lake depth, basin steepness, thickness of lake sediments and degree of confinement between the lake and the UFAS. Lateral groundwater outflow can be induced if a lake is at an artificially high level from augmentation or intense rainfall events (Stewart and Hughes 1974, and Belanger and Kirkner 1994). Sacks et al. (1998) also concluded that for a set of study lakes in the Lake Wales ridge:

> "…the deeper aquifer never contributes ground-water inflow to the study lakes, but it does influence vertical ground-water outflow. In contrast to lateral ground-water outflow described in the preceding section, this vertical outflow is controlled by the head difference between the lake and the deeper aquifer and by the physical characteristics of the sublake geology."

Deevey (1988) evaluated 16 lakes (including some sandhill lakes). These lakes responded with little or no lag period to wet and dry months, implying immediate responses to rainfall. Net precipitation accounted for 34 to 62 percent of the variance in lake water levels.

Pedology

Hydric soil characteristics are markers of persistent inundation and, when evaluated at lake's edge, may provide a record of inundation patterns over time. One way to judge the importance of fluctuating water levels in these systems is to study the development of hydric soil indicators within the shoreline elevation range in upland sandhill lakes. Cyclic hydrologic fluctuations that have a consistent range should result in the development of fringe wetlands (both in time and space) and identifiable soil characteristics within specific elevations of a lake's hydrologic range. Conversely, irregular hydrologic fluctuations should result in the absence of, or randomly located development of, fringe wetlands along the range of water-level fluctuations. This would result in inconsistent hydric soil characteristics, or the complete lack of hydric features.

Vepraskas (2001) has reviewed the literature on morphological features of seasonally reduced soils and focused on features that develop as a result of reducing O_2, Mn^{+4}, Fe^{3+}, and SO_4^{3-}. His findings included consideration of chemical, hydrologic, and temporal issues in the development of hydric soil characteristics, and are summarized as follows:

- Redoximorphic features can develop rapidly (within days to weeks). Hydric soil features developed from iron and manganese may develop in any case in less than 3 years under reducing conditions. Important factors in the development and persistence of these hydric features include the length of time the site is inundated, percent of organic matter in the soil, availability of iron and manganese, and temperature during development of the horizon.

- Development of these horizons is site specific.
- Location in the landscape is an important consideration when identifying hydric soil indicators, particularly in soils that are poor in iron and manganese.
- Remnant features of these horizons may persist for up to 30 years as relicts after the generating conditions have been eliminated. Hydrologic information is necessary to confirm the cause of the development of these relict features.
- Hydrologic models that simulate water-table changes have been used to demonstrate that rare (e.g., 1 in 20-year) inundation events are likely not preserved in the soil record.
- Inundation of the soil, rather than saturation, leads to redox depletions.
- Soils with very low or no iron-bearing minerals may produce false features with the appearance of reduced conditions. Landscape position and hydrologic regime must be carefully considered in these situations.

These findings suggest that while interpretation of soil features found at the edges of sandhill lakes may require considerable expert analysis (Hurt and Carlisle 2001) the effort should produce valuable results. If there are sufficient hydrologic records, investigation of soil characteristics that develop within the range of lake-level fluctuation can be related to the hydrologic fluctuations and their regularity. Lake-level fluctuation patterns that maintain the upland sandhill aquatic ecosystem can be inferred from these data. It may, in some cases, also be possible to differentiate baseflow characteristics of the lake edge (Hurt and Carlisle 2001).

The cycle of fluctuations is shorter than 20 years for some lakes but longer than that for others based on inspection of published sandhill lake hydrologic records (such as, Annable et al. 1996, and Merritt 2001). It then seems logical, following the Vepraskas conclusions concerning the period of time necessary to create soil horizons, that the fluctuations will leave a record in the soil. Those soil features should be useful in evaluating sandhill lake water-level fluctuations, and also for setting sandhill lake MFL elevations. The elevation of hydric soil features on lakes with reasonably long hydrologic records may provide support for minimum frequent high, minimum frequent low, and, possibly, other levels on these lakes. Hydric soil characteristics of historic hydrology in sandhill lakes are currently being investigated by Debra Segal (Jones Edmonds & Associates [JEA]) and G. Wade Hurt (U.S. Department of Agriculture Natural Resources Conservation Service [NRCS]) under contract to SJRWMD (Sonny Hall, personal communication 2002). Florida sandy soil hydric indicators are defined most currently in Segal et al. (1995). Based on interim results provided by Segal and Hurt to SJRWMD, they are characterizing the hydric soil indicators along shoreline elevation gradients in a number of sandhill lakes within SJRWMD. The elevations or range of elevations of the hydric soil indicators will be related to long-term water level exceedence calculations from lake elevation records, or hydrologic models.

Limnological Characteristics

While specific upland lakes in Florida have not typically been characterized as "upland sandhill" using the definitions of upland clastic lakes and upland sandhill lakes presented previously in this document, a considerable amount of information is available on upland seepage lakes. There is sufficient information on these lakes to know that clastic and sandhill lakes often share general limnological characteristics, and the literature for lakes in ridge areas of Florida is treated in this way. Reevaluation of the data for specific lakes after clear distinctions are made between clastic and sandhill sites may provide distinctions not currently apparent. The literature was reviewed for general limnological characteristics so it is likely that data from both types of lakes are presented in this document to demonstrate sandhill lake characteristics.

Upland sandhill lakes are naturally acidic given their low base cation concentrations and low acid-neutralizing capacity in water from the surficial aquifer system (Shannon and Brezonik 1972, Canfield 1983, Brenner et al.1990, and Pollman and Canfield 1991). The lakes, in pristine study areas (e.g. Lake Annie and Saddle Blanket Lake in Highland County, Florida) have the lowest pH values (less than 6). In terms of dissolved minerals, these lakes are dilute (specific conductance generally less than 100 µhos/cm) and dominated by sodium and chloride ions. Calcium and sulfate concentrations are depleted relative to atmospheric deposition (Sacks et al. 1998). The causes for this depletion are not discussed, but it is reasonable to conclude that passage through the living community and associated soils is responsible. It is also noted that, in developed watersheds, the pH is elevated above 7 and the concentration of some major ions and nutrients, particularly nitrate nitrogen, increases above background (pristine) conditions. Other studies report similar results from citrus-growing areas.

Sweets (1992) characterized oligotrophic seepage lakes as neutral to slightly acid pH. He attributed part of the acidification of the lakes he studied to acid rain. Naturally poor buffering capacity in these lakes may contribute to the degree of human-induced acidification of about 0.2 to 0.5 pH units. He also hypothesized that "clear water lakes are more susceptible than colored lakes due to buffering potential of organic acids."

In a study of groundwater and lakewater interactions in the Lake Wales Ridge area, Sacks et al. (1998) found that major-ion concentrations in groundwater typically varied both temporally and spatially within a lake basin. In undeveloped lake basins, spatial and temporal variability were similar. However, in the other (more developed) lake basins, spatial variability was always more than twice that of the temporal variability, and solute concentrations could vary spatially by more than 100 percent in a given lake basin. In these same lakes, chlorophyll *a* and primary productivity were correlated to anthropogenic nutrient enrichment (McDiffit 1980).

Chemical constituents entering the lake may be concentrated by evaporation and long residence times (nominally 3 to 6 years) (Brenner et al. 1990, p. 372). A long residence time may result in sensitivity to nutrient loading. However, these authors did not consider the effect of widely fluctuating water levels on average residence time. Actual residence times are difficult to estimate because of the fluctuations in water levels and the strong influence of SAS groundwater in the water budget, both in inflow and outflow terms of the water budget (Brenner et al. 1990).

Sandhill lakes are typically shallow and are assumed to be well mixed. A few deeper lakes such as Lake Annie or Sandhill (Lowry Lake, Clay County) may temporarily or seasonally develop stratification.

Dominant sources for chemical constituents in the water are directly related to the hydrologic budget. The surficial aquifer system and rainfall provide the majority of the chemical constituents (including nutrients) and groundwater flow is the primary outflow path. Relatively small amounts of carbon, minerals, and nutrients may be bound in the surficial sediments and build up over time into a gytta that is present in the deeper, less frequently exposed portions of the lake bed (Kindinger et al. 1999). Gytta is a Swedish word, pronounced "yut-tya." It is defined as nutrient-rich lake sediment consisting mainly of plankton, other plant and animal residues, and mineral mud. Organic matter content is less than 50 percent and carbon-to-nitrogen (C/N) ratio is near or below 10 percent (Wetzel 1983). It is deposited in water as fine particles. Examples of north-central Florida sandhill lake sediments that fit this description are provided in Flannery et al. (1982).

Biology and Ecology

Clastic and sandhill upland lakes have characteristic biological features that can be generally used to distinguish them from other types of lakes. The definition of the expected communities found in FNAI and FDNR (1990) distinguishes the sandhill upland lakes as generally without trees and larger shrubs that inhabit the edges of the more stable clastic upland lakes (FNAI and FDNR 1990 and http://www.ordway.ufl.edu/communities.htm) as follows:

- **Upland Sandhill Lakes:** shallow, rounded solution depressions found in sandy upland communities. The open water tends to be permanent, but levels may fluctuate dramatically with complete drying during extreme drought. These lakes are lentic with no significant surface inflows or outflows. The substrate is sand with organic deposits that increase with depth. The water is clear, circumneutral to slightly acidic, and moderately soft with a variable mineral content. These lakes are seldom eutrophic unless artificially fertilized through human activity. Vegetation can vary from a narrow band along the shore, to broad bands of emergent, submerged, and floating plants. These plants include panicums (*Panicum* spp.), rushes, sawgrass *(Cladium jamaicense),* pickerelweed (*Pontederia cordata*), arrowheads (*Sagittaria* spp.), yellow-eyed grass (*Xyris* spp.), and sundews (*Drosera* spp.). Upland Sandhill Lakes are often extremely important breeding areas for terrestrial amphibians like the gopher frog *(Rana capitoaesopus).* The lakes are frequently significant recharge areas to the Floridan aquifer and chemical pollution can have serious effects. Water pollution is particularly harmful to these lakes because of their lentic trait. The lakes are also vulnerable to hydrologic manipulations, especially those affecting water tables.

