IMPROVED ASSESSMENT OF BASELINE CONDITIONS AND CHANGE IN WETLANDS ASSOCIATED WITH GROUNDWATER WITHDRAWAL AND DIVERSION

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REFERENCE: Proceedings of the 1995 Georgia Water Resources Conference, held April 11 and 12, 1995, at The University of Georgia, Kathryn J. Hatcher, Editor, Carl Vinson Institute of Government, Athens, Georgia.

Abstract. Some deficiencies with current approaches for maintaining environmental integrity where ground water is being withdrawn or diverted include: 1) lack of metered withdrawals and monitored water table responses; 2) failure to consider cumulative impacts of multiple withdrawals and diversions; 3) lack of sufficient baseline data and general knowledge of wetland hydroperiods; 4) assumptions that water table responses in wetlands approximate those in uplands; 5) inability to predict aquifer responses to long-term groundwater perturbations, and under heterogeneous and anisotropic conditions; 6) lack of knowledge of short and long-term ecological responses to groundwater perturbations; and 7) limited assessment techniques for detecting ecological degradation due to groundwater perturbations. Alternative approaches for site selection and improved detection of changes in wetland hydroperiod in areas of groundwater withdrawal or diversion include 1) ground-penetrating radar and fracture trace analyses; 2) networks of surveyed elevations; and 3) qualitative and quantitative assessments of ecological indicators. Activities such as proposed groundwater withdrawals which are capable of causing widespread, irreversible environmental damage and social problems should include Environmental Impact Statements during the planning stage.

INTRODUCTION

Groundwater withdrawals from residential, industrial, and municipal wells, in addition to use of groundwater for irrigation of golf courses and agricultural crops, commonly result in declines of the water table in the Southeastern Coastal Plain (SCP) physiographic province of the United States (Rochow 1994, Rochow and Rhinesmith 1991, Bacchus 1994, Bacchus 1995). Some activities which may result in diversion-related drawdowns in SCP wetlands include trenched firelines, ditches, stormwater ponds, borrow pits, excavated man-made lakes, and surface mining operations (Bacchus 1995).

Withdrawal or diversion of ground water from the surficial or underlying, semiconfined aquifers can adversely affect nearby wetlands by altering the natural fluctuations of the water table. Bernaldez *et al.* (1993) identify aquifer depletion as the primary cause of wetland alterations, based on studies from various European countries. Where groundwater withdrawals exceed the rate of aquifer recharge groundwater mining occurs. Under these circumstances, groundwater is considered a nonrenewable resource.

Insidious Drainage

Destruction of approximately 6,880 hectares (17,000 acres) of wetlands in the central portion of a single county in west central Florida has been attributed to withdrawal of ground water from the Floridan aquifer (House Committee on Natural Resources 1994). The groundwater pumping activities in this region of Florida also are thought to have contributed to the failure of more than 1,000 private wells (repaired or redrilled at a cost of 3.5 to 4 million dollars), in addition to draining lakes and streams and increasing the rate of sinkhole formation in the area. Groundwater withdrawal world wide also has been identified as a major component in the rise of sea level in the twentieth century (Sahagian *et al.* 1994). This paper will address only wetland impacts associated with anthropogenic perturbations of groundwater resources, with emphasis on groundwater withdrawals.

Wetlands are dependent on specific hydroperiods for maintenance of characteristic plant and animal communities. Wetland hydroperiods vary from one wetland type to another. Three important aspects of a wetland hydroperiod are: 1) the depth or level of fluctuating surface and ground water; 2) the duration of the fluctuating water levels; and 3) the periodicity or seasonality of the water level fluctuations. Disruption of any one of these three aspects can lead to the degradation and ultimate destruction of the wetland and the biota it supports. For example, the vegetation in many forested wetlands is dormant during the winter months. Therefore, adverse impacts of alterations of water levels during the winter months may result in less severe short-term impacts to the vegetation than the same alterations during the spring or summer (i.e., peak growing season). Unfortunately peak groundwater withdrawals often occur during the seasons of greatest vulnerability for the wetlands. Ormiston *et al.* (1994) reported that at the Cypress Creek municipal well field in Pasco County, Florida, the lowest average daily withdrawals (~21 mgd) occurred during November 1992, while the highest average daily withdrawals (~34 mgd) occurred during May, June and August 1993.

Subsidence. Wetlands experiencing watertable declines due to groundwater withdrawals or diversions routinely exhibit signs of surface subsidence (e.g., oxidation of organic material from the surface). Wetlands subjected to natural drought cycles, without anthropogenic perturbations of ground water, lack signs of surface subsidence and indicators of stress. Surface subsidence can result in irreversible damage to wetland tree species when roots and bases of trees formerly covered by organic soil are exposed to aerobic conditions and are subjected to decay (Bacchus, unpub. data). Although forested depressional wetlands which a lack a surface layer with organic material are uncommon in Florida and may not be widespread in other portions of the SCP (Bacchus unpub. data), these wetlands would not experience significant surface subsidence.

Considerable subsurface subsidence may occur in strata underlying these wetlands. Subsurface subsidence, in the form of dissolution, collapse and compression of the semiconfined aquifer matrix, may occur independently or in conjunction with surface subsidence. A lowering of the entire land mass (i.e., uplands and wetlands) or a preferential lowering of elevations in depressional wetlands, due to differences in underlying strata between the upland and wetlands, will result from subsurface subsidence. Detection and documentation of subsurface subsidence is more difficult than detection of subsidence of surface material (see Kashef and Chang 1976 for more detailed discussion of subsurface subsidence due to overexploitation of ground water and Rochow and Rhinesmith, 1991, Bacchus 1994, Bacchus 1995, for more detailed discussion of subsidence associated with wetlands).

Hydrologic Models. Alteration of wetland hydroperiods, and concomitant subsidence and destruction of wetland vegetation, often are more pronounced than predictions based on hydrologic models. One likely reason is because hydrologic models generally assume that aquifers and semiconfining strata are homogeneous and isotropic. These assumptions rarely are substantiated under a given set of natural conditions and are not valid assumptions for karst systems such as the Floridan aquifer. Hydrologic models generally are closed systems attempting to approximate natural, open systems. Even in cases where extensive evaluations of subsurface strata have been conducted, actual flow paths of water are difficult to determine during pre-perturbation conditions. Flow paths may change considerably during anthropogenic perturbations, such as withdrawals associated with municipal well fields, and responses to long-term pumping may vary dramatically from responses to short-term pumping. Finally, some types of groundwater withdrawals (e.g., agricultural irrigation, private residential wells) generally are not monitored and are not included in hydrologic models designed to predict responses to a single proposed perturbation, but the unmonitored withdrawals contribute to the overall stress of the aquifer. Without adequate and accurate data, hydrologic models cannot provide realistic predictions of responses of ground water to anthropogenic perturbations.

