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Determining Sustainable Yield for Karst Aquifers of the Southeastern Coastal Plain: A Need for New Approaches

Sydney T. Bacchus

Institute of Ecology, University of Georgia, Athens, Georgia 30602-2202
e-mail: sbacchus@uga.cc.uga.edu

ABSTRACT

Ground water from semiconfined aquifers is a primary source of water for municipal, agricultural, industrial, and domestic use in the southeastern Coastal Plain physiographic province of the United States. This source of water has been considered inexpensive and inexhaustible. However, past and current prices for ground water have not included environmental costs for attempted restoration of natural resources, such as wetlands, lakes, and streams, that have been degraded or destroyed due to ground-water withdrawals. In some areas of Florida, ground-water withdrawals exceeded the sustainable yield of semiconfined aquifers years ago. Unfortunately, this condition went unrecognized because of monitoring constraints and the lengthy time lag between the onset of the problem and when the damage became obvious. In one west-central Florida county, destruction of 6880 hectares (17,000 acres) of wetlands, in addition to the failure of more than 1000 private wells, have been attributed to withdrawals of ground water from the Floridan aquifer. Localized subsidence of organic soils and structural collapse have been documented in these wetlands and adjacent uplands. Reimbursements to private landowners whose wells have failed due to physical destruction, or contamination, and whose property was devalued subsequent to extensive ground-water withdrawals, also have not been considered.

Florida is not the only state where ground-water withdrawals have contributed to localized subsidence caused by oxidation of organic soils and structural collapse of subsurface cavities in forested wetlands and uplands. Similar responses to ground-water withdrawals have been observed in the

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southeastern Coastal-Plain region of Georgia and South Carolina. Preliminary research suggests that pondcypress (*Taxodium ascendens*) may be used to detect unsustainable ground-water withdrawals before extensive economic and environmental damage occurs. Identification of high-risk pondcypress wetlands using geophysical methods, such as ground penetrating radar and fracture-trace analysis could reduce the time, extent, and expense of environmental monitoring by eliminating from the monitoring network less sensitive wetlands and uplands that would have a longer response time. This approach could improve determinations of sustainable yield for karst aquifers while reducing or eliminating large-scale environmental damage due to hydroperiod perturbations and subsequent damage to private property from unsustainable use of ground-water resources.

INTRODUCTION

The primary source of water for residential, commercial and agricultural activities in the southeastern Coastal Plain (SCP) is ground water because of its perceived low cost and limitless availability. However, failure of approximately 1000 private wells in west-central Florida by 1994 due to physical destruction or contamination has been attributed to ground-water withdrawals from the Floridan aquifer. Costs of repairing or redrilling these wells totaled approximately $4 million based on 1994 figures (House Committee On Natural Resources, 1994). Additional economic losses that have not been passed on to water users include loss of timber, devalued lakefront property, and costs of removing diseased trees (Bacchus, unpublished data; Kenneth Webber, Florida Division of Forestry, written communication, January 5, 1995, oral communication, September 11, 1995). Lawsuits are pending for restitution of additional damage to personal property, including damage from subsidence, increased threat of fire, destruction of trees, and other environmental damage. Central Florida can be used as an example of problems which are expected to increase throughout the SCP if current trends of ground-water use continue.

Federal (i.e., Section 404, Public Law 92-500) and state (e.g., Ch. 373, Florida Statutes) laws have existed at least since the 1970s to reduce damage to and loss of wetlands from land-surface alterations because of the contribution of wetlands to water quality and wildlife habitat. These laws regulate land-surface alterations that affect wetlands, such as construction of ditches and placement of fill. Recent estimates that approximately 6880 hectares (17,000 acres) of wetlands have been damaged or destroyed in the central portion of Pasco County, in west-central Florida, due to ground-water withdrawals (House Committee On Natural Resources, 1994) suggest that this activity results in a greater magnitude of damage and destruction to wetlands than the surface alterations that are regulated by federal and state agencies. Federally endangered species, such as wood storks and eagles, use pondcypress (*Taxodium ascendens*) trees for nesting. Therefore, the ramifications of loss of this habitat is greater than mere loss of timber. Currently environmental costs are not included in the price of ground water.

Extensive environmental damage to similar forested depressional wetlands and lakes has been documented in other counties in the central Florida region of the SCP physiographic province, along the Highlands Ridge, and also is attributed to ground-water withdrawals from the Floridan aquifer in west-central Florida (Southwest Florida Water Management District, 1993). The hydrogeologic setting of the coastal karst area is given by Hutchinson (1984). Miller (1984) described similarities of the Floridan sys-

tem as it extends throughout Florida into parts of Georgia, South Carolina and Alabama.