- **Upland Clastic Lake:** irregular-shaped depressions or basins found in uplands. The substrates are generally clay with some organics. The water is circumneutral to slightly acidic and soft, with a low mineral content. These bodies of water are lentic without significant surficial outflows. Water is usually dissipated through evaporation and transpiration, and sometimes through direct connections to deeper aquifers. The vegetation of Upland Clastic Lakes varies. Shorelines may be dominated by herbaceous vegetation, such as grasses (Poaceae), sedges (Cyperaceae), and rushes (Juncaceae); shrubs like buttonbush (*Cephalanthus occidentalis*), wax myrtle (*Myrica cerifera*), Virginia willow *(Itea virginica),* and elderberry *(Sambucus canadense);* or hydrophytic trees such as bald and pond cypress (*Taxodium distichum* and *T. ascendens*), red maple *(Acer rubrum),* water oak *(Quercus nigra),* and laurel oak *(Quercus hemisphaerica).* Shallow water zones usually are densely vegetated by concentric bands that include spatterdock *(Nuphar* spp.), pickerelweed, and arrowheads (FNAI and FDNR, 1990). Typical fauna include the Florida gar *(Lepisosteus platyrhincus),* yellow bullhead *(Ictalurus natalis),* pirate perch *(Aphredoderus sayanus),* newts (*Notophthalmus* spp.), the pig frog (*Rana grylio*), cricket frog *(Acris gryllus),* mud turtle (*Kinosternon* spp.), stinkpot *(Sternotherus odoratus),* alligator *(Alligator mississippiensis),* banded watersnake *(Nerodia fasciata),* white ibis *(Eudocimus albus),* herons (*Egretta* spp.), beaver *(Castor canadensis),* and river otter *(Lutra canadensis).*

Sandhill lakes are distinguished by a lack of obligate and facultative woody wetland species, particularly cypress, at the lake fringe, and relatively depauperate plant and animal communities, most likely a result of the "dramatic fluctuations" in water levels that select among the community members for those best adapted to these hydrologic fluctuations, and those that can most rapidly recolonize under the appropriate conditions.

Sandhill lake plant communities are composed of species typically found in oligotrophic, relatively low pH waters (Hoyer et al. 1996). These species typically decrease in abundance as a response to human-induced disturbance, particularly nutrient enrichment (Rochow 1994, Doherty et al. 2000).

The plant community serves as an important habitat for prey species (Osborne et al. 1976), as well as being an important component of the nutrient cycle in these lakes. Nutrient limitation appears to control algal density and composition (Whitmore 1989, Binford et al. 1987, Glooschenko and Alvis 1973). Macrophytes are an important component of biomass and productivity for the lake and are believed to compete with microalgae for nutrients (Brenner et al. 1990, Canfield et al. 1983a, and Fontaine and Ewel 1981). Macrophytes also play a role in nutrient cycling, because they extract nutrients from the sediment, much of which gets released to the water column either by leakage from the plant or by decomposition when plant parts senesce (Ewel and Fontaine 1983), and thus may contribute to the maintenance of the biological community.

Free-floating vegetation is uncommon in sandhill lakes. Common macrophytes include *Juncus scripoides, Leersia hexandra*, bladderworts *(Utricularia cornuta* and *U. resupinata)*, red root (*Lachnanthes carolianum*), *Xyris jupicai*, and *Eriocaulon lineare.* Macrophyte species composition includes few submerged species, and the species tend to be adapted to poorly buffered water, with low nutrient concentrations (Garren 1982).

Phytoplankton and zoooplankton communities of lakes in the Upper Etonia Creek basin, the Ocala National Forest, and the Lake Wales Ridge have been investigated repeatedly, either in synoptic studies, evaluations of lake chains, or single lake studies within one or more geographic areas. Zooplankton communities were found to have high diversity and low abundance in oligotrophic lakes— dominated by rotifers and small cladocerans (Billets and Osborne 1985). Battoe (1985) characterized the phytoplankton of Lake Annie as dominated by small green algae (chlorophytes) and dinoflagellates. He indicated that this was typical in the Lake Wales Ridge lakes that were not eutrophied.

Total zooplankton biomass has been found to be positively correlated to trophic state (Bays and Crisman 1983) and larger animals were replaced by smaller animals in more eutrophic systems (Beaver and Crisman 1982).

Relatively low fish standing stocks have been found in Florida oligotrophic lakes (Bachmann et al. 1996). The fish communities are dominated by centrarchids (bluegill, warmouth, and largemouth bass). In fish assemblages, the number of species is most strongly correlated to lake isolation (degree of connectedness) (Jennings 1990) and the stability of water levels.

A Conceptual Model of Sandhill Lakes: Astatic Behavior and Ecosystem Stability and Resilience

While two types of upland lakes were identified previously, only the clastic upland lake fits the concept of a typical lake ecosystem. Upland sandhill lakes have a more complex relationship to the surrounding uplands because of their unique hydrology. While there has been considerable research effort devoted to the geology, limnology, population, and community aspects of sandhill lake ecosystems, there is little research connecting the surface water body to the surrounding landscape across the hydrologic cycle of these lakes. The following discussion, therefore, draws together the current research discussed previously and proposes a description of the sandhill lake ecosystem that emphasizes the interaction between the upland and aquatic systems that results in the maintenance of these oligotrophic lakes.

Sandhill upland lakes are *astatic*, because they appear to lack a mean around which the system is organized. Rather than considering the mean water elevation as an organizing condition, critical system behaviors of sandhill lakes may be related most strongly to high and low water levels corresponding to drought cycles and multidecadal climate cycles. Both high and low water conditions are necessary to maintain expected ecosystem structure and functions.

Pulses in natural forces such as sunlight, rainfall, and hydroperiod fluctuation control ecosystem structure and function. Those pulses maximize energy flows and biological productivity within the ecosystem (Hall 1995, Odum 1983). The productivity pulse concept is also a widely applied organizing principle in aquatic ecology. Current views of productivity and species composition of riverine ecosystems are based on three theories: the river continuum concept (RCC), the flood pulse concept (FPC), and the riverine productivity model (RPM). These models differ mainly in the role of different forms of organic matter as food sources. The RCC emphasizes the importance of fine particulate organic matter derived from upstream processing (Sedell et al. 1989). Leaf litter accumulation on the floodplain floor later enters the system during periods of high water and provides a key food source in the FPC (Junk et al. 1989). The RPM suggests that instream production and direct input from riparian vegetation are the most important food sources to large rivers (Thorp and Delong 1994).

Middleton (1999) reviewed and summarized the research related to disturbance or pulses and its importance to many wetland systems, concluding that the research demonstrates that both individual species and community dynamics can be organized around disturbance or pulses. Declines in growth and productivity can be related to elimination or alteration of the disturbance or pulse cycle. The importance of fully understanding the influence of these pulses on sandhill lake ecosystem characteristics and persistence cannot be overstated. Hobbs and Norton (1996) noted that a lack of consideration regarding spatial and temporal variability has been cited as a reason for failure of many restoration efforts. Similarly, a lack of consideration for temporal and spatial variability of sandhill lakes limits management options for these unique ecosystems.

Like many ecological systems, sandhill lakes are organized through hydrologic regimes, albeit of rather longer duration than usually considered for wetland systems. Maintenance of the hydrologic disturbances that characterize sandhill lakes may be a prerequisite for the long-term health and persistence of these unique systems. This concept has not been researched. The typical hydrologic analyses (such as hydrologic exceedences for the lake stage record) do not focus on all aspects of the record that are important in this regard. Raw lake-level fluctuation records (Robison 1992, Merritt, 2001) hint that different statistical summaries, particularly frequency, as well as time-series analysis, may characterize the hydrologic conditions in ways that will provide additional understanding of the hydrologic drivers of the lake ecosystem cycle. The existing ecological research on these lakes has not tested this hypothesis, that is, approaching these systems as static systems organized around a mean.

As with riverine systems, pulse hydrology drives the productivity of sandhill lakes. Water-level fluctuations in sandhill lakes induce pulsed changes in connectivity to surrounding landscape, biological production, community growth and senescence, community structure, habitat condition, biogeochemical cycling, and resource availability. A significant portion of the biological productivity in these lakes may occur within the zone of water-level fluctuation. The zone may also provide the significant habitat and protection for fish during critical life stages. More broadly, the functional "value" of water-level fluctuation may be as a mechanism for biogeochemical cycling and energy processing of organic matter and other materials within the lake system. The materials-processing function is likely related to the habitat and species diversity within the lakes.

This pulsing hydrologic regime concept parallels the major theories describing the structure and function of riverine systems. In the case of riverine systems the structural characteristics of the floodplain, such as levees, channels, hydric soils, and lichen lines, can provide the ecological benchmarks upon which to set minimum levels to protect critical functions. This is, in fact, the approach SJRWMD used to set the MFLs for the St. John's River at SR44 (Mace 2005 draft) and the Wekiva River (Hupalo et al. 1994).