Depressional wetlands, particularly those dominated by pondcypress (*Taxodium ascendens*), appear to be extremely sensitive to groundwater perturbations (Bacchus unpub. data). These wetlands are breeding sites for the Florida sandhill crane (Dwyer 1990), the wood stork (a federally endangered species), and an array of amphibians, as well as habitat for other wildlife (Moler and Franz 1987). Depressional wetlands typical of the SCP occur throughout Florida, southern Georgia, North Carolina, South Carolina, Alabama, Mississippi and a portion of Louisiana. The range of pondcypress wetlands extends throughout Florida and is approximately coincident with the limits of the Floridan aquifer in Alabama, Georgia and South Carolina (Figure 1). Pondcypress wetlands continue throughout the SCP physiographic province of North Carolina, Mississippi and the southeastern portion of Louisiana.

Ecological Changes. One or more of the following ecological changes may occur in wetlands following anthropogenic perturbations of the water table: 1) decline and death of canopy species in forested wetlands; 2) replacement of characteristic sparse understory vegetation by a dense growth of subcanopy and shrub species; 3) a shift from wetland to upland groundcover species; 4) a shift from wetland to aquatic groundcover species; and 5) a shift in faunal assemblages utilizing the wetlands (Rochow 1994, Bacchus unpub. data).

The shift to aquatic species is least expected and often misinterpreted as meaning that the hydroperiod has not been adversely affected. This response occurs when ground elevations in the wetland are lowered via surface or subsurface subsidence, followed by periodic (e.g., seasonal) reductions in groundwater withdrawals. This scenario results in increased depths and more prolonged periods of surface water during times of reduced groundwater use, because of lowered surface elevations. During periods of greatest use, when no surface water is present, estimates of minimum-use water depths in wetlands of this nature often can be made by measuring the length of petioles or stems of aquatic plants, particularly those with floating leaves. The herbaceous species which become established under these conditions are capable of surviving for months without standing water. Concomitant changes in faunal assemblages following subsurface drainage of the wetlands have been reported in central Florida (Rochow and Rhinesmith 1991) and would be expected for other wetlands subjected to subsurface drainage. Unfortunately, faunal populations rarely are monitored in conjunction with withdrawal or diversion of ground water. Natural, short-term fluctuations in faunal assemblages can occur and would complicate interpretation of the data from sites with groundwater perturbations.

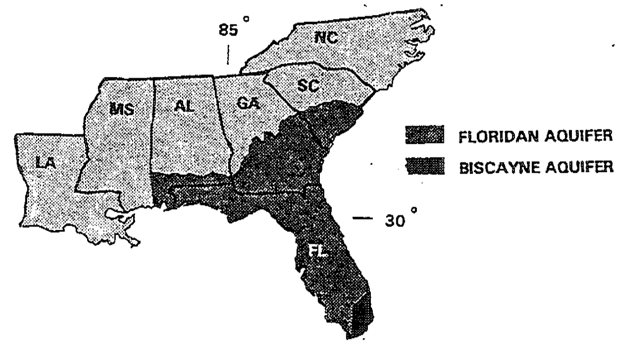

Figure 1. Southeastern Coastal Plain states (LA, MS, AL, GA, SC, NC, FL) and the approximate extent of the Floridan Aquifer in Florida, Georgia, South Carolina and Alabama (modified from Miller 1984).

Documented responses to groundwater withdrawals from the Floridan aquifer in Florida, in conjunction with observations of similar responses in depressional wetlands of south Georgia and South Carolina, referenced above, suggest that wetlands throughout the extent of the Floridan aquifer (Figure 1) and the remaining SCP may be susceptible to widespread destruction from subsurface drainage. A detailed description of the hydrogeologic characteristics of the Floridan aquifer in Florida, Georgia, South Carolina, and Alabama is provided by Miller (1984).

Objectives

The objectives of this paper are to: 1) increase awareness of ecological problems associated with withdrawal and diversion of ground water in the SCP; 2) identify deficiencies with current approaches for monitoring areas where ground water is being withdrawn or diverted; and 3) suggest alternative approaches for site selection and monitoring of wetlands in proximity to areas of groundwater withdrawal or diversion, for the purpose of improving detection of changes in wetland hydroperiod.

CURRENT APPROACHES FOR MONITORING

The Hydrologic Approach

Because of the recognized functions of wetlands it is important to ensure that groundwater withdrawals and diversions do not result in the inadvertent destruction of nearby wetlands. In the case of groundwater diversion activities, groundwater levels rarely are monitored. When monitoring does occur it generally is initiated after the fact. The most common approach for evaluating hydrologic changes related to groundwater withdrawal activities consists of collecting water level data from wells constructed in uplands. A more appropriate approach is to construct a series of nested piezometers along a transect from the upland through the wetland and into the upland on the opposite side. Precipitation at the site also must be monitored at one or more locations, depending on the size of the area involved. This approach is costly if automated water level recorders must be purchased, labor intensive if water levels are measured manually at sufficient intervals (and also costly if existing staff at a public agency are not available to collect and analyze data), provides information which has both temporal and spatial limitations, and provides no information about whether associated wetlands are being adversely affected by groundwater diversions or withdrawals.

Lack of Adequate Baseline Data. One constraint of the hydrologic approach results from common lack of baseline (e.g., pre-withdrawal) data. Even one or two years of baseline data provides limited insight regarding the long-term natural hydroperiod of a wetland. To complicate matters, water level data collected in wetlands may be interpreted as representing the natural hydroperiod of a wetland when in fact, insidious, anthropogenic alterations of the hydroperiod may have occurred in the past and may be continuing to occur due to unidentified groundwater diversions or withdrawals. Many types of groundwater withdrawals are not metered, and sources of groundwater diversions often are not recognized, thereby reducing the ability of water resource managers to correlate hydroperiod response to withdrawals or diversions. As a result, any available baseline data generally are insufficient to determine the characteristics of the natural hydroperiod, including the response of the surficial aquifer to varying rainfall patterns in the absence of perturbation.