Florida law requires that municipal and agricultural withdrawals from the Floridan and intermediate aquifers cause no significant effects on the overlying water-table aquifer (Ch. 373, Florida Statutes). Early hydrologic models for the west-central Florida area predicted the surficial (water-table) aquifer would not respond significantly to pumping from the Floridan or Intermediate aquifers. However, these models assumed homogeneous, isotropic aquifer conditions, presumably to simplify the modeling effort.

Extensive damage to depressional wetlands was evident several years after initiation of pumping in the west-central Florida area. A cooperative investigation was initiated to determine whether the geophysical characteristics of the wetlands could explain the observed magnitude and patterns of wetland destruction. This cooperative investigation resulted in both hydrogeologic and hydroecologic findings (Stewart and Stedje, 1990; Watson and others, 1990; Rochow, 1994; Rochow and Rhinesmith, 1991) and will be discussed as a case study because of its notable contribution to geophysical characterization of depressional wetlands. However, inherent problems with the study also will be addressed.

Ground-water withdrawals in the SCP are expected to increase with increases in population and development. Currently, no mechanism exists to determine the sustainable yield of aquifers in the SCP because the sensitivity of ecosystems to hydroperiod alterations has not been quantified. Therefore, this factor cannot be incorporated readily into standard hydrologic equations since fluctuations of the water table, if known, cannot be translated into ecosystem response. The economic and other disadvantages of using current approaches to determine sustainable yield (e.g., shallow observation wells) are discussed by Bacchus (1994, 1995b).

This paper describes some of the responses to municipal and agricultural ground-water withdrawals that have been observed in Florida, where extensive hydrologic data (e.g., surface and ground-water levels, aquifer drawdown responses) are available. Results of ground-penetrating radar (GPR) surveys of depressional wetlands in west-central Florida during the case study are compared with recent GPR results from surveys of depressional wetlands in other areas of Florida and in Georgia where extensive water-level data associated with depressional wetlands are not available. The purpose of this comparison is to suggest that depressional wetlands in different locations of the SCP share geophysical characteristics that may result in similar responses to ground-water withdrawals despite differences in local aquifer characteristics.

The primary objectives of this paper are to (1) summarize why current hydrologic approaches for determining the sustainable yield of aquifers in the SCP are inadequate; (2) suggest that ground penetrating radar can be used in conjunction with fracture-trace analysis to identify wetlands that will respond most rapidly and severely to ground-water withdrawals; and (3) propose that monitoring of depressional wetlands supersede water resource criteria that rely on traditional sustainable yield calculations. This paper addresses aspects of several technical fields, with terminology that is not common from one field to the next. Additionally, some technical terms are not applied consistently from region to region, whereas other terms may need to be readdressed for improved application. A discussion of germane terminology will improve communication between disciplines and increase consistency of the application in different geographic regions. Selected terms are addressed here to facilitate the discussion that follows.

TERMINOLOGY

Hydroperiod

Ecological systems such as wetlands depend on natural fluctuations of the water table to maintain their functions. These fluctuations of the water table are known as the hydroperiod. Three important components of a wetland hydroperiod are (1) the depth or stage of fluctuating ground and surface water; (2) the dura-

tion of the water level at a given depth or stage; and (3) the periodicity or seasonality of the water level fluctuations. Disruption of any one of these three aspects can lead to the degradation and ultimate destruction of the wetland and the biota it supports (Bacchus, 1995b).

As an example of (1) and (2), abnormally low or high water levels may have little impact on wetland vegetation if these perturbations are of short duration. However, alterations of water levels that are maintained for longer periods of time may cause significant disruption of wetland vegetation and the ecological system. Likewise, repeated periods of these perturbations would be expected to have more severe impacts on the ecological systems than a single event. The seasonal component (3) is important because most vegetation becomes dormant during winter months. Perturbations of the natural hydroperiod during the winter would be expected to have less impact on the vegetation than the same perturbations during periods of new growth, flowering, or fruiting (spring); or during the growing season and high temperatures (summer).

When they are regulated, ground-water withdrawals generally are constrained physically, for example, by specifying average annual discharge. Seasonal drawdowns of ground-water levels generally are ignored providing that a rebound occurs during the year and "average annual levels" are maintained. This management approach may avoid some ground-water use problems, such as salt-water intrusion or upconing, but probably is inadequate for preventing extraction-related subsidence, and is of little value for preventing ecosystem problems. Seasonal drawdowns generally occur during the spring or summer when ecosystem needs are greatest.