A conceptual ecological model for sandhill lakes highlights the role that a given structure or function plays in sustaining the health and productivity of the lake ecosystem. Once these roles are identified and described, the ecosystem features that must be protected from harm are also revealed. The model suggests that the seasonally and climatically pulsing water levels control energy flow and transfers, nutrient cycling, primary and secondary productivity, habitat and species diversity, and many other environmental values. For example, seasonal and climatic lake level fluxes results in:

- Encroachment and die-back of upland and emergent wetland vegetation that provides energy source and organic matter input and a more diverse habitat structure for aquatic and wetland food chains
- Productivity pulse where the flux converts plant biomass to animal biomass (e.g., fish)
- Drawdown-flood sequence stimulating fish production
- Changing physical and biological conditions that alter the nature of the organic matter inputs (for example, as water levels drop, primary production becomes more terrestrial)

- A diversity of habitats created by fluctuating water levels, which, in turn, may support higher biological diversity.

High Water Ecosystem Processes

Under high water conditions in sandhill lakes the following can occur:

- Surface discharge and connectivity can occur when lake surface area increases at high water levels. In some cases, adjacent lake systems become connected; in other cases, a surface water outflow is created. Benefits accrue to recreation, navigation, species dispersal, etc.
- Aquifer recharge may occur. Periodic high lake levels are important to recharge the SAS and increase the overall water availability within the local landscape for recharge to the Floridan aquifer.
- An increase in water volume leads to dilution of dissolved and suspended constituents in the water column.
- With the lake's surface area at a maximum, the zone of aquatic energy and material capture is greatest.
- Nutrient cycling adjusts to wetland and aquatic conditions, and the expanded lake surface can capture both autochthonous (internal) and allochthonous (external) inputs.
- A biological productivity pulse may occur in both primary and secondary production.
- Conditions in soils may be reduced because of low dissolved oxygen, which plays a role in nutrient cycling.
- Reduced conditions also contribute to maintenance of hydric soils.
- Size and volume of available habitat may increase along with an increase in habitat and species diversity.
- The upland support function can create breeding islands for wading birds; may transport seed and organic matter upslope; and may raise the surficial water table in the adjacent uplands.
- A change in zonation of plant communities may occur when higher water levels eliminate encroachment by upland species and may submerge and kill upland vegetation that had become established during low water conditions; regeneration of wetland and aquatic vegetation is also expected as water levels rise.
- Expansion of wetland and aquatic vegetation may increase the aerial extent of zones or the diversity of zones by adding a zone.
- There may be a greater dispersal ability of vertebrate and invertebrate fauna.
- The reproductive cycle may be triggered in plants and animals, especially for some fish species.

Rapid water level rise results in submergence of wetland plants in the littoral zone of the low water lake, and submergence and die-back of upland plants that colonized the drained and exposed areas of the lake. The living and dead organic material in the formerly exposed portions of the lakebed become the energy source for primary and secondary production in littoral and aquatic habitat areas.

Upland vegetation that developed during the previous low water conditions decays rapidly in the new aquatic conditions, releasing carbon, nutrients and mixing with new detrital material from developing aquatic vegetation communities. Inundation links this new detritus and consumers in what is essentially a floodplain condition. The detrital materials provide food for macroinvertebrates that, in turn, support fish and other vertebrate population. It is possible that the initial flooding is accompanied by a flush (temporary high rate) of primary and secondary production.

Water levels in sandhill lakes are strongly influenced by SAS levels. At high water stages, water column solute concentrations are most dilute; nutrient concentrations and pH are likely to be lower unless there are contributing sources of pollutants in the watershed. If lake levels rise sufficiently, overland flow may create connections to other lakes or transient flows to perennial streams, e.g. in the Upper Etonia Creek Chain of Lakes (Robison 1992), and exchanges of aquatic biota can occur.

Plant and fish populations expand with the availability of habitat space. Bands of emergent vegetation develop from both the incoming seed rain and the seed bank. Submersed vegetation develops from dormant buds, rhizomes and seeds (Pitts 2003). Aquatic plants provide food and cover for aquatic insects, crustaceans, snails, amphibians, reptiles, and fish, which, in turn, become a food source for many other animals. In addition, waterfowl, muskrats, and other species use aquatic plants for cover and nesting. Aquatic and wetland plant communities provide habitat for spawning, nest construction, and refuge for immature and young fishes, and prey species (Pitts 2003). The plants obtain nutrients from the sediment and water column, likely helping to maintain oligotrophic clear water conditions in the lake.

With time, a new lake fringe wetland develops and submerged species expand from their low-water refuge. Lake sediments may develop with time, and those sediments tend to get deposited in deeper areas.

The large fringe wetland that develops at the lake edge is available for amphibious species to breed and develop. Terrestrial species have easy access to the water as well. During high water periods the lake may come into direct contact with woody upland vegetation on the lake borders. This vegetation may include live oak and longleaf pine, which will contribute additional organic matter to the aquatic system. If seeds or propagules of woody wetland species are contained in the seed bank, then they may sprout during high-water periods.

Low Water Ecosystem Processes

When the water levels fall because of declining surficial aquifer and/or decreased rainfall or drought, several structural and functional changes occur:

- Area and volume of aquatic habitat contract, which concentrates resources.

- Nutrient cycling shifts to a combination of terrestrial and aquatic processes. Water levels recede, leading to a concentration of resources and materials in residual deep areas, as well as a change in thermal and oxygen regimes.
- Organic matter and detritus input and decomposition processes adjust to changing mix of terrestrial and aquatic habitat; littoral and aquatic zones decline, while upland plants invade the exposed lake bed.
- Soil maintenance functions change with soils exposed to more aerobic conditions.
- The zone of wetland and aquatic vegetation will shift; this may decrease littoral area and diversity of wetland and aquatic habitat.
- Exposed lakebed may be colonized by upland plants, creating terrestrial habitat conditions.
- Fish and wildlife populations redistribute, which increases upland habitat, concentrates fish and aquatic species, and potentially eliminates aquatic populations in very small lakes.
- Reproductive cycles of some species may be triggered (e.g., woodstorks responding to concentrated fish populations).

Some of the detrital material produced during high water may be transported and deposited in the remaining deep areas of the lake. Sandy-bottom sediments and associated living and dead plant material are exposed to terrestrial conditions. There is a rapid colonization of the new habitat space by facultative wetland and upland weedy species. These colonizers trap nutrients present in newly exposed sediments and keep them from moving into the surficial aquifer and out of the lake system. Some nutrients and carbon may be sequestered within the soil profile. Nutrients not rapidly captured are leached into the surficial aquifer and/or may be retained within the water column of the receding lake.

Over time, the new upland vegetation detrital material is exposed in the lakebed. However, this material is rapidly leached of nutrients and minerals in the highly drained conditions of the exposed sandy lakebed. As the lake recedes further the terrestrial ecosystem moves farther into the lakebed. If sufficient time passes, small pine trees, oaks, red maples, and other woody species can invade (B. Dunn, personal observation of lakes in the Interlachen Hills and Upper Etonia Creek Basin of SJRWMD 2003). If the water level continues to decline, the lake may be reduced to one or more small pools representing the deepest areas of the lake. These pools provide refuge for aquatic plants and both aquatic and terrestrial animal species. Moler and Franz (1987) noted that fish in the sandhill lakes of the Ordway Preserve of north-central Florida congregate in the remaining pools as water levels recede in the shallow ponds and marshes. They hypothesized that upstream movement of fishes occurs when high water conditions result in discharge from one water body to another (as described in Annable et al. (1996) in the Upper Etonia Creek Basin). The fish and other aquatic forms recolonize areas that completely dried during the previous low-water periods. If an isolated lake goes dry it may result in extirpation of multiple species.

Maintenance of Structure and Function in Sandhill Lake Ecosystems

Sandhill lake structure and functions are maintained through the hydrologic fluctuations that characterize the system. Nutrient dynamics, productivity and structure of plant and animal communities, and sediment structure are organized around the hydrology.

Nutrient inputs, particularly phosphorus (P), to sandhill lakes are constrained by the primary hydrologic inputs to these lakes—surficial aquifer water and rainwater. Rainwater, already low in P, is stripped of nutrients as it passes through the upland biological and soil systems and emerges into the lake with even lower concentrations of these constituents (Sacks et al. 1998). Typical sandhill lake macrophytes are adapted to succeed in these nutrient-poor conditions. Low or moderate rates of phosphorus inputs promote low rates of P recycling (Carpenter and Cottingham 1997). Rooted macrophytes can, however, act as nutrient pumps, recycling stores of macro- and micronutrients from soils and sediments. This macrophyte pumping action may be a key means of P cycling from sediments back into biological system because chemical release of P from sediments to the water column is limited under aerobic conditions. Sediments in deep areas of sandhill lakes are typically P sinks. Chemical release of P from the sediments occurs under anaerobic conditions, but is inhibited by aerobic conditions. Because sandhill lakes are relatively shallow they tend to be physically well mixed resulting in aerobic conditions throughout the water column, except at the sediment water interface in deep areas. An oxygenated water column generally inhibits release of P from the sediments, which acts as a constraint on primary productivity.

Phosphorus is a limiting nutrient in sandhill lake ecosystems. Phosphorus is sequestered in the biomass of macrophytes, and phytoplankton. Nutrients, minerals, and carbon sequestered by plants support a complex food chain of invertebrate and vertebrate species through grazing consumption. Grazers, in turn, support additional levels of lower and higher predators, such as larger macroinvertebrates like dragonfly larvae and larger centrarchids (Carpenter and Kitchell 1993). Larger zooplankton grazers in the system also control phytoplankton biomass (Carpenter et al. 1991) that is already in competition with macrophytes for phosphorus. This system process continues throughout the pulses of high and low water levels tied to the hydrologic cycle.