Early groundwater withdrawals for municipal use in west central Florida began at the Eldridge-Wilde well field in 1956 (Ted Rochow pers. comm.). The initiation of these withdrawals predated recognition of the magnitude of damage that groundwater perturbations were capable of causing, the importance of wetlands, and wetland regulations. These and other groundwater withdrawals in the west central Florida region currently are regulated by the Southwest Florida Water Management District (SWFWMD), one of five regional water management agencies in Florida. Results of early groundwater modeling at subsequent well fields in SWFWMD's region indicated that the surficial aquifer (water table) and associated wetlands would not be adversely affected by withdrawals from the semiconfined Floridan aquifer. However, environmental staff observed signs of hydrologic problems within the first year of withdrawals at some subsequent well fields. As a result, some of the most extensive wetland monitoring in the southeastern U. S. related to groundwater withdrawals has been conducted under the direction of SWFWMD, in an attempt to resolve the problem of associated wetland destruction.

Static Elevation Assumptions. The research conducted in west central Florida, as discussed in this paper, exemplifies the progressive approach taken by SWFWMD in collaborating with hydrogeologists at the University of South Florida to evaluate and attempt to explain the wetland-related problems occurring in the vicinity of the municipal wellfields in their region. Knowledge gained from the problems encountered at these well fields and approaches currently being developed can be used to improve site selection and monitoring in the future. In the studies by Stewart and Stedje (1990) and Watson *et al.* (1990), "affected" wetlands appear to have been distinguished from "unaffected" wetlands in the Starkey well field (Pasco County) and Eldridge-Wilde well field (Pinellas and Hillsborough Counties) based on the appearance of surface water during some portion of the year (Figure 2). The elevation of the wetland floor was assumed to have remained constant.

The characterization of "unaffected" and "affected" wetlands continued to be applied in other studies of these well fields (Rochow and Rhinesmith 1991). However, groundwater withdrawals were initiated at Starkey in the early 1970's while the referenced studies at these well fields were not initiated until late 1988. One must assume that some lowering of wetland floor elevations due to subsidence had occurred in the 18+ years between the time that withdrawals were initiated and when these studies began. This assumption is made based on the following: 1) approximately 0.5 m of surface subsidence can occur in wetlands within the first year of watertable declines and thereafter (Victor Carlisle pers. comm., Bacchus unpub. data), and 2) approximately 0.5 m of surface subsidence had occurred within 18 months of constructing observation wells in the interior of selected depressional wetlands at the Starkey well field in late 1988. The surface subsidence was noted because the observation wells had been grouted to the surface in 1988 and approximately 18 months later the grouted portion of some interior wells was exposed above the lowered surface of the wetland floor (Figure 3). In reality, the natural hydroperiod of a wetland cannot be determined in areas associated with groundwater diversion or withdrawal activities if only water level data are available, because an unknown amount of surface and subsurface subsidence will occur.

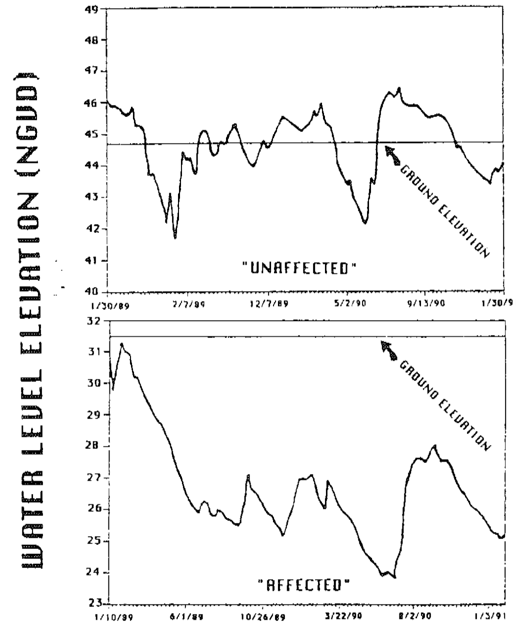

Figure 2. Hydrographs of a depressional wetland assumed to be unaffected by groundwater withdrawals (upper) and similar wetland known to be affected by groundwater withdrawals (lower) at the Starkey municipal well field, Pasco County, Florida, USA (from Rochow and Rhinesmith 1991).

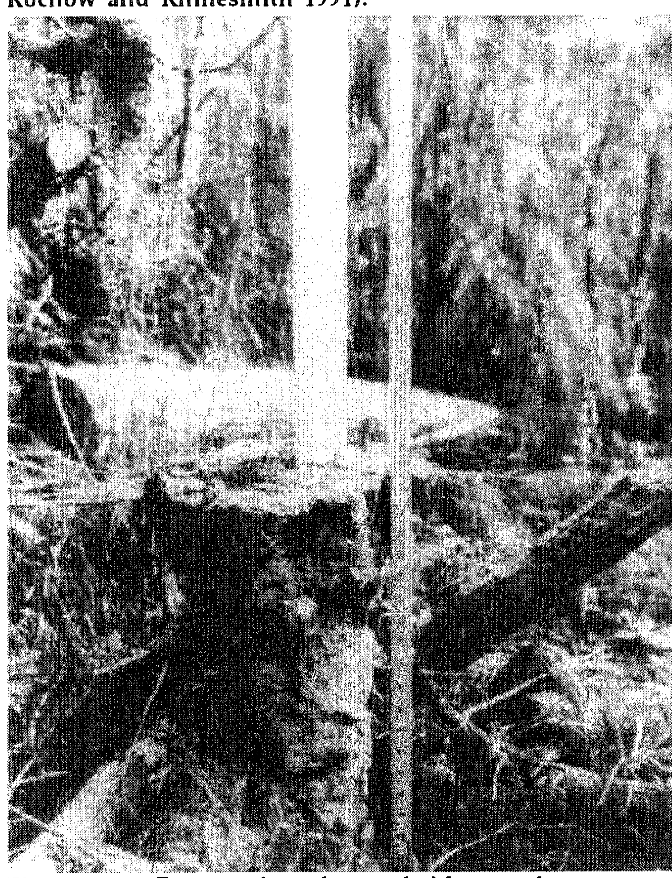

Figure 3. Extent of surface subsidence after approximately 18 months (~0.5 m from top of cement grouting to current wetland floor) associated with a shallow observation well installed in the center of a depressional wetland (Starkey West) in the Starkey municipal well field, Pasco County, Florida, USA (from Rochow and Rhinesmith 1991).