Ground-Water Mining and Overdraft

Two terms, overdraft and mining, are used to describe excessive ground-water withdrawals. Overdraft is the condition of the aquifer when ground water is withdrawn at a long-term average rate that exceeds the aquifer's sustainable yield. Ground-water mining occurs when the total pumping rate plus any reduced ground-water discharge exceeds induced recharge. A strict interpretation of ground-water mining is applied where the piezometric surface continually falls and may be capable of depleting the aquifer.

The current definition of overdraft is inadequate for protecting sensitive ecosystems because sustainable yield is computed from long-term responses and average rates. Irreversible damage to environmental systems and private property can occur following excessive short-term ground-water withdrawals or excessive pumping during times of ecological sensitivity (e.g., periods of low rainfall, reproduction, or intensive growth), even when withdrawals are reduced later so that average withdrawals are moderate. The connotation of the term "overdraft" is innocuous considering the magnitude of damage that can be associated with ground-water withdrawals based on long-term averages. For these reasons, consideration should be given to abandoning the term "overdraft" and applying the term "ground-water mining" to all ground-water withdrawals that exceed the aquifer's sustainable yield, without constraints of long-term responses or average rates.

This recommendation has a political rather than semantic basis. Regulations for other types of mining activities provide routine consideration of environmental impacts and include extensive environmental monitoring. Environmental damage from unsustainable ground-water withdrawals appears to be comparable to environmental damage from other types of mining. Therefore, regulation of ground-water withdrawals that may result in unsustainable yields should be comparable to regulations for other types of mining.

Semiconfined Aquifer

This term is synonymous with "leaky aquifer," which was described by Hantush (1964) and discussed in detail by Fetter (1988). A recent definition is "aquifers, whether artesian or water-table, that lose or gain water through adjacent less permeable layers" (U.S.

Geological Survey, 1989). Karst aquifers in general are semiconfined aquifers (Mark Stewart, University of South Florida, oral communication, 1991, 1995). The importance of the concept of semiconfined aquifers is that leakage through the semiconfining layers is dynamic and will respond to changes in hydraulic head due to pumping. These responses can vary both spatially and temporally, as discussed in the following sections.

Subsidence

The term "subsidence" occasionally is misconstrued to be distinct from the concept of "collapse." This misconception is particularly significant in the southeastern United States where subsidence associated with ground-water withdrawals is considered to be restricted to compaction of unconsolidated alluvial sediments, and is not thought to occur in karst aquifers of the SCP.

The sixth edition of Challinor's *Dictionary of Geology* includes the following definition of subsidence, "When used in relation to the materials that make up the surface layers of the earth, subsidence may mean sinking to a lower level..., but it may also mean a sudden collapse of surface material into a subterranean void" (Challinor, 1986). Subsidence is defined by Allaby and Allaby (1990) as "a progressive depression of the Earth's crust..." and a "sinking or settling of the ground surface due to natural or anthropogenic causes. Surface material with no free side is displaced vertically downward with little or no horizontal movement." Therefore, any lowering of the earth's surface is subsidence, and collapse merely is one form of subsidence. Poland (1984) provided extensive descriptions of subsidence associated with ground-water extraction.

Sustainable Yield

Determining the sustainable yield of an aquifer requires a multidisciplinary approach including physical, chemical, and ecological responses. Problems in determining sustainable yield arise when one or more of these responses is ignored. An early definition of safe, or sustainable, yield from an aquifer was the amount of ground water that can be withdrawn from a basin annually, without producing an undesired result (Todd, 1959). Undesired results later were defined as (1) depletion of ground-water reserves; (2) intrusion of water of undesirable quality; (3) contravention of existing water rights; and (4) deterioration of the economic advantages of pumping (Domenico, 1972).

To this list, Freeze and Cherry (1979) added (5) excessive depletion of streamflow by induced infiltration; and (6) land subsidence. Dingman (1994) provided a more elaborate description on items (2–6), and supplemented the list with the following undesirable environmental results: (7) reductions of levels and/or extent of lakes and wetlands, with consequent loss of valued habitat; (8) reductions in extent of areas where water is available to plants that exploit the capillary fringe, with consequent loss of habitat; and (9) reductions of ground-water outflow to the ocean, with consequent effect on coastal wetlands and/or nearshore benthic marine habitats.

The previous discussion of hydroperiod emphasized the importance of periodicity and seasonality of water-level fluctuations. This is relevant because the standard definition of sustainable yield references "...the amount of ground water that can be withdrawn from a basin annually...." Dingman (1994) more accurately included timing, in conjunction with rates and location of ground-water extraction, as a critical factor for computing sustainable yield. Restricting determinations of sustainable yield to average conditions during a year is ill-founded.