At the waters edge, the upland plant community interacts with the aquatic ecosystem. Exposed habitat is colonized as the water periodically recedes. This may trap at least some of the nutrients stored in the exposed sediments and decaying aquatic plant materials that may persist in the upper soil or be provided from refugia when the water levels again increase.

The plant communities within the aquatic boundaries of the system are composed primarily of species adapted to rapid growth and recolonization, uptake and cycling of nutrients at low concentrations, and clear water. Sandhill lake vegetation characteristically has a fringe of upland species bordering the landward edge of the lake basin and a large expanse of bare sand with herbaceous vegetation that may be sparse to dense depending on site-specific conditions. This uppermost zone of the lake supports a mixture of upland and wetland plant invaders under low water conditions. The plant species assemblage in this zone does not include cypress and other wetland woody species typically found under seasonally flooded to typically saturated hydroperiod regime (as defined in SJRWMD, 2002a) in lakes with more stable water levels. The characteristic lack of a woody wetland community in sandhill lakes clearly indicates that appropriate conditions for sprouting, establishment, and maturation are not maintained for a sufficient period at any point within the sandhill lake hydrologic cycle. The ability of woody plants to establish themselves within the littoral zone of sandhill lakes does not appear to be constrained by a lack of seed dispersal ability. Seed dispersal is not likely to be a constraint for woody species because the seeds can move either by air, water, or mammalian and avian vectors. Wetland plant species of all types (shrubs and trees, as well as herbaceous vegetation) that became established at the high water lake edge may not survive the drier conditions; however, propagules may remain viable in a seed bank for long periods of time (Schneider and Sharitz 1988). Middleton (1999) has summarized the current research on cypress (*Taxodium* spp.) (primarily baldcypress (*T. distchum))* seedling survival and growth. That summary indicates that the seedlings are very sensitive to water-level fluctuations, as shown by different survival and growth demographics of seedlings in different fixed water levels and seedling cohort death as a result of periodic floodplain inundation. McNight et al. (1981) indicated that pond cypress (*Taxodium ascendens)* seedlings had a similar response to flooding conditions as bald cypress.

Organic sediment accumulation most typically occurs in the permanently aquatic portions of the lake because large permanent fringing wetlands are not typically a component of sandhill lake ecosystems. Detritus accumulation in the fluctuating littoral zone is temporary. Sediment accumulation occurs to the extent of a lake's fluctuation range, resulting in a relatively small area of permanent sediments and a relatively clear sandy bottom in most lakes. The lack of organic soils in sandhill lakes clearly indicates that the magnitude and duration of low water conditions eliminate or severely restrict accumulation of organic soils, which develop very slowly, but rapidly decay when exposed to oxidizing conditions (Stephens 1984).

Values of Sandhill Lakes

Because a sandhill lake can vary so greatly in appearance, from isolated pockets of water surrounded by "weeds" to expanses of open water that inundate lakeside docks, the ecological values of these lakes may be overlooked. Sandhill lakes are aquatic ecosystems embedded in an otherwise excessively drained environment. They serve as a primary source of water for a wide variety of organisms and provide breeding habitat for amphibians and other aquatic vertebrates in a landscape where perennial streams are relatively scarce. The deepest areas of the lakes provide refugia for aquatic communities during low-water conditions.

Sandhill lakes can be valued simply as a component of a much larger ecosystem that should be maintained for the ecological values they provide, or because of their economic and aesthetic values to human beings:

- Most fundamentally, this ecosystem type is a component of the larger landscape and for that reason it should be protected from harm. The state of knowledge of sandhill lakes, while growing, is yet insufficient to ensure that large alterations or elimination of sandhill lake functions do not have other, unintended consequences we have yet to consider. Viewed from another aspect, sandhill lakes may provide information about the landscape (including subsurface conditions) that is otherwise unavailable or very costly to provide. These lakes should be considered as potential integrators of conditions within the landscape and thus cost-effective monitoring systems. The ecological system provides values to the larger biome. The potential ecological consequences of the loss of the sandhill lake system include extirpation of species, significant habitat reduction, and again, unknown consequences to the entire landscape.

- These lakes and their associated biota have values to humans that can be quantified. Aesthetic, economic, and recreational values of sandhill lakes are accepted, if not fully quantified. The condition of the ecosystem can be a major factor in the value humans assign to sandhill lakes.

Ecological Values of Sandhill Lakes

Sandhill lakes can be altered or eliminated by reduction of SAS water levels. Because the fluctuations in SAS water levels directly affect the biological and biogeochemical functions of these lake systems, any reduction of SAS water levels may alter the cycle of high and low lake levels that maintains these ecosystems. Relatively minimally impacted groundwater levels may cause these lakes to vary from overflowing, to small isolated pools. Permanent reductions and the controls on lake level are specific to each lake. The amount that groundwater elevations could be reduced without affecting the current hydrologic regime would seem to be difficult to predict given the current level of understanding. The pulsing astatic hydrologic regime drives the productivity of the sandhill lake. It controls the carbon, nutrient, and energy cycling within the system. It affects primary and secondary production, and the structure and diversity of floral and faunal assemblages. These lakes have ecological values that are expressed in regional economic value.

A primary benefit of maintaining astatic sandhill lake ecosystems is the persistence of the natural variety of ecosystems within the landscape. The lakes provide the primary source of surface water for a large number of species. In a Florida sandhill landscape, streams are largely absent or ephemeral in nature. Elimination of the lakes through permanent reduction of the SAS water level elevations would likely result in the elimination of those species that depend on the habitat for breeding, nesting and rearing purposes, and the local extirpation of species that depend on the habitat for drinking water. Significant reductions of the SAS water levels would also result in the reduction or elimination of high water conditions in sandhill lakes. This would severely limit surface water routes for biological exchanges that allow for movement of species that help maintain diversity in lakes with ephemeral flows. Many of the sandhill lakes are totally isolated, so if SAS water levels are lowered significantly, then recovery after low water conditions, especially a complete loss of the surface water, would likely be limited.

Many sandhill upland reptiles and amphibians typically breed in temporary pools. However, during prolonged droughts, temporary pools do not develop and remaining surface water may be restricted to isolated pools of the sandhill lakes. This occurred in the early 1990s (Dodd 1992). Dodd recorded the decline in herpetofaunal abundance as a result of the loss of temporary pools, but did not compare the use of permanent water bodies to temporary pools. It seems likely, however, that these remaining pools would be critical breeding habitat for these species.

Human-Use and Economic Valuation of Sandhill Lakes

The value of sandhill lakes to humans reaches its maximum during high water conditions Visual qualities of the lake and recreation opportunities are at a maximum during these times. Swimming, fishing, boating, and viewing animal activities are all fully available.

During low water conditions, these amenities are not as convenient or are absent. However, the low water levels and reduced ecosystem size likely do not permanently affect the economic value that can be realized.

The value of high water quality has been recognized for at least a quarter of a century (USEPA 1973, Wilson and Carpenter 1999). Current research has focused on water clarity as a key to identification of value (Steinnes 1992, Poor et al. 2001). These aesthetic values are often reflected in the value of lakeshore property. The economic benefits of good water quality (Michael et al. 2000), water quality improvements (Carson et al. 1990), and the effects of water quality on residential land prices (Leggett and Bockstael 1998) have also been investigated. The value of a view and aesthetic values of lakes have been quantified. Benson et al. (1998) and Lansford et al. (1995a and 1995b) measured the increase in quality associated with the perception of recreational and aesthetic benefits. The economic importance of maintaining lake quality is currently being recognized and approaches are being tested (State of Wisconsin DNR 2003, Shapiro et al. 2001, Spalatro et al., 2001, Pezzini et al. 2001). Leggett and Bockstael (1998) noted, however, that the paucity of hedonic water quality studies is startling, particularly in light of the widespread application of hedonic techniques to air pollution. Most studies employ observations on water clarity, a proxy for water quality with ambiguous ecological merit. This assessment has not changed greatly in 4 years.

The available research suggests that while the distance from a lake or wetland may affect the value of a property (Milon et al. 1984), the type of wetland does not (Mahan et al. 2000). Property values may rebound from undesirable or low-quality environmental conditions (Dale et al. 1999). Lansford and Jones (1995) found that lakefront location, distance to lake, and scenic view were significant characteristics of housing value. Waterfront properties commanded a premium price for the private access they offer. Beyond the waterfront, the recreational and aesthetic value fell rapidly with increasing distance, becoming asymptotic to some minimum. It was found that 22 percent of the housing price could be attributed to the recreational and aesthetic component of the Texas housing market around the lake studied. Waterfront view (Benson et al. 1998) and water clarity (Steinnes 1992) were also found to be important property value determinants. Steinnes pointed out that the perception of clarity, rather than actual measurement values, may be most important. "Sand bottom lakes" are known for their clarity, thus there is an expectation that the water will be clear when it returns if it is not present at the time the property is examined.

The loss of value associated with water-level deviations (such as temporary changes in lake level) on property sale values and recreational values has been estimated for reservoirs in Texas (Lansford and Jones 1995), Alabama (Hanson and Hatch 2001), and Tennessee (Stewart et al. 2001). Stewart et al. (2001) provided a review of recent literature regarding economic valuation of a variety of environmental resources relevant (more and less) to sandhill lakes, including economic effects of water-level variations in reservoirs, economic values of recreational activities, and waterfront property values. They identified significant losses in value associated with permanently reduced pool sizes for a sample of their reservoirs. The projected effect of permanent reservoir water-level reduction was estimated by Hanson and Hatch (2001) as significant—10 percent for a reduction of 1 foot, and up to nearly a 50 percent reduction for a permanent 4-foot reduction. It is reasonable to assume that permanent water level reductions would have a significantly negative effect on lakeshore property values for sandhill lakes.