Stratigraphic Assumptions. Another constraint with the current approach for monitoring wetlands subjected to anthropogenic perturbations of ground water is that observation wells generally are constructed in uplands, presumably because of the difficulty of constructing wells in wetlands which have not been drained. Additionally, the underlying stratigraphy of depressional wetlands is assumed to be similar to the lithologic descriptions prepared from boring logs of wells in adjacent uplands. Stewart and Stedje (1990) and Watson *et al.* (1990) found that the latter assumption was not well-founded, with some depressional wetlands lacking significant "confining" layers (Figure 4). Discontinuities in lower permeability strata would suggest that water table responses in those wetlands would not be similar to responses observed in nearby uplands which lack discontinuities. The general assumption that groundwater responses for wetlands are comparable to those observed in upland wells also is not well founded.

In the case of groundwater withdrawals from a semi-confined aquifer such as the Floridan, the withdrawals can result in lowered water tables in the overlying surficial aquifer and subsequent alteration of wetland hydroperiods. Two factors which can contribute to the disruption of wetland hydroperiods are: 1) discontinuous lower permeability strata beneath the wetlands, and 2) increased porosity of associated fracture zones. Greater downward leakage from the wetlands compared to that occurring in the uplands results in rapid subsurface drainage of the wetlands due to vertical preferential flow. Subsurface drainage of wetlands also may occur via horizontal preferential flow along bedding planes and fracture zones. Subsurface drainage of wetlands occasionally is referenced as induced recharge because water from the surficial aquifer flows into the underlying aquifer in greater volumes and/or at greater velocities than would occur naturally, because of artificially increased pressure gradients. The ability of anthropogenic activities such as groundwater withdrawals to change the vertical flow characteristics of an aquifer is one reason why aquifers within the SCP often are referenced as "semiconfined", rather than "confined".

Hydrologic models of karst systems which do not incorporate aspects of preferential flow in the vertical and horizontal directions are unlikely to accurately predict the responses of wetland hydroperiods to groundwater withdrawals or diversion. Even if hydrologic models evolved to a level where watertable responses could be predicted accurately, a hydrologic model provides no information regarding the accompanying response of the living components of the system. To assume that the ability to predict drawdown levels of a given depth in a water table will reveal whether ecological components of an associated wetland will be adversely affected is to fall prey to the first misconception of modeling: "A model can substitute for lack of understanding of a system" (Reynolds 1979).

The Ecological Approach

The current approach of establishing ecological baseline conditions and documenting a change from these conditions over time also has limitations. Field methods for monitoring wetlands were designed primarily to estimate dominance (e.g., largest relative basal area, greatest height, greatest percentage of areal cover, greatest number of stems, spatial extent), or simply to determine commonly occurring plant species (Environmental Laboratory 1987, Federal Interagency Committee for Wetland Delineation 1989, Sherman *et al.* 1988), rather than to detect and measure responses of natural systems to imposed stresses. Although standard approaches may provide some insight into stress responses, such interpretations are difficult because the majority of monitoring is short term, there is a dearth of data on stress responses in wetland species, and few individuals responsible for monitoring wetlands are trained to recognize physiological stress responses. Thus, current field methods generally are inadequate for providing a timely interpretation of responses of natural systems to imposed stresses.

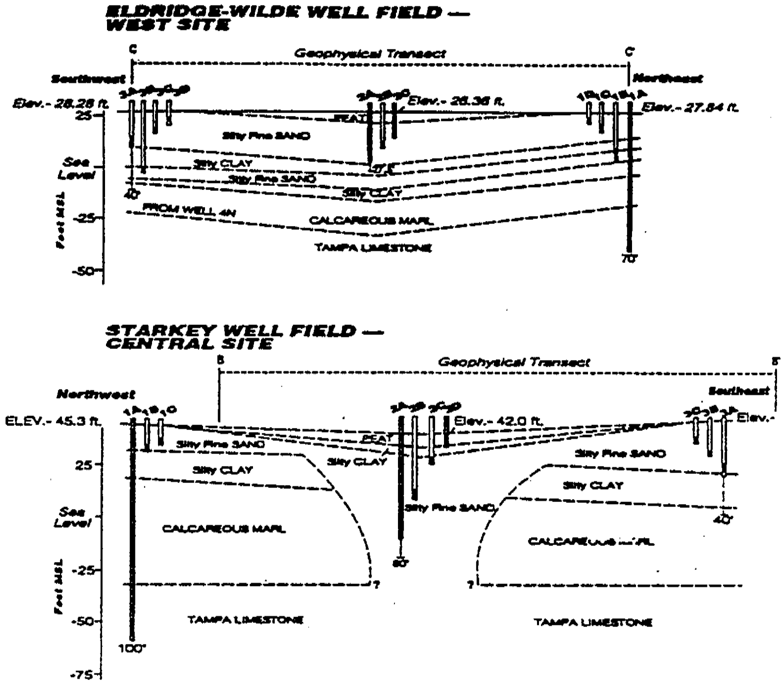

Figure 4. Representative geologic cross-sections from west central Florida of depressional wetlands with continuous subsurface strata (upper) and depressional wetlands with thick surficial sand units (lower, modified from Watson *et al.* 1990).

The problem of selecting suitable methodology for monitoring forested wetlands subjected to groundwater withdrawal and diversion, of the magnitude associated with activities such as municipal well fields and surface mining, is compounded by 1) the relative newness of these types of perturbations in the southeastern portion of the U. S., and 2) the lengthy delay between the onset of the perturbation and the death of the canopy species. For example, Penfound (1952) found only 10% mortality of baldcypress (*T. distichum*) had occurred 4 years after abnormal increases in the hydroperiod of impounded "Lake Chico", but mortality increased at this site to 50% after 18 years. The trees in this study were not responding to factors associated with subsurface drainage; however, since groundwater perturbations can result in abnormal increases in water depths and durations, responses such as those in Penfound's study are of interest. Similar trends of prolonged declines in tree vigor after initiation of hydroperiod perturbation (e.g., approximately 15 to 20 years), followed by death of the canopy species have been observed in pondcypress (Bacchus unpub. data, Bob Keeland and Joy Young pers. comm.) and baldcypress wetlands (Miller *et al.* 1993) in the SCP. Unfortunately, in the case of forested wetlands, the slow decline of the trees over a prolonged period of time (~20 years) before they finally die, restricts the use of this method to one that documents long-term, irreversible damage to the wetland.