Commonly, the sustainable rate of extraction of ground water from a basin is assumed to be equivalent to the rate of natural recharge (R_{nat}). However, Dingman computed ground-water yield during development, as

$$\Sigma Q_w = \Delta R - \Delta Q_{GW} + \Delta S/\Delta t \qquad (1)$$

where ΣQ_w is the total pumping rate, ΔR and ΔQ_{GW} are the induced changes in recharge and

discharge, respectively, and $\Delta S/\Delta t$ is the rate at which water is withdrawn from aquifer storage. Therefore, the rate of extraction is the result of a decrease in storage and changes in recharge and discharge (Dingman, 1994).

Extraction of ground water can result in increased, or induced, recharge, particularly from depressional wetlands. The primary producing aquifers in the SCP are semiconfined limestone aquifers. The overlying, unconfined aquifers in these karst regions generally contain more acidic water, with the pH of depressional pondcypress wetlands approximating 4.5 (Miller and others, 1993; Bacchus, unpublished data). Therefore, the increased rate and volume of acidic water moving through the limestone may greatly increase the rate of natural dissolution, potentially increasing preferential flow of ground water through the limestone aquifer over the span of years that ground water is withdrawn. This suggests that any increased rate of recharge calculated for a specific discharge is not static and may increase over time.

Unfortunately, virtually no information is available regarding hydroperiod requirements for native flora or fauna that are dependent on ground water. That, combined with regional variations in environmental factors, are some of the reasons why there is no general formula for computing sustainable yield. Determination of sustainable yield in the SCP physiographic province may be feasible by identifying and monitoring high risk wetlands, such as forested depressional wetlands dominated by pondcypress. With this approach, pondcypress wetlands could serve as the "canary in the mine shaft," allowing early detection of unsustainable ground-water withdrawals before costly damage occurs to private property and environmental resources.

CHARACTERISTICS OF DEPRESSIONAL WETLANDS

Pondcypress is a dominant canopy species in forested depressional wetlands throughout the SCP. In Florida, these depressional wetlands are called domes because of the convex-shaped canopy silhouette. Elongated depressional wetlands are called sloughs. In Georgia and the Carolinas, similar depressional wetlands are known as grady ponds and Carolina Bays, respectively.

Sinclair (1982) described cypress wetlands as remnants of sinkholes and sites of active karst. This description suggests that responses to regional ground-water withdrawals may occur locally in depressional wetlands before becoming more widespread. Data from the west-central Florida case study discussed below support Sinclair's conclusions by documenting that the "geology beneath the dome centers was found to be relatively complex, and differs from the geology outside of the domes" (Watson and others, 1990). Aquifer responses routinely are monitored in uplands surrounding depressional wetlands. Consequently, any localized responses in depressional wetlands might not be detected using this approach.

Geomorphology

Collapse Features and Breaches in Lower Permeability Zones

A case study in west-central Florida used four geophysical methods to investigate the subsurface characteristics of selected depressional wetlands: (1) GPR; (2) loop-loop electromagnetics (LLEM); (3) very low frequency (VLF); and (4) horizontal electrical profiling (HEP). Conclusions were that GPR was "the most efficient and effective geophysical method for studying the shallow structural features of cypress domes" (Stewart and Stedje, 1990; Watson and others, 1990). Bacchus and Brook (1996) provided additional details of GPR analysis of the case study and results of a similar study conducted in depressional wetlands in south Georgia and portions of Florida.

Data from the GPR transects across depressional wetlands, in conjunction with lithologic logs from wells constructed at the end points and midpoint of each transect, were used in the case study to describe the following three types of geologic settings in depressional wetlands: (1) shallow depressions (no reported

discontinuities); (2) shallow-depressions with solution features (fig. 1*A*), and 3) relict sinkhole systems (fig. 1*B*). An example of each of the three types of wetland geologic settings was provided and discussed by Watson and others (1990). Type 1 is characterized by an area with a continuous, saucer-shaped, attenuated signal across the transect, representing zones of silty clay and marl. The saucer shape is characteristic of depressional wetlands. Types 2 and 3 are characterized by a reflection-free zone near the center of the wetland, flanked by dipping reflectors on both sides. The reflection-free zone for the type 2 wetland corresponds to fine sand in the center of the wetland, at depths where zones of silty clay and marl occur near the periphery. The fine sand apparently extends to the Tampa Limestone approximately 25 m below land surface. The absence of low-permeability zones in the wetland center was documented by lithologic logs to a depth of approximately 20 m, the maximum depth of a portable tripod drilling rig. The reflection-free zone for the type 3 wetland corresponded to an apparent downward displacement of the silty clay and marl zones into a limestone void through the Tampa formation just above the Suwannee Limestone. Supportive evidence was provided by well cuttings obtained while drilling a 125-m test hole. Use of a tracked all-terrain drilling rig in the interior of this wetland was possible only because production wells caused extensive drawdown of the water table at this site.