Synthesis: Relating MFL Criteria and Functional Values to Protective Criteria and Threshold Measures for Sandhill Lakes

SJRWMD has established minimum lake levels for 95 lakes, of which a number are upland lakes in recharge areas, including sandhill lakes with fluctuating water levels (Lake Brooklyn, Clay County; and Cowpen Lake, Putnam County) (SJRWMD, 2002a, 2002b). State Water Policy (Rule 62-40.473, *F.A.C.*) provides guidance for the establishment of MFLs, requiring that consideration be given to the protection of water resources, natural seasonal fluctuations in water flows or levels, environmental, and socioeconomic values associated with coastal, estuarine, aquatic, and wetlands ecology including:

- Recreation in and on the water
- Fish and wildlife habitats and the passage of fish
- Estuarine Resources
- Transfer of detrital material
- Maintenance of freshwater storage and supply
- Aesthetic and scenic attributes
- Filtration and absorption of nutrients and other pollutants
- Sediment loads
- Water quality
- Navigation

The relevance of these 10 values to sandhill lakes stems primarily from a lake's position in the landscape, and the recreational and aesthetic value that humans place on these lakes. Sandhill lakes are typically isolated or only intermittently connected to others; they have little impact on navigation and estuarine resources, and thus these two resource values require no further consideration.

In addition to the eight remaining values, four others need to be considered. Rule 62-40.473, *F.A.C.*, requires that SJRWMD consider the value of water resources and the natural seasonal fluctuations in water levels. The literature review highlighted productivity and nutrient and materials cycling as two additional functional values of sandhill lakes. The sandhill lakes model provides the linkage of the water resource values, functional values, and criteria and threshold measures that are necessary for protecting the water resource values of sandhill lakes. This model clearly ties back to the MFLs in Section 373.042, *FS*, and Rule 62-40.473, *F.A.C*. The conceptual model and limited functional values can be described as follows.

For each of the 12 functional values, Exhibit 1 provides a progression of information that:

- Links each value to the conceptual sandhill lake model
- Summarizes the specific functional benefits provided by the lake under high and low water conditions
- Lists specific evaluation criteria that can protect the identified high and low water functions

- Lists threshold measures and measurements that can be used to determine whether protective criteria are being met

The central thesis of the sandhill lake conceptual model is that maintaining water-level fluctuations on sandhill lakes (both high and low water conditions) is the key to maintaining these lakes in a healthy state. High levels provide conditions for the expansion of organisms into habitats depleted by previous low water elevations (Values 2 and 3). For existing plant and animal communities it provides the population expansion and growth necessary to maintain the health and diversity of member populations (Values 2 and 3). High water conditions provide the conditions necessary to rapidly process nutrients that move from the groundwater system into the lake biological system where they are processed and trapped by sedimentation or removed by gasification instead of entering the deeper groundwater aquifer as recharge (Values 4 and 7). They also trap sediment and other solids that move from the upland into the lake (Values 5, 8, and 9). Low water conditions result in a contraction of the biological community to the new lower water level. The contracted lake provides a refuge for aquatic species (Values 1, 3, and 11), and focuses detrital material into the deeper areas of the lake (Values 4 and 5), and provides water sources for many animals that rely on upland temporary pools during wetter periods (Values 2 and 3). The pools continue to filter and absorb nutrients and other pollutants (Value 2, 4, 5, 8, and 9) before the water acts to recharge the Floridan aquifer (Value 6).

Socioeconomic values of sandhill lakes (Values 1 and 6) are apparent. They are popular recreational sites, and public access to these lakes is at a premium. Often access is primarily through private property. Public parks and preserves that include waterfront property are heavily used. Lakeside property is typically priced per foot of lakefront, rather than on an acreage basis typical for non-lakefront properties. The values are not permanently affected by water fluctuations because of the value of the clear, clean water present in healthy sandhill lakes.

Summary and Recommendations

Criteria for setting MFLs are intended to protect recognized environmental and socioeconomic resource values. It has been shown that these resource values can be applied to sandhill lakes. There is generally a sufficient understanding of sandhill lakes in terms of the specific geology, hydrology, limnology, and ecology to support functional value definitions associated with the cycle of high and low lake-level fluctuations. These minimum fluctuations will maintain the ecological and economic values of these aquatic ecosystems. However, some information critical to these functional values is still being collected. Additional analysis of existing data may strengthen current concepts and better support criteria development. Additional understanding of some of the fundamental structural and functional aspects of sandhill lakes should be developed. The following recommendations are made:

EXHIBIT 1
Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
1. Recreation in and on the water [62.40.473 (1) (a)]	Recreational use of many sandhill lakes is high. They are widely used for fishing, hunting waterfowl, water skiing, boating, and nature observation. Public and private holiday events are held at public access points and a number of towns have developed public facilities for recreational uses. Economic benefits accrue from recreation expenditures and license fees.	**High Water**—maximizes lake area available for fishing, waterfowl hunting, swimming water skiing, boating, nature observation, etc. **Low Water**—falling water levels concentrate populations of fish, wading birds, and water fowl. Brown and Dinsmore, 1986; Hoyer and Canfield, 1994; Benson et al., 1998; Lansford,1995; Mohan et al., 2000; Spalatro et al., 2001; and McDiffit 1980	**High Water** • Maintains depths sufficient to allow recreational access for boats for water skiing, fishing, and general recreation. • Provides depths sufficient to inundate beach and provide swimming areas. **Low Water** • Maintains minimum depths sufficient to preserve fish and wildlife populations. • Maintains structural habitat features needed for recovery and response (hydric soils, seed bank, and refugia for vertebrates and invertebrates). • Maintains depths sufficient to prevent boat damage (such as propeller scarring of lake bottom, and damage to plant communities and fish and wildlife habitat).	**High Water** • Following periods of low water, upland plants that invaded during periods of low water are killed by flooding. • Fish populations are healthy and have expected age structure. Standard fish population protocols can be used. • Lake meets long-term annual expected average recreational use percentages by use category. Recreational use surveys may be conducted periodically as a means to estimate level of use and economic benefits. **Low Water** • Standing water refugia remain during low water periods. Required conditions may be defined based on the floral and faunal assemblages present in the particular lake. • Hydric soils are maintained. Soils may be sampled along the elevation profile to monitor hydric soil condition. • Over the long term, species composition and the structure of plant communities is not undergoing successional change to drier species assemblage. Permanent plots or transects, and photo stations may be used to track the vegetative community's structure and composition. **High and Low Water** • Water quality is acceptable for human contact. Water quality may be monitored to maintain desirable conditions, focusing on nutrients and productivity measures, and to maintain aesthetically acceptable conditions (high clarity and low water column productivity). Key indicators may include pH, alkalinity and hardness, Chlorophyll *a*, total phosphorus (TP), soluble reactive phosphorus (SRP), turbidity, Sechhi Disk, and total suspended solids (TSS). • Water elevations can be monitored through time and, in some cases, may be modeled with explanatory variables to develop expected versus observed water-level responses.
2. Biological Productivity	The biological community processes materials and energy in coupling of production (primary and secondary) and decomposition. Primary productivity results in plant biomass. Secondary productivity yields microbial and animal (vertebrates and invertebrate) biomass. Hydric soils provide nutrient storage. The fluctuating water regime in sandhill lakes induce pulses in biological productivity. Seasonally and climatically pulsing water levels control energy flow and transfers, nutrient cycling, and primary and secondary productivity. Decomposition provides for material recycling and is mediated by invertebrates, fungi, and bacteria.	**High Water**—aquatic habitat volume increases, maximizing foraging area and the zone of energy and materials capture; zone for aquatic plants expands; upland plants that have invaded during low water are flooded and decompose. In connected systems, there may be possible dispersal and interchange of organisms; reproductive cycles may be triggered in some species; resting, nesting, and refugia areas may expand; and there may be a pulse in both primary and secondary productivity. **Low Water**—aquatic habitat volume contracts, resources are concentrated; reproductive cycles in some plants, vertebrates, and invertebrates are triggered; upland and transitional habitats expand, and upland species colonize exposed shoreline. In extreme low water conditions some populations of vertebrates may be eliminated in very shallow lakes.	**High Water** • Provides levels that allow expansion of aquatic fauna into areas exposed during low water. • Provides for re-growth of plant communities from seed bank and buried propagules. • Promotes die-back and decomposition of upland facultative plant species that invaded during low water periods. • Prevents permanent encroachment of upland plant species into the lake basin. **Low Water** • Maintains hydric soil features at historic elevations, especially organic horizons in deep	**High Water** • Littoral wetland and aquatic vegetation recover after die-back during a low water period. • Upland plants that encroached on the exposed lakebed during low water are killed by flooding. • Key vertebrate species' populations are healthy and have expected age structure for their populations. **Low Water** • Standing water refugia remain during low water periods. • For some of the key vertebrate species, reproduction is triggered by low water conditions. Field sampling may be used to assess the health and age structure of the population. • Hydric soil conditions are maintained.