Ecological monitoring occasionally includes mortality studies, but more generally is restricted to: 1) various assessments of groundcover and subcanopy vegetation to detect changes in species composition over time, and 2) radial growth measured at a standard height (dbh) on wetland trees. These methods can provide erroneous data and can result in spurious conclusions about the impacts of anthropogenic changes in the water table, as discussed below. Mortality studies in herbaceous wetlands may provide an accurate assessment of damage, but herbaceous wetlands may be more responsive to natural fluctuations in weather conditions. Interpretation of changes recorded during studies of short duration are more likely to be misinterpreted. Assessment of mortality in forested wetlands does not provide an opportunity for implementing corrective measures before irreversible damage occurs to the wetlands.

Changes in Groundcover and Subcanopy Composition. If abnormal weather patterns are considered, assessments of groundcover and subcanopy vegetation can provide excellent information regarding alterations of natural hydroperiods. For example, shifts from typical sparse understories to dense thickets of shrub and subcanopy species in pondcypress and similar depressional wetlands are indicative of anthropogenic perturbations of the ground water (Rochow 1994, Bacchus 1994, Bacchus 1995).

Problems with the species composition approach arises from misinterpretation of the data. For example, increases in the frequency or density of aquatic species can be interpreted to mean that the hydroperiod of the wetland has not been adversely affected. As noted previously, subsidence associated with withdrawal or diversion of ground water lowers the floor elevation of the wetland. Therefore, when groundwater pumping or diversion is periodically reduced or halted as anthropogenic use diminishes, surface water will exceed pre-alteration depths and/or durations. These conditions will favor growth of aquatic species, including undesirable species such as cattails. Increased surface water levels or durations following subsidence also can lead to the decline and ultimate death of wetland trees.

Occasionally recruitment studies are conducted as part of the monitoring plan for wetlands associated with anthropogenic groundwater perturbations. This approach can be extremely sensitive to increases in upland groundcover species, which may be an early signal of watertable declines. Consequently, this approach provides a greater response time to implement corrective measures than mortality studies for forested wetlands. However, results from recruitment studies also can be misinterpreted. For example, cypress require periods of more than a year without significant standing water for germination and seedling survival to occur. Although these conditions occur naturally, on an infrequent basis, they are much more likely to occur in wetlands near areas of groundwater withdrawals or diversions. As a result recruitment data showing increases of seedlings of canopy species such as cypress also may be an early warning of future wetland decline. Observations of pondcypress seedling recruitment have been made at several wetlands within the Starkey and Cypress Creek wellfields in Pasco County, Florida. Extensive death of canopy cypress and conversion to upland species in lower vegetative strata followed. The cypress seedlings have not persisted in these wetlands (Bacchus unpub. data, Ted Rochow pers. comm.).

Changes in Canopy Integrity. Assessments of canopy integrity generally are not included in monitoring programs for areas of groundwater withdrawals or diversion. Because of extensive wetland degradation which was occurring at well fields in west central Florida, SWFWMD staff implemented an analysis of aerial photographs in an effort to improve detection of wetland damage (Rochow and Rhinesmith 1991). Conclusions were that readily available photography (e.g., 1"=2,000') was at a scale too coarse to evaluate the condition of the cypress. Problems with evaluation of canopy integrity also occur because cypress are deciduous, and aerial photography generally is taken during the fall or winter months when cypress leaves are beginning to turn brown or after abscission. As a solution to these problems, SWFWMD initiated aerial flights during the growing season to obtain photography at scales of 1"=850', 450' and 226' so that canopy thinning and windthrow could be detected. This approach has the advantage of large-scale coverage, but temporal sensitivity is limited because wetland damage is extensive before it is detectable using aerial photographs. This approach also is very expensive because of the larger number of photographs required at the preferred scales.

Field Analysis of Radial Growth in Canopy Species. Radial growth of wetland trees has been monitored at some municipal wellfield sites as a means of evaluating the condition of the wetlands. The method apparently used in these studies was to measure the tree diameter at breast height (dbh) by wrapping a diameter tape around selected trees, parallel to and 1.37 m above the ground. Theoretically, a nail or other device is used to mark the point of measurement to improve the precision of measurements taken in subsequent years.

In a study of shortleaf pines (*Pinus echinata*), Bower and Blocker (1966) found that radial growth measured with a diameter tape frequently resulted in errors when reading to the nearest 0.25 cm. They also found that it was difficult to place the diameter tape at exactly the same location on the bole for each repeated measurement. They determined that errors due to the former could be reduced by using a vernier to measure to the nearest 0.025 cm. Errors due to placement can be avoided by using dendrometer bands, installed for long-term measurement (Cattelino *et al.* 1986). The use of dendrometer bands is more time consuming and expensive than measurement with a diameter tape because of the installation of long-term monitoring bands on each tree which is to be measured.

Cameron and Lea (1980) concluded that measurements using diameter tapes provided growth estimates of similar precision to those obtained with dendrometer bands. However, they noted that if the dendrometer band is considered the standard of accuracy, the data obtained using the diameter tape overestimates growth by approximately 11% for all species collectively. The trees evaluated by Cameron and Lea included yellow birch, sugar maple, red maple and American beech. Overestimation for red maple alone was twice the amount reported for all study species collectively. The authors suggested that the increased bark roughness of red maple, as compared with the remaining species in the study, might be responsible for the greater discrepancy.

The bark of red maple (*Acer rubrum*) and other wetland species such as sweetbay (*Magnolia virginiana*) is relatively smooth compared to pondcypress. Pondcypress is a major canopy constituent in forested depressional wetlands in the SCP and has characteristically thick, shaggy bark which can be compressed to varying degrees during measurement with a diameter tape. Pondcypress also grow relatively slowly under natural conditions. Bacchus (unpub. data) found that measurement error for repeated measurements of the same pondcypress trees by different data collectors and by the same data collectors using the diameter tape method for various pondcypress stands in central Florida equaled or exceeded the 0.02 to 0.33 cm annual growth range reported for cypress in Florida by Mitsch and Ewel (1979). Although distinctions between bald and pondcypress were not made in the latter study, the value of 0.02 cm was reported for a "ponded cypress dome", the typical habitat of pondcypress.