Water levels in the surficial aquifer, measured in the center of the type 2 wetland, were approximately 4 m higher than the potentiometric surface of the upper Floridan during the case study period of January 1989 through June 1990. Partial maintenance of the wetland hydroperiod was attributed to a thin layer of clay identified immediately beneath the surface layer of peat in this wetland. Water levels in the surficial aquifer in the type

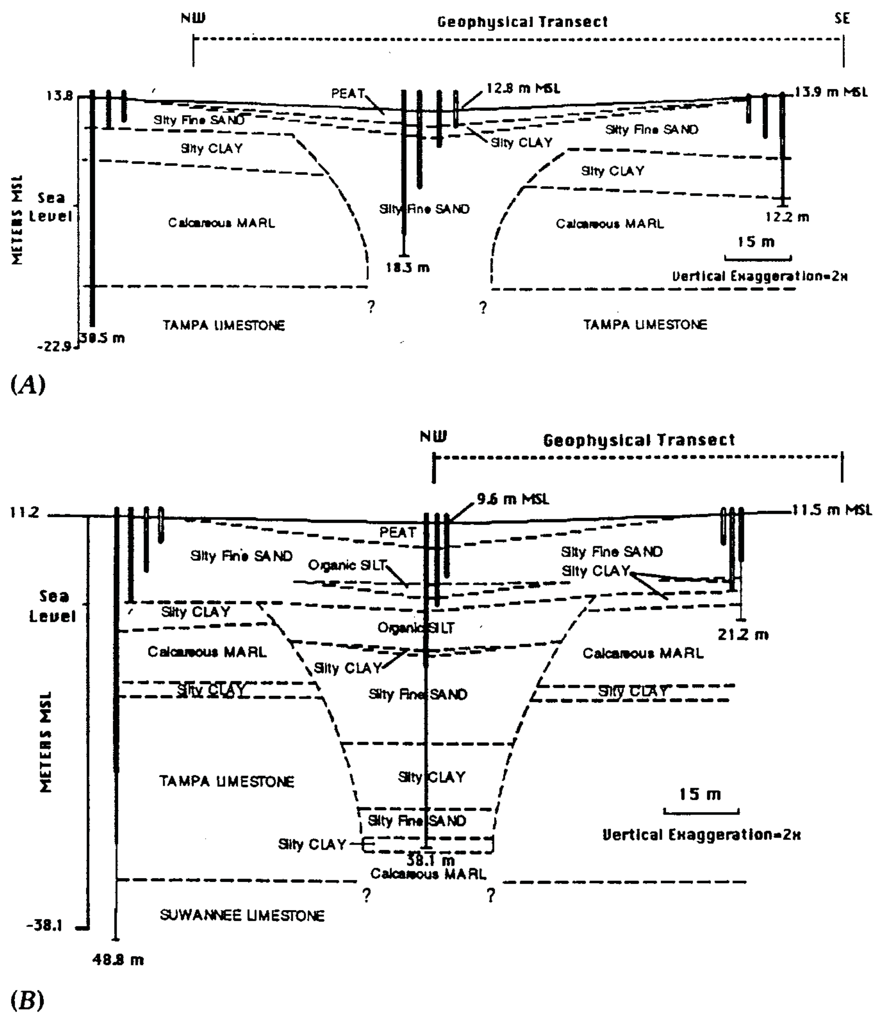


Figure 1. Representative geologic cross sections of depressional pond-cypress wetlands in west-central Florida. (*A*) solution features (type 2 wetland) and (*B*) relict sinkhole features (type 3 wetland). Cross sections are based on geophysical data collected along transects and lithologic data from boreholes in the central and west wetland sites, respectively, of the Starkey well field in Pasco County, Florida (modified from Watson and others, 1990).

3 wetland were less than 1 m above the potentiometric surface of the upper Floridan, and the water levels in the two aquifers responded similarly during the same study period. Therefore, it was concluded that the two aquifers in the type 3 wetland were connected through a leaky confining bed under the wetland.

Fracture Networks

Fracture networks are documented throughout the SCP (Brook, 1985; Brook and Allison, 1986; Brook and Sun, 1982; Brook and others, 1988). Fracture networks often occur with depressional features, such as dolines or sinkholes of various size, uvalas or vertical-sided sinkholes, springs, grady ponds, Carolina bays, pondcypress domes and sloughs, and blind valleys. Fractures are capable of increasing well productivity via increased secondary permeability and preferential flow (Brook, 1985; Brook and Sun, 1982; Brook and others, 1988); therefore, it is reasonable to hypothesize that production wells associated with fracture networks may affect the hydroperiods of depressional wetlands due to localized induced recharge to a regional artesian aquifer, similar to responses associated with breaches in lower permeability strata.