EXHIBIT 1
Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
2. Biological Productivity continued		Bachmann et al., 1996; Brown et al.,1998; Cooke, 1980; Cyr and Downing, 1988; Dodd, 1992; Ewel and Fontaine, 1983; Garret, 1982; Jennings, 1990; Middleton, 1999; and Pitts, 2003	zones. • Provides refugia to protect the biological system's drought-recovery response mechanisms (such as seed bank, buried propagules, eggs, larvae, etc.). **Low and High Water** • Maintains oligotrophic conditions for biological communities appropriate to sandhill lakes.	**Low and High Water** • Water quality reflects biological productivity and oligotrophy typical for sandhill aquatic ecosystem. Water quality parameters may include total and dissolved nutrients, chlorophyll a, TSS, algal biomass, and counts by species. • Plant and animal communities are healthy and self-maintaining over time. For the littoral zone and submersed species, plant species composition, cover, density, biomass, and spatial distribution may be assessed using plots, transects or photo stations.
3. Fish and wildlife habitats and the passage of fish [62.40.473 (1) (b)]	The range of water-level fluctuations provide habitat or resources for resting and sleeping, nesting, drinking, foraging, nursing, etc. Some sandhill lakes provide significant fish (game and sport fish) and wildlife (mammals, wading birds, waterfowl, reptiles, and amphibians) habitat, and pulsing lake levels are critical to the life cycle of many of the ecologically and recreationally important fish species. Upland and amphibian species use these lakes for drinking water, breeding sites, and general habitat purposes.	**High Water**—dispersal of fish is maximized; subaqueous soil structure is maintained; and upland support function remains as lake provides drinking water and food source for birds, vertebrates, reptiles, insects, etc. For connected lake basins, movement of individuals and populations between basins can occur. For lakes that have surface inflow or outflow, movement in and out of the lake may occur. Habitat diversity is maximized with shallow areas, littoral marsh, upland edge, and deep water zone. **Low Water**—available habitat for fish and other aquatic fauna is minimized. Residual pools provide for aquatic species refuge and maintenance of organic soils and seed and propagule banks. Bachmann et al., 1996; Hoyer and Canfield, 1986; Dodd, 1992; Moler and Franz, 1987; and Pitts, 2003	**High Water** • Provides levels that allow expansion of aquatic populations into previously (low water related) exposed lake bottom. • Provides for regrowth of aquatic plants from seed bank and buried propagules. • Prevents permanent encroachment of upland plant species into the lake basin. **Low Water** • Maintains hydric soils. • Protects the biological system's drought-recovery response (seed bank, buried propagules, eggs, larvae, etc.).	**High Water** • Fish move between connected lake basins. For lakes with surface water inflow or outflow channels, then fish may move into or out of the lake through channels. • Populations of vertebrate species are healthy and have expected age structure. Measurements may include sampling of population structure and presence of young of the year. • Aquatic and wetland plant communities regenerate from low water condition. Measurements may include species composition, density, biomass, diversity. **Low Water** • Residual pools are present and provide refugia for aquatic species. • Seed bank and other stored propagules are maintained. • Hydric soil conditions are maintained. **High Water and Low Water** • Fish and wildlife populations have expected diversity, density, health, and age structure. Sampling efforts may focus on centrarchid and forage fish communities and avian community measures. • Fish communities may be sampled to monitor biomass and diversity. Amphibian presence, biomass, and use can be surveyed. • Avian community monitoring may assess species diversity, density, and use per unit distance of littoral zone and shoreline.
4. Nutrient and materials cycling	A seasonally and climatically fluctuating hydrologic regime cycling between periods of high and low water influences the nutrient and materials cycles in the lake basin. Hydrologic cycles also influence the landscape level interactions with uplands in the contributing watershed, maintenance of SAS, and export of materials for those lake systems that have outflow to a downstream system. Alternating high and low levels act as material collection and processing (high level) and then concentration, and storage, and ongoing processing (low level).	**High Water**—at high water the areal extent of reducing conditions in soils is maximized, but throughout the lake, aerobic and anaerobic zones are juxtaposed, which can strongly influence biogeochemical cycles, such as the coupled nitrification and denitrification pathways. Die-back and decomposition of encroaching upland plants occurs, along with allochthonous and autochthonous inputs. Inflow and/or outflow exchanges may occur if connection to adjacent lakes is present, or if there is a surface inflow or outflow to the lake. **Low Water**—aquatic and wetland plants die back as water levels fall, creating detritus. Aerated conditions in areas of exposed soil or sediment will accelerate	**High Water** • For lake systems with an outflow, provides for downstream transport of carbon, nutrients, and minerals. • Maintains mix of aerated and reduced aquatic zones needed for efficient nutrient cycling • Maximizes lake surface area for energy capture by aquatic system. • Maximizes lake/upland edge for exchange of energy and materials.	**High Water** • Aquatic and wetland plant communities regenerate from the low-water condition. Measurements may include species composition, density, biomass, and diversity. • Vertebrate and invertebrate populations recover from low levels and disperse throughout the lake. Measurements may include diversity, population structure, and biomass. **Low Water** • Residual pools provide refugia for aquatic species. Measurements may include vegetation community structure and water quality, as described for other value measures and measurements.

EXHIBIT 1
Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
4. Nutrient and materials cycling continued		decomposition of this and other detrital materials. Upland species invade exposed soils as primary productivity shifts from wetland and aquatic species to upland and transitional species. Some organic and inorganic materials are sequestered in the soil column in areas no longer inundated. Residual pools retain reducing conditions in soil/sediment, and both aerobic and anaerobic zones in the water column. Carpenter and Kitchell, 1993; Carpenter and Cottingham, 1997; Stephens, 1984; and Thompson, 1981.	**Low Water** • Prevents loss of structural features of hydric soils. • Prevents alteration of biological trophic structure. Prevents loss of carbon, micro and macro nutrients, etc.	• Residual pools and saturated soils protect seed bank and other stored propagules. **High and Low Water** • Water quality reflects biological productivity and oligotrophic conditions that maintain sandhill aquatic ecosystems. Water quality parameters that may be tracked include total and dissolved nutrients, chlorophyll a, TSS, algal biomass, and counts by species. • Plant and animal communities are healthy and self-maintaining over time. For the littoral zone and submersed species, plant species composition, cover, density, biomass, and spatial distribution may be assessed using plots, transects or photo stations. • Plant and/or animal indicators of ecosystem change should be identified based on expected/observed species composition and dominance structure.
5. Transfer of detrital material [62.40.473 (1) (d)]	Transfer of detrital material is a key element of the lake level pulse concept. Pulsing lake levels transport detrital materials from the upland and littoral edges into the deeper portions of the lake. This movement of detritus is one pathway in the cycling of nutrients and carbon, as well as other materials, in the lake system, and is also part of the decomposition process and material recycling. Biological breakdown of detritus involves a wide array of invertebrates, bacteria, and fungi. The transfer results in “sand-bottom” lake conditions that are a desirable aesthetic and economic commodity. These lakes also transfer materials through intermittent discharges or perennial streams to downstream areas. Some portion of the organic matter in detritus may end up sequestered in organic soil horizons.	**High Water**—under high water conditions, surface area and volume enlarges, biological production (total amount) may increase, while productivity (amount per unit area) decreases as a result of dilution of materials. The lake’s decomposition cycle changes. Biologically mediated breakdown of detritus occurs in the water column and at the soil-water interface. Flooding of the upper edges of the lake’s basin kills upland plants that have encroached. This die-back creates a source of detritus. Detritus also enters the lake from other sources (upland vegetation, wind, runoff, and surface inflow). **Low Water**—falling water levels transport and concentrate dissolved and suspended detrital materials into deep water areas in which both aerobic and anaerobic zones occur. Invertebrates and microbes continue to process detrital material. Carpenter and Kitchell, 1993; Carpenter and Cottingham, 1997; McDiffit, 1980; Kindinger, 1999; Swancar et al., 2000; and Stephens, 1984	**High Water** • Maximizes lake surface area for collection and processing of detrital materials. • Maintains mix of aerated and reduced zones needed for efficient detrital processing. **Low Water** • Concentrates and stores detritus at lowest lake-bottom elevations. • Provides refugia for all trophic levels involved in detrital processing.	**High Water** • Upland plants that invaded during periods of low water are killed by flooding. • Fish populations are healthy and have expected age structure. Standard fish population protocols can be used. • The littoral zone is inundated and an array of aerated and reduced zones are present in the lake. **Low Water** • Hydric soil conditions are maintained. • Residual pools and areas of saturated soils maintain seed bank and stored propagules. • Residual pools provide refugia for aquatic species. **High Water and Low Water** • Standards for maximum allowable water quality productivity may be set for sandhill aquatic ecosystem maintenance. • Plant and or animal indicators of ecosystem change may be identified based on expected/observed species composition and dominance structure. • Water quality and vegetation communities may be monitored and may be compared to standards for maintenance of oligotrophy. • Depth and changes in depth of permanent autochthonous lake sediments (those generated by lake processes) maybe monitored.