Another problem with using radial growth as a means of monitoring wetlands subjected to groundwater perturbations is the difficulty in comparing and interpreting the data. Complications in comparing data may arise due to varying degrees of surface subsidence. Radial growth measurements routinely are taken at 1.37 m above the surface of the ground (exceptions are made for situations such as extensive butt swell in baldcypress). For sites with extensive surface subsidence, measurements made at 1.37 m above the present surface could be 0.5 m or more below the standard point of measurement. Growth responses in this portion of the bole may be different from responses at true breast height.

With respect to interpretation of data, wetland trees in general and cypress trees specifically, can exhibit a temporary increase in radial growth following initial reductions or increases in the natural hydroperiod. For example, Young *et al.* (in press) found that growth of baldcypress increased for 3 years (>2 S.D. above the mean) following artificial flooding of a wetland in South Carolina. Growth of these trees then declined for the following 16 years (< 2 S.D. below the mean). Stahle *et al.* (1992) reported a similar trend for a baldcypress wetland subjected to an increased hydroperiod. Radial growth increased (> 8 S. D. above the mean) for 3 years following hydroperiod perturbation, then declined for 30 years following the period of increase. Increase in radial growth of canopy pondcypress has been reported in wetlands subjected to subsurface drainage by municipal well fields (CH2M Hill 1990), but many of those trees now are dying.

Prolonged increases and decreases in wetland hydroperiod ultimately can lead to the death of dominant wetland tree species such as pondcypress. As pondcypress trees begin to decline in vigor following groundwater perturbation, separation of their thick bark from the cambium can occur (Bacchus unpub. data). In the early stages of exfoliation, which may continue for years, any increase in diameter that is measured will include true growth and "false growth", the latter due to separation of the bark. An apparent increase in diameter growth for pondcypress at one well field in Florida led researchers to report that the wetland was in good condition (CH2M Hill 1990). Field observations in subsequent years revealed advanced stages of bark exfoliation, extensive windthrow, and death of the pondcypress trees (Bacchus unpub. data). Similar responses are occurring at the Cypress Creek well field, in wetlands "augmented" with water from the Floridan aquifer.

Precise field assessment of radial growth of pondcypress is difficult and labor intensive. These considerations, in addition to problems associated with accurate interpretation of data, as discussed above, appear to limit the usefulness of this approach for year-to-year assessment of wetland health.

Laboratory Analysis of Radial Growth in Canopy Species. Methods for analysis of radial growth described above are nondestructive but have severe limitations when applied to trees with highly textured or spongy bark and slow rates of growth. Dendrochronology, an alternative method of analysis, involves laboratory examination of growth rings in wood tissue samples and correlation of these rings with specific years. Dendrochronology is destructive, requiring either a sample of increment cores along approximately four radii per tree or cross-sectional slabs. Extraction of cores generally does not result in damage that would threaten a healthy tree, since scar tissue readily seals the wounds. Obtaining cross-sectional slabs requires felling the tree.

Like diameter measurements, dendro-chronologies generally are conducted on samples collected from 1.37 meters above the ground. However, some types of stresses may result in abnormal growth at considerable distances above this level (Swetnam *et al.* 1985), necessitating that access to the canopy be obtained to collect cores (e.g., climbing), or that the tree be felled to obtain cross-sections from higher on the bole. After collection, cores are mounted in grooved wood to facilitate sanding. Cores and slabs are sanded with progressively finer sandpaper so that the growth rings can be examined microscopically. Samples are crossdated, with skeleton plots prepared as a first step, to reduce the chance of error due to growth anomalies such as false or missing rings (Fritts and Swetnam 1989, Stokes and Smiley 1968). The width of growth rings and distances between rings can be measured using a Hensen University Model Incremental Measuring Machine (mechanical stage attached to a potentiometer) or scanners which produce a computer file containing an image of the core or portion of slab. The latter method reportedly is less accurate for trees with very narrow rings, such as pondcypress, and for species with diffuse porous wood, such as tupelo (*Nyssa* spp., Bob Keeland pers. comm.).

Cypress in general and pondcypress specifically display false rings (i.e., more than one growth ring per year) and have locally absent or merging rings (Young *et al.* 1993, Joy Young pers. comm.). These characteristics increase the effort required to evaluate growth responses of cypress over time. For example, a preliminary stem analysis of pondcypress from sites apparently subjected to subsurface drainage revealed that anomalous growth rings were concentrated near the bases of these trees and extended through the samples from standard breast height positions. Therefore, cross-sections taken from these levels were difficult to interpret. Consequently, samples from 3 m and 6 m above breast height were required for crossdating (Bacchus and Joy Young unpub. data). Cross-section samples from the standard height under these circumstances could confirm that the tree had or was experiencing stress, but chronology analyses based on cross-section slabs or increment core samples under these conditions would be dubious and misleading.

ALTERNATIVE APPROACHES FOR SITE SELECTION AND MONITORING

Geophysics. Ground penetrating radar (GPR) has been used by Stewart and Stedje (1990) and Watson *et al.* (1990), in addition to Barr (1993), Beres and Haeni (1991), Clasen (1989) and Johnson (1992) for hydrogeologic investigations. Transects across depressional wetlands, using GPR methods described by Stewart and Stedje (1990) and Watson *et al.* (1990), can identify which wetlands have discontinuous, lower permeability strata or thicker surficial sand units (i.e., lack impediments to vertical flow). These conditions may be the result of natural processes or may be an artifact of groundwater withdrawals. Perturbations of groundwater in semiconfined aquifers can hasten natural processes such as dissolution and collapse of the underlying limestone, creating solution channels and "karst windows" (Mark Barcelo pers. comm.). Wetlands with these characteristics should be considered high risk wetlands which will experience relatively rapid subsurface drainage following groundwater withdrawals from underlying, semiconfined aquifers because of increased magnitudes and velocities of downward leakage. Geophysical evaluations of depressional wetlands at potential wellfield sites should be conducted using GPR, as described in the studies by Stewart and Stedje, and Watson *et al.* referenced above. Sites with high risk wetlands should be eliminated from consideration during the planning stage.