The west-central Florida case study incorporated photolinear or fracture-trace analysis of the study area using color infrared aerial photographs at a scale of 1:56,000. Linear trends observed in these photographs were depicted with three degrees of certainty. Fracture traces may represent fracture networks, another form of discontinuity associated with depressional wetlands.

Field verification can confirm that fracture traces represent zones of increased fracture density but the degree of connection and continuity of fractures is difficult to determine. Stewart and Stedje (1990) described these areas as "vertical zones of generally higher hydraulic conductivity that can be vertical pathways for ground-water flow between the surficial and semiconfined aquifers." Severely damaged wetlands (type 3 wetlands) in the case study area were in close proximity to fracture traces. Thus, case study researchers considered fracture networks, in addition to collapse features and breaches in lower permeability strata beneath the wetlands as potential factors influencing the response of the wetlands to ground-water production.

The reported associations of fracture traces with depressional systems in the west-central Florida area (Stewart and Stedje, 1990) and other southeastern states suggest that similar responses to ground-water withdrawals may occur throughout the SCP. In summary, discontinuities in the form of collapse features, breaches in zones of lower permeability, and potential fracture zones underlying and associated with depressional cypress wetlands examined in the SCP, represent both spatial and temporal (e.g., delayed response) scale problems that are difficult to resolve using current hydrologic approaches for determining sustainable yield. Hydrologic models that do not account for anisotropy in the form of higher hydraulic conductivity and deviations from Darcian flow along bedding planes and joint sets, or in areas with collapse features and breaches in lower permeability zones, will have limited ability to determine the response of the surficial aquifer in these areas.

EMPIRICAL EVIDENCE OF WETLAND RESPONSE TO GROUND-WATER WITHDRAWAL

Drought

Empirical evidence supports the conclusion that the current decline and death of pondcypress and subsidence of organic soil in depressional wetlands cannot be attributed to natural periods of drought. Fossil records indicate that cypress has occupied the SCP region since emergence of the land mass in the Pleistocene. Throughout this time pondcypress has been exposed to countless droughts, and has evolved an effective mechanism for conserving water during cyclical periods of low rainfall. During these periods, pondcypress drops its leaves, halting transpiration. As transpira-

tion ceases, ground-water levels remain near land surface, maintaining sufficient soil moisture to prevent oxidation of organic soils and destruction of the trees by pathogens. When a more favorable hydrologic cycle returns, regrowth of pondcypress leaves occurs.

Dingman (1994) described how pumping can decrease capillary rise by lowering the capillary fringe beyond the reach of plant roots. This phenomenon also may contribute to subsidence of organic soil in the wetlands. The integrity of organic soils in forested depressional wetlands not associated with ground-water withdrawals, or other activities that result in significant hydroperiod alterations, provides further support that subsidence of organic soils is not associated with natural periods of drought.

Old Age

The longevity of pondcypress has been documented by trees estimated to be approximately 600 years old, as determined from stands in the Okefenokee National Wildlife Refuge, Georgia (Duever, 1979). The dead and declining trees associated with areas of ground-water withdrawals do not exhibit characteristics of old age, such as "flat-tops," and estimated ages of dead pondcypress trees at these sites are considerably less than 200 years (Bacchus, unpublished data). Therefore, old age also can be eliminated as the cause of the decline and death of these trees. The existence of stands of pondcypress hundreds of years old provides additional evidence that this species is not affected by natural drought cycles. Concentrations of dead and declining pondcypress near sites of ground-water withdrawals also suggest that periods of below-average rainfall are not the primary causes of the loss of pondcypress wetlands.

Stress Responses

Despite the ability to live hundreds of years, pondcypress appears to be one of the first species to exhibit visible stress responses such as crown dieback in areas of anthropogenic ground-water perturbations (Rochow, 1994; Rochow and Rhinesmith, 1991). In Georgia and South Carolina, pondcypress appear to be affected similarly (Bacchus, 1994; Bacchus, unpublished data). Susceptibility of trees to attack by nonaggressive fungal species has been attributed to ground-water withdrawals in west-central Florida (Kenneth Webber, Florida Division of Forestry, oral communication, September 11, 1995). Similar responses in peach trees grown commercially in Georgia were attributed to water stress (Brown and Britton, 1986). Cessation of irrigation following peach harvests may be an important factor in allowing *Botryosphaeria rhodina* and similar opportunistic fungi to penetrate to interior wood of the peach trees (Kerry O. Britton, USDA Forest Service, 1993, oral communication). This fungal species, in addition to *Fusarium* species, later were isolated from the interior, wood tissue of mature pondcypress trees associated with areas of hydroperiod perturbations in central Florida. A subsequent growth chamber experiment showed that *Botryosphaeria* did not occur in the interior, wood tissue of young pondcypress until after prolonged, controlled water stress (Bacchus, unpublished data).