Exhibit 1

Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
6. Maintenance of freshwater storage and supply [62.40.473 (1) (e)]	Sandhill lakes play a role in freshwater storage, because many of these lakes recharge groundwater. Maintenance of the sandhill lake ecosystem qualities should include maintenance of both hydrologic levels and water quality conditions. These are both critical potable water supply issues. Sandhill lakes are sensitive to pollutants and may be considered integrators of water quality in the surficial aquifer of the surrounding landscape. Some lakes have intermittent to quasi-permanent outflows. These lakes contribute flows in support of downstream ecological systems.	**High Water**—storage is maximized, as is the area available for recharging SAS and lower aquifers. Some lakes are used for crop irrigation (e.g. citrus grove). For lakes with a surface outflow, water flows to a downstream system and may provide critical support function. **Low Water**—available flood storage volume is maximized. Low water is attractive to some wildlife species (wood storks, for example). Annable et al., 1996; Deevey, 1988; Hughes, 1974; Kindinger et al., 1999; Merritt, 2001; and Sacks et al., 1998	**High Water** • Maximizes lake surface area for maximal recharge. • Outflow may occur, or (for lakes with persistent outflows) may be maximized and downstream systems thus benefit. **Low Water** • Exposed lake bottom provides aquifer recharge area similar to the surrounding sandhill landscape.	**High Water** • Recharge to SAS from the lakes occurs under high water conditions. Surface outflows provide flow to downstream systems and provide connectivity for faunal movements. **Low Water** • Residual pools remain because fine particulate organic and inorganic material deposits retard seepage loss. **High and Low Water** • Water elevations may be monitored through time and can be modeled with explanatory variables to develop expected versus observed water-level responses. • Water quality in the SAS may be monitored for nutrients and other pollutants entering the lake at discharge points supplying the lake. These results can then be compared to water quality sample data from recharge points to assess water quality changes and maintenance of high-quality recharge water.
7. Aesthetic and scenic attributes [62.40.473 (1) (f)]	These lakes have high aesthetic and scenic values. They are in demand as areas for residences. They are also significant features in parks and reserves such as Gold Head Branch State Park. Houses are often designed specifically to emphasize the lake view and/or to face the lake, presenting the back of the house to the upland. The typical clarity of the water provides viewing pleasure, both from a distance as part of the landscape and when next to or in the lake.	**High Water**—aesthetics are high, attractiveness of landscape is high, and expanse of open water is very appealing. High water eliminates temporary invasion of woody plants that can interfere with aesthetic and scenic setting. **Low water**—changes in the shoreline community contribute variation to the scenery. Wildlife populations are concentrated, which may make observation easier. Benson et al., 1998; Lansford and Jones 1995; Milon et al., 1984; Steinnes, 1992; and Stewart et al., 2001	**High Water** • Protects viewscape. • Prevents permanent invasion by upland and facultative plant species. • Protects integrity of biological system. **Low water** • Provides limited periods of low and extreme low water that help maintain the aesthetic and scenic qualities associated with sandhill lakes. • Provides opportunity to observe wildlife concentrated by reduced aquatic habitat area.	**High Water** • Invading woody species die back at high water and are not permanently established in the littoral zone. • Wetland and aquatic vegetative communities reestablish after high water levels and recover following a low water period. • The lake maintains diverse and healthy populations of vertebrates, including major taxa expected to be present, such as fish, reptiles, amphibians, wading birds, and water fowl. **Low Water** • Residual pools and saturated soils maintain seed bank and stored propagules. • Residual pools provide refugia for aquatic flora and fauna. **High and Low Water** • Water quality reflects aesthetically acceptable conditions (high clarity and low water column productivity). Primary parameters of interest may include water clarity, turbidity, TSS, and chlorophyll *a*. • In the long term, species composition and structure of plant communities is self-maintaining, and not undergoing successional change to drier species assemblage, either under high or low water conditions. Permanent plots or transects, and photo stations can be used to track the vegetative community's structure and composition. • The lake system is relatively free of nuisance or exotic vegetation.

Exhibit 1
Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
8. Filtration and absorption of nutrients and other pollutants [62.40.473 (1) (g)]	Sandhill lakes are oligotrophic systems where nutrient processing occurs in the littoral zone and detrital systems of the littoral zone wetland community. Biological processing of nutrients entering with groundwater flows keeps these materials from entering the aquifer with recharge water, but sandhill lakes may have a relatively low pollutant assimilation capacity relative to other, more eutrophic lake types. Sandhill lakes are likely phosphorus-limited and may act to trap and store this nutrient in particular. Fluctuating water levels produce a complex array of aerated and reduced soils, and aerobic and anaerobic zones in the water column. Deep and shallow areas also provide a mix of aerobic and anaerobic zones that allow for decomposition and biochemical transformations, some of which are coupled like nitrification-denitrification.	**High Water**—surface area and volume of lake are maximized, providing large area and volume for capturing and settling materials carried into the lake by wind, rain, runoff, surface inflow, or seepage. Once nutrients or other pollutants are within the lake, they may be filtered, removed, absorbed, assimilated, transformed, precipitated, or sequestered by a complex array of biogeochemical processes. Maximum extent of soils under reduced conditions. Maximum extent of interface of aerobic and anaerobic zones. Maximum extent of biologically active surfaces. Level of biological activity high because of large aquatic biomass and a well developed trophic structure. Import and export of nutrients and other chemical constituents may occur via surface inflow or outflow, rain, runoff, and seepage (both in and out). **Low Water**—falling water levels concentrate dissolved and suspended materials into deep areas, increasing the rate of biological activity and related biogeochemical processes; this results in assimilation, removal, deposition, and burial. More quiescent conditions, because of reduced fetch, promote settling of suspended materials. Carpenter and Kitchell, 1993; Carpenter and Cottingham, 1997; McDiffit, 1980; Kindinger, 1999; Swancar et al., 2000; Stephens, 1984; and Thompson, 1981	**High Water** • Provides conditions for settling, removal, assimilation. • Provides a mix of aerated and reduced conditions. • Provides maximum extent of biological community for nutrient and pollutant assimilation. **Low Water** • Provides naturally increased nutrient concentrations from reduced water exchange and reduced assimilative capacity because of reduced area and concentrated in-lake nutrients and organic solids.	**High Water** • Water quality reflects desirable conditions, focusing on low levels of nutrients and biological productivity measures. Key indicators may include pH, alkalinity and hardness, chlorophyll *a*, TP, SRP, turbidity, Sechhi Disk, and TSS. • Wetland and aquatic plant communities are self-maintaining, persist through time, and are healthy. Permanent plots or transects, and photo stations can be used to track the vegetative community's structure and composition. • Flora and fauna characteristic of sandhill lakes are maintained, and do not exhibit an imbalance that could be caused by eutrophication of the lake. **Low Water** • Species composition and plant communities structure remain stable through time, and are not undergoing successional change to a drier species assemblage. Permanent plots or transects, and photo stations can be used to track the vegetative community's structure and composition. • Standing water refugia remain during low water periods. Required conditions may be defined based on the floral and faunal assemblages present in the particular lake. • Hydric soils are maintained. Soils may be sampled along elevation profiles to monitor hydric soil condition. **High Water and Low Water** • Water and chemical budgets can be defined, including groundwater, surface water, and precipitation inputs. The assimilation capacity may be estimated and nutrient loading limits can be set. • Water quality sampling may be conducted. Key indicators include total and dissolved nutrients, chlorophyll *a*, algal species composition and biomass, TSS, and turbidity. Sampling could include all sources and sinks. • Rate of soil erosion from surrounding landscape is not accelerated. The lake may be monitored for presence of eroding areas, lakeside construction activities and use of best management practices, poorly operating or leaking septic tanks, and illegal discharges.

Exhibit 1
Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
9. Sediment loads [62.40.473 (1) (h)]	Sandhill lakes are created by the movement of surficial sand sediments into sinkholes, and they continue to develop through the movement of these coarse sediments from the surrounding landscape into the sinkhole basin. Lakes, by their very nature, are natural sedimentary basins. Transport of materials is via rain, wind, runoff, and surface inflow. Autochthonous and allochthonous solids settle into sandhill lakes and are focused in the deeper areas of the lakes, helping to maintain ecosystem characteristics. Sandhill lakes may be sensitive to external loadings of materials and the nutrients that they may carry. Causes of excessive loading may particularly include construction of various kinds but, in particular, lakeside development, or excessive recreational activity.	**High Water**—surface area and volume of lake is maximized providing large area and volume for capturing and settling sediment and materials carried into the lake by wind, rain, runoff, or surface inflow. Once sediments are within the lake, they settle and may be processed by the biological community. Littoral vegetation acts as a filter for solids removal and inhibits transport and re-suspension effects of the wind. **Low Water**—falling water levels concentrate sediment and suspended materials into deep areas, resulting in settling, deposition, and burial. More quiescent conditions, resulting from reduced fetch, promote settling and consolidation of transported and suspended materials into a cohesive lake sediment. Kindinger et al., 1999; and Swancar, 2000	**High Water and Low water** • Maintain water level fluctuations typical of Sandhill Lakes. • Limit sediment loading from human impacts and land use alteration.	**High water and Low Water** • Sediment deposition rates and TSS levels may be monitored and the results can be compared to rates and levels expected for sandhill lakes. • Appropriate construction practices may be monitored for compliance with best management practices (BMPs) for sediment and erosion control.
10. Water quality [62.40.473 (1) (i)]	Sandhill lakes are typically oligotrophic. Water quality is related to nutrient and mineral-poor surficial aquifer system water and rainfall that dominate inflow sources of water to these lakes, to movement of nutrients into the aquifer from exposed sediments as water elevations fall, and through tight cycling of nutrients, particularly phosphorus, that enter the system. As noted in several places in this table, water quality is also influenced by biological productivity (Value 2), nutrient and materials cycling (Value 4), transfer of detrital materials (Value 5), filtration and absorption (Value 8), and sediment loads (Value 9), as well as land uses in the surrounding uplands.	**High Water**—volume of water is maximized, increasing surface area of macrophytes and attached community (algae, bacteria, invertebrates); maximum area of water-sediment interface created; maximum amount of mix of aerobic and anaerobic zones created. **Low Water**—wetland/aquatic processing zones concentrated to residual pools and low areas within the lake basin. In lakes with sparse or ephemeral littoral vegetation, the portions of the basin that are no longer inundated may develop an upland and/or transitional community as upland species invade the open space. Brenner et al., 1990; Doherty et al., 2000; EPA, 1973, McDiffit 1980; Rochow, 1994; Sacks et al., 1998; and Wilson and Carpenter, 1999	**High and Low Water** • Maintain oligotrophic conditions in the water column. • Maintain native plant communities typical of oligotrophic conditions.	**High and Low Water** • Water quality is acceptable for human uses and for maintaining health of the lake's plant and animal communities. Water quality may be monitored for maintenance of desirable conditions, focusing on nutrients and productivity measures, and for maintenance of aesthetically acceptable conditions (high clarity and low water column productivity). Key indicators may include pH, alkalinity and hardness, chlorophyll *a*, total nitrogen (TN), ammonia nitrogen, nitrate+nitrite nitrogen, TP, soluble reactive phosphorus (SRP), turbidity, Sechhi Disk, and TSS. • Water quality sampling results can be compared to defined standards for each specific lake. • The plant community composition is self-maintaining through time, and does not undergo successional changes from eutrophication. • Human activity, particularly septic discharges, construction, heavy recreational activity, and fertilizer use may be monitored to ensure that these sources do not alter the natural loading conditions in the lake basin.
11. Protection of water resources (62-40.473)	"Water resources" is a broad term that applies to sandhill lakes; the specific water resource values are covered by the values contained in 62-40.473 (1) (a) through (j), and described in rows 1 through 10, above.	**High Water—**provides an array of functional values, as described in rows 1 through 10, above. **Low Water—** provides an array of functional values as described in rows 1 through 10, above.	**High Water and Low Water** See Evaluation Criteria identified for MFL Criteria 1 through 10, above.	**High Water and Low Water** See Threshold Measures identified for MFL Criteria 1 through 10, above.