Depressional wetlands with continuous, lower permeability strata, as determined by GPR methods referenced above, are susceptible to subsurface drainage by groundwater diversion (Bacchus 1994, Bacchus 1995), and are not necessarily immune to subsurface drainage by groundwater withdrawals from underlying aquifers. The assumption that wetlands with continuous, lower permeability strata are unaffected by groundwater withdrawals may be invalidated for one or both of the following reasons. Withdrawals from underlying aquifers may result in increased downward leakage through zones which serve as aquitards or aquicludes under unperturbed conditions. Additionally, the wetlands may be associated with fracture zones. Declines in the water table can be greater than predicted where preferential flow from the wetlands occurs through fractures in proximity to active pumping wells. Fracture traces may be detected by photolinear analysis, which should be conducted in conjunction with the geophysical analysis referenced above. The following discussion of photolinear analyses is not meant to be a review of the literature on this topic, but simply a selection of some relevant work that has been conducted in the SCP.

Fracture Trace Analysis. As a preliminary analysis of selected Florida well fields, Stewart and Stedje (1990) chose 1:56,000 color infrared aerial photography to document the location of photolinears. Photolinears are linear trends identified on aerial photographs that may represent zones of increased fracture density or fracture traces with higher hydraulic conductivity that can be vertical pathways for groundwater flow between the surficial and semiconfined aquifers (Stewart and Stedje 1990). During the preliminary analysis, photolinears were mapped at high, medium, or low confidence levels based on the clarity of the linear features on the photographs. Wetlands which were classified as "affected" sites were intersected by photolinears. The only wetland discussed which was classified as "unaffected" was found to have "a high concentration of photolinears near its northern edge". As noted previously, wetlands identified in these studies as "unaffected", later were determined to be adversely affected by the groundwater withdrawals. A statistical analysis of the association of photolinears with depressional wetlands near the municipal well fields was not included in these studies; however, subsequent site evaluations confirmed that the forested wetlands in proximity to fracture traces, as well as those intersected by fracture traces have experienced irreversible damage from groundwater withdrawals (Bacchus unpub. data).

Brook and Sun (1982) compared the following five types of remotely sensed imagery for the Dougherty Plain in southwest Georgia: LANDSAT MSS images, SKYLAB ETC images, and 1:59,000 scale black and white, 1:24,000 scale color infrared and 1:20,000 scale black and white aerial photographs. They found that LANDSAT imagery (ground resolution of ~200 to 250 m) and SKYLAB imagery (ground resolution of ~15 to 30 m) were not suitable for fracture trace mapping in the Dougherty Plain. Color infrared aerial photographs at a scale of 1:24,000 (ground resolution of ~1 m) and black and white aerial photographs at a scale of 1:20,000 (ground resolution of ~0.8 m) were found to be equally suitable for fracture trace mapping. However, the authors commented that water levels were high at the time that both of these photographs were taken and that high water levels facilitated photographic identification of both fracture traces and sinkholes.

Wells in closest proximity to fracture traces in the Dougherty Plain had higher specific capacities (Brook and Sun 1982). In addition to improving predictions of water well productivity (Brook 1985, Brook *et al.* 1988), fracture traces were predicted to be associated with areas of ground subsidence in the karst region of Georgia (Brook and Allison 1986). Although that study did not identify depressional wetlands associated with fracture traces, pondcypress wetlands are associated with many of the depressional water bodies in that region. Based on the findings of these studies in Florida and Georgia, and similar observations in the upper SCP of South Carolina, as discussed by Bacchus (1994), wetlands associated with photolinears should be considered high risk wetlands susceptible to destruction when located in areas of proposed groundwater withdrawal.

Observations of wetlands in Florida in the vicinity of well fields of various ages, and varying average and maximum daily withdrawals, revealed an apparent common response: surface subsidence and stress symptoms extending approximately 5 km from the source of pumping (Bacchus unpub. data). This apparent trend may reflect the approximate extent of preferential flow through fractures exposed to groundwater pumping. Fracture traces have not been investigated for all of the well fields observed; however, the association of depressional wetlands with fracture traces in Florida, and the SCP of Georgia and South Carolina suggests that this phenomenon may be characteristic of depressional wetlands throughout the SCP.

Although GPR and fracture trace analyses are not monitoring approaches, they represent important initial steps which should be included prior to final selection of locations for groundwater withdrawals. To minimize the widespread destruction of wetlands in the future, potential wellfield sites should not contain high risk depressional wetlands within a 5 km radius of the proposed location of production wells. Information from these analyses also is important in determining where monitoring efforts should be concentrated (e.g., which wetlands will respond most rapidly and severely to groundwater perturbations) in areas where groundwater withdrawals have been initiated. For existing well fields, monitoring plans should require that data from wetlands near the area of groundwater withdrawals be compared to data from "reference" wetlands which have not been subjected to surface of subsurface drainage. In cases where fracture traces are apparent, reference wetlands should be located beyond a 5 km radius surrounding pumping wells.

Network of Surveyed Elevations. Establishing a grid network of surveyed points throughout a wetland and extending into the surrounding uplands, prior to initiation of groundwater perturbations, will provide a basis for monitoring the onset and degree of subsidence. Sighting to a staff gage, centrally located in each wetland, during collection of field data (i.e., every two weeks) also will provide a basis for monitoring the onset and degree of subsidence. The potential for surface subsidence will be greatest for wetlands with a high proportion of organic substrate at the surface. Wetlands which fit this description should be considered high risk wetlands which may be subject to immediate subsidence from either groundwater withdrawals or diversions.

Wetlands containing primarily mineral surface soils also can experience comparable degrees of subsidence via subsurface dissolution, collapse and compaction of the semiconfined aquifer matrix. Subsidence in these wetlands may be delayed for a number of years after initiation of pumping. A network of surveyed elevations and regularly monitored staff gages provides one means for detection of change in wetland hydroperiod and an early warning mechanism for future wetland decline so that corrective measures can be implemented before extensive damage occurs in wetlands experiencing subsidence of surface soils, but may be less effective in wetlands subjected to subsurface subsidence.

Ecological Indicators. Standard vegetative monitoring techniques are not designed to detect early warning signs for wetlands subjected to subsurface drainage. Therefore, water resource managers must seek innovative approaches for detecting wetland declines from groundwater perturbations before damage becomes irreversible.

Aberrant patterns of growth rings in trees and biochemical changes in leaf and wood tissue are internal indicators of periods of stress (Miller *et al.* 1993, Sinclair *et al.* 1987). Since native plants are adapted to natural seasonal and annual variations in water supply for the area in which they grow, only unusually severe conditions are likely to cause noticeable adverse responses to native plants (Sinclair *et al.* 1987). Groundwater withdrawals or diversions can magnify vegetative responses to natural periods of drought or induce water-stress responses during periods of normal or above average rainfall. Consequently, growth rings in trees can reflect periods of groundwater withdrawals based on initiation of growth abnormalities.