Complexes of *Fusarium* species, including the same species found in central Florida pondcypress with decayed roots and bases of trunks, were isolated from nursery-grown eastern white pine seedlings with root rot in the north central United States (Ocamb and Juzwik, 1995). Penetration and infection of the pine roots by this fungi is attributed, in part, to stress associated with nonoptimal nursery irrigation (Cynthia M. Ocamb, USDA Forest Service, 1996, oral communication).

The sensitivity of young pondcypress to short-term stress from abnormal water deficits also was documented in a growth chamber study. Changes in carbohydrate composition and reduced leaf size after leaf-out occurred in trees when water was withheld (Bacchus and Hamazaki, 1996). Both responses have been reported in other species of trees subjected to water stress in field and controlled settings. Field observations described previously and

results of this experiment suggest that pond-cypress are sufficiently sensitive to be used as an indicator species for early detection of anthropogenic alteration of natural hydroperiods.

SPATIAL AND TEMPORAL FACTORS REDUCING THE EFFECTIVENESS OF CURRENT APPROACHES FOR DETERMINING SUSTAINABLE YIELD

Model Constraints

Ground-water flow models used to predict hydraulic head in aquifers of west-central Florida assume that zones of low permeability identified in uplands are continuous. These assumptions simplify large-scale hydrologic models, but contribute to the failure to predict significant, localized adverse impacts to depressional wetlands from ground-water withdrawals.

Results of a recent study of forested depressional wetlands and a limited number of herbaceous depressional wetlands south, east, and north of the wetlands evaluated in the case study (Bacchus and Brook, 1996) revealed geophysical characteristics similar to those observed in the west-central Florida case study (fig. 2). Reflection-free zones and dipping reflectors were observed singly, or in combination in many of the wetlands evaluated. Reflection-free zones are areas where the GPR signal is not attenuated, such as zones of sand, or cavities filled with water or air, respectively, as the water table fluctuates. Reflection-free zones represent windows to the underlying aquifer (Dan Delea, Geophysical Survey Systems, Inc., oral communication, April 1996) and provide support that the scale problems described above may extend throughout the SCP.

Subsurface limestone chambers or cavities may be particularly susceptible to delayed responses from ground-water pumping as dissolution of the limestone increases. Structural support of the limestone is reduced as dissolution increases and/or water is removed from void spaces in the aquifer. Delayed collapse of limestone chambers or cavities could explain signs of stress and decline in depressional wetlands of the Southern Water Use Caution Area (SWUCA) east of Sarasota, Florida. These are similar to the signs of stress and decline associated with well fields in the North Tampa Bay Water Use Caution Area (NTBWUCA) area, despite thick confining beds in the SWUCA that are absent in the NTBWUCA.

Increases in dissolution of the underlying calcareous substrate are expected to occur over time, due to the increased volume and/or rate of acidic recharge leaking from the surficial aquifer to the Floridan aquifer. Hydraulic connection between depressional wetlands and underlying regional aquifers may be increased by long-term ground-water withdrawals as a result of factors such as dissolution, cavern collapse, or other forms of subsidence associated with ground-water withdrawals.

These characteristics of depressional wetlands in karst aquifers represent both temporal (e.g., delayed responses associated with geophysical discontinuities) and spatial scale problems that are difficult to resolve with current hydrologic models. Therefore, accurate model predictions of hydraulic head from these aquifers should not be expected. However, output from these models currently is used to determine the sustainable yield of the aquifer.

Delayed Responses to Pumping

Determination of the sustainable yield of a karst aquifer is hindered by the common hydrologic practices described above, in addition to the aquifer's changing response to pumping over time. Some of the phenomena can be predicted, but are difficult to incorporate into hydrologic models to determine sustainable yield. One example is the inelastic response of clastic aquifers to long-term stresses (Fetter, 1988). Other phenomena are less predictable. Some of the short- and long-term delayed responses influencing determinations of sustainable yield are discussed below.

Short-Term Pumping Tests

The hydrologic characteristics of a semiconfined aquifer frequently are determined by pumping tests. This approach reveals immediate responses of the producing aquifer and any overlying water-bearing units, including the unconfined aquifer, or water table. However, long-term responses may vary significantly from short-term responses. Aquifer tests generally fail to determine long-term responses of the unconfined aquifer to ground-water withdrawals from an underlying aquifer because the tests are discontinued before the head changes propagate through the aquitard into the overlying unconfined aquifer (Kruseman and de Ridder, 1990). Long-term aquifer pumping tests are physically and economically infeasible in the SCP because of the difficulty of removing the pump water from the radius of influence of the well.