Exhibit 1
Summary of Conceptual Sandhill Lake Model Linkage of Functional Values to Protective Criteria and Threshold Measures under Fluctuating High and Low Water Conditions

Environmental or Socioeconomic Value	Relevance of Functional Value to the Conceptual Sandhill Lakes Model	Specific Functional Values Provided by Sandhill Lakes Under High and Low Water Conditions	Evaluation Criteria that Protect Functional Values Under High and Low Water Conditions	Threshold Measures and Measurements for Protective Criteria for Sandhill Lake
12. Protection of natural seasonal fluctuation in water flows or levels (62-40.473)	Water level fluctuations are key to the limnology and biological integrity of sandhill lake ecosystems and are the foundation of the conceptual model proposed. Fluctuations drive the biological productivity of these systems along with the material, nutrient, and energy cycles. The fluctuating level regime also helps maintain clear sand bottoms and high water clarity; reduces buildup of organic matter within the system and on its edges; and contributes to the typical oligotrophic condition that organizes the desirable (low biomass) herb-dominated plant community, centrarchid-dominated fish community, and other qualities of the system.	**High Water—**provides an array of functional values as described in rows 1 through 10, above. **Low Water—**provides an array of functional values as described in the rows 1 through 10, above. Hobbs and Norton, 1996; and Middleton, 1999	See Evaluation Criteria identified for MFL Criteria 1 through 10, above. **High Water** • Maintains depths sufficient to allow recreational access for boats for water skiing, fishing, and general recreation. • Provides depths sufficient to inundate beach and provide swimming areas. • Provides levels that allow expansion of aquatic fauna into areas exposed during low water. • Provides for re-growth of plant communities from seed bank and buried propagules. • Promotes die-back and decomposition of upland facultative plant species that invaded during low water periods. • Prevents permanent encroachment of upland plant species into the lake basin. • For lake systems with an outflow, provides for downstream transport of carbon, nutrients, and minerals. • Maintains mix of aerated and reduced aquatic zones needed for efficient nutrient cycling • Maximizes lake surface area for energy capture by aquatic system. • Maximizes lake/upland edge for exchange of energy and materials. • Maximizes lake surface area for collection and processing of detrital materials. • Maintains mix of aerated and reduced zones needed for efficient detrital processing. **Low Water** • Maintains minimum depths sufficient to preserve fish and wildlife populations. • Maintains structural habitat features needed for recovery and response (hydric soils, seed bank, and refugia for vertebrates and invertebrates). • Maintains depths sufficient to prevent boat damage (such as propeller scarring of lake bottom, and damage to plant communities and fish and wildlife habitat). • Maintains hydric soil features at historic elevations, especially organic horizons in deep zones. • Prevents alteration of biological trophic structure. • Prevents loss of carbon, micro and macro nutrients, etc. • Concentrates and stores detritus at lowest lake-bottom elevations. • Provides refugia for all trophic levels involved in detrital processing.	See Threshold Measures identified for MFL Criteria 1 through 10, above. **High Water** • Following periods of low water, upland plants that invaded during periods of low water are killed by flooding. • Fish populations are healthy and have expected age structure. Standard fish population protocols can be used. • Lake meets long-term annual expected average recreational use percentages by use category. Recreational use surveys may be conducted periodically as a means to estimate level of use and economic benefits. • Littoral wetland and aquatic vegetation recovers after die-back during a low water period. • Upland plants that encroached on the exposed lakebed during low water are killed by flooding. • Key vertebrate species' populations are healthy and have expected age structure for their populations. • Fish move between connected lake basins. For lakes with surface water inflow or outflow channels, then fish may move into or out of the lake through channels. • Populations of vertebrate species are healthy and have expected age structure. Measurements may include sampling of population structure and presence of young of the year. • Aquatic and wetland plant communities regenerate from low water condition. Measurements may include species composition, density, biomass, diversity. **Low Water** • Standing water refugia remain during low water periods. Required conditions may be defined based on the floral and faunal assemblages present in the particular lake. • Hydric soils are maintained. Soils may be sampled along the elevation profile to monitor hydric soil condition. • Over the long term species composition and the structure of plant communities is not undergoing successional change to drier species assemblage. Permanent plots or transects, and photo stations may be used to track the vegetative community's structure and composition. • Standing water refugia remain during low water periods. • For some of the key vertebrate species reproduction is triggered by low water conditions. Field sampling may be used to assess the health and age structure of the population. • Seed bank and other stored propagules are maintained. **High Water and Low Water** • Water and chemical budgets may be monitored, including groundwater, surface water, and precipitation inputs; the assimilation capacity may be estimated; and nutrient loading limits may be set. • Water quality is acceptable for human uses and for maintaining health of the lake's plant and animal communities. Water quality may be monitored for maintenance of desirable conditions, focusing on nutrients and productivity measures, and for maintenance of aesthetically acceptable conditions (high clarity and low water column productivity). Key indicators may include pH, alkalinity and hardness, Chlorophyll *a*, total nitrogen (TN), ammonia nitrogen, nitrate+nitrite nitrogen, total phosphorus (TP), soluble reactive phosphorus (SRP), turbidity, Sechhi Disk, and TSS. • Plant and animal communities are healthy and self-maintaining over time. For the littoral zone and submersed species, plant species composition, cover, density, biomass, and spatial distribution may be assessed using plots, transects or photo stations.

- Develop specific criteria and thresholds for both high and low MFLs.
  Criteria and thresholds that will protect the water resource values, along with threshold measures, can be developed to protect criteria. This approach does not, however, define what the protective minimum levels should be. Defining the protective levels, then, is SJRWMD's next challenge. By way of example, a set of levels might include:

  – **Minimum Infrequent High**: the level that prevents permanent encroachment of perennial upland species into the lake basin, maintaining the distinct upland edge. For connected basins, a hydrologic connection must be provided between adjacent systems.
  – **Minimum Frequent High**: the level that maintains the landward extent of wetland vegetation (for example, littoral fringe community), and maintaining the in-situ propagule sources for community regeneration such as seed bank, rhizomes, root system, or other reproductive structures; for lakes that have surface discharge, minimum flow must be provided to maintain the downstream system.
  – **Minimum Frequent Low**: the level that maintains a residual pool sufficient to provide refugia for aquatic species, in particular vertebrate species.
  – **Minimum Infrequent Low**: the level that prevents the extirpation of aquatic plant and animal communities that is the loss of the biological system regenerative capacity (such as seed bank, propagules, eggs, etc.).

- Determine if relationships exist between stage exceedences and soil indicators. Other SJRWMD projects currently under way on hydric soil indicators and elevations related to stage exceedence statistics should be completed. Additional analysis of lake elevation records and their drivers, such as rainfall and SAS water level elevations, should be used to further quantify the hydrologic cycles and periods that create these markers. Time series analysis may provide a means to further develop stage fluctuation-based soil indicator hypotheses.

- Quantify the aesthetic value of sandhill lakes, and the influence of lake level fluctuations on those quantities in order to provide one scale for weighing the impact of decisions with the potential to affect these systems.

- Develop a more specific classification of the lakes in SJRWMD. Separation of upland clastic lakes from the upland sandhill lakes in SJRWMD is particularly important so that a clear picture of the extent of sandhill lakes can be developed. In general, accurate lake classification will help identify the most effective tools for defining and supporting the MFLs in each situation. A broader and more comprehensive knowledge of lake resources in SJRWMD will result.

- Investigate the movement of nutrients to and through these lakes across the water-level cycle and the role of the exposed shoreline during low water periods. There is only a weak understanding of the movement of nutrients and other materials through these systems. There is anecdotal information and correlative evidence from

- land use changes that these lakes may be very sensitive to nonpoint source pollution. For these reasons a better understanding of the movements of nutrients in and through sandhill lakes would help further develop the means to protect and

  maintain their values. The use of these lakes as water-quality sentinels should also be considered. They may serve as a cost-effective means of monitoring the effect of human activities in a large landscape on local and regional the water quality the SAS and Floridan aquifer.

- Investigate the wildlife uses of the lakes in order to provide a broader picture of the value of these lakes to the surrounding uplands. Most of the animal research in sandhill aquatic systems has focused on temporary ponds and marshes. More information on the use by wildlife of the permanent pools would be a valuable addition.

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