Several external ecological indicators are correlated with conditions of stress and subsequent decline in plant vigor. Listed in order of increasing response time, these external indicators include: proliferation of reproductive structures, Spanish moss, and lichens; dieback; and windthrow (Bacchus unpub. data, Bertrand and Hadden 1992, Hendrix, Jr. and Campbell 1990, Sinclair *et al.* 1987). These same external changes, in addition to the establishment of dense, woody, evergreen understory vegetation, occur in depressional wetlands subjected to subsurface drainage (Figure 5, windthrow is not pictured in this photograph). Proliferation of reproductive structures, dieback and windthrow are associated with severe root damage (Hendrix, Jr. and Campbell 1990). The role of some of these and other potential ecological indicators which have been observed in conjunction with depressional wetlands in areas of groundwater perturbations are discussed by Bacchus (1994) and Rochow (1994).

Some vegetative changes can be assessed quantitatively or qualitatively, by establishing permanent locations with rebar where seasonal or annual photographs can be taken. Qualitative information can be gained by panoramic photographs taken perpendicular to the ground, with the camera revolving about the photopoint axis (e.g., 180° at the exterior of a wetland or 360° in the interior of a wetland). A single frame illustrating how this photographic approach can be used to detect encroachment of shrubs and other ecological indicators which may be characteristic of watertable declines is shown in Figure 5.

Similar photopoints can be used to gather quantitative data by positioning the camera parallel to the ground. Photographs of this nature can be taken of groundcover, subcanopy or canopy vegetation using standard or hemispheric lenses (Bacchus and Owen 1993, Bacchus unpub. data). Areas of future groundwater withdrawals, such as the proposed well

Figure 5. Pondcypress wetland responding to subsurface drainage in the Starkey municipal well field, Pasco County, Florida, USA (from Rochow and Rhinesmith 1991). Note dieback of branches, dense subcanopy of evergreen species, and proliferation of Spanish moss.

field west of Albany, Georgia, provide an opportunity to improve past approaches for wetland monitoring. Additional research should be conducted to develop quantitative means for using ecological indicators, in addition to improving qualitative analyses of these indicators.

SUMMARY

Current approaches for monitoring wetlands associated with anthropogenic perturbations of ground water most commonly include: water level data collected subsequent to initiation of groundwater withdrawals or diversions; measurement of water levels in wells constructed in adjacent uplands; evaluation of change in composition of groundcover and subcanopy vegetation; and measurement of radial growth of wetland trees. All of these approaches have constraints which can hinder reliable interpretation of the impact that groundwater withdrawal or diversion is having on nearby wetlands.

Geophysical investigations using ground penetrating radar have been successful in characterizing subsurface strata in depressional wetlands. These data facilitate predictions of high risk wetlands which are susceptible to rapid and severe adverse impacts from subsurface drainage. Additional high risk wetlands are those associated with fracture traces, as determined by identification of photolinears on aerial photographs. Preferential flow through fracture zones may result in destruction of depressional wetlands at considerable distances beyond the cone of depression associated with pumping wells, as predicted by hydrologic models. Photolinear analysis and GPR evaluations can be used to identify wetlands where intensive monitoring should be conducted if anthropogenic groundwater perturbations are occurring. More importantly, these approaches should be used to evaluate proposed locations for groundwater withdrawals to provide a more accurate estimation of the potential loss of natural resources which may occur if proposed withdrawals are initiated. Proposed pumping sites with high risk wetlands located within a 5 km radius of proposed wells should be abandoned in favor of alternative sites.

Water level data rarely are capable of providing accurate documentation of the natural hydroperiod of depressional wetlands associated with areas of groundwater perturbation because sufficient predisturbance data (e.g., ~10 yrs.) are not available and an unknown amount of subsidence occurs in conjunction with groundwater withdrawals. When established prior to initiation of groundwater perturbation, surveyed grid points extending from the uplands through target wetlands, and staff gages centrally located in wetlands, will aid in the detection of subsidence. Comparisons of preperturbation and post-perturbation elevations can provide a means for early detection of irreversible damage to wetlands, so that corrective measures can be taken (e.g., cessation of pumping). These data also can be used to increase accuracy when interpreting water level data. To maintain the integrity of associated wetlands, groundwater perturbations which result in subsidence should be avoided.

Finally, geophysical and hydrologic data alone are incapable of revealing how alterations of the natural hydroperiod are affecting associated wetlands. Therefore, appropriate ecological indicators for the wetland systems involved should be incorporated into standard monitoring programs where groundwater perturbations occur, to improve early detection of adverse impacts to associated wetlands. Support is needed for the development of nondestructive ecological indicators capable of early detection of stress in forested depressional wetlands. If reference wetlands are included in the monitoring plan they should be located beyond the actual cone of depression and beyond the effects of fracture zones (e.g., ~5 km from municipal wells), in wetlands which have not experienced surface or subsurface drainage. All sources of groundwater withdrawals should be metered so that a more accurate estimate of the aquifer stress can be predicted.

Incorporation of recommended alternatives can reduce wetland destruction due to subsurface drainage in the Coastal Plain of Georgia and other southeastern states by avoidance of sites with high risk wetlands. These alternatives also can increase spatial and temporal sensitivity for detecting wetland declines so that modifications can be made before irreversible damage to wetlands occurs. Activities such as proposed groundwater withdrawals which are capable of causing such widespread, irreversible environmental and social problems should include Environmental Impact Statements during the planning stage. Comprehensive evaluations of potential impacts of groundwater withdrawals and diversions do not appear to be a common practice in the SCP.

ACKNOWLEDGMENTS

The author is grateful to the Southwest Florida Water Management District for providing guided access to and information about various wetlands associated with the Starkey, Cypress Creek and Eldridge-Wilde well fields. The manuscript was improved significantly by comments on the initial draft provided by Ted Rochow, SWFWMD; Harold H. Zehner, USGS; and an anonymous hydrogeologist; and by comments on a subsequent draft provided by Ted Rochow and Mark Barcelo, SWFWMD, Ruark Cleary, Florida Department of Environmental Protection, and Bob Keeland, USDI National Biological Survey. Mark Koenig assisted in preparation of Figure 1. Funding was provided, in part, by a grant from the Odum Research Foundation, through the Institute of Ecology, University of Georgia. Additional support was provided by the Gidden Endowment and the Nelson Foundation.

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