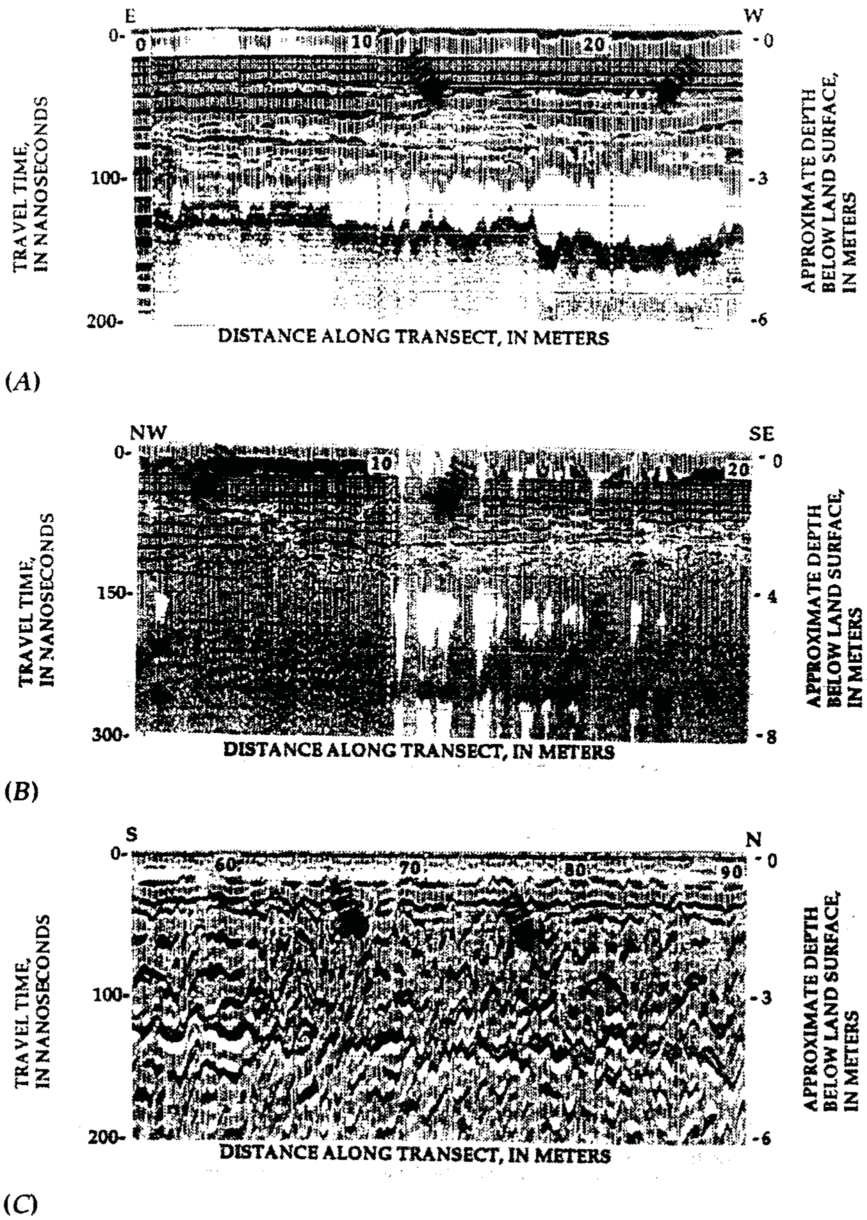


Figure 2. Ground penetrating radar profiles of representative depressional pondcypress wetlands in the southeastern Coastal Plain. Arrows indicate (*A*) reflection-free zones at Wet Prairie #1, Myakka River State Park, southwest Florida; (*B*) subsidence (left arrow) and reflection-free zones (right arrow) at the East Dome, Tosohatchee State Reserve, east-central Florida; and (*C*) dipping reflectors at Dome #4, Okefenokee National Wildlife Refuge, southeast Georgia. Distance (in meters) along the transect is given at the top of the charts (surface), to the left of the 10-m interval ticks (modified from Bacchus and Brook, 1996).

Subsidence of Organic Soils

Subsidence of organic soils is an example of a delayed response that may occur following abnormal drawdown of the water table due to induced recharge. Drawdown of the water table can cause oxidation of drained organic soil layers and may result in a general lowering of the surface of the ground. Surface subsidence can occur within the first year after initiation of ground-water withdrawals and can continue for years as additional organic soils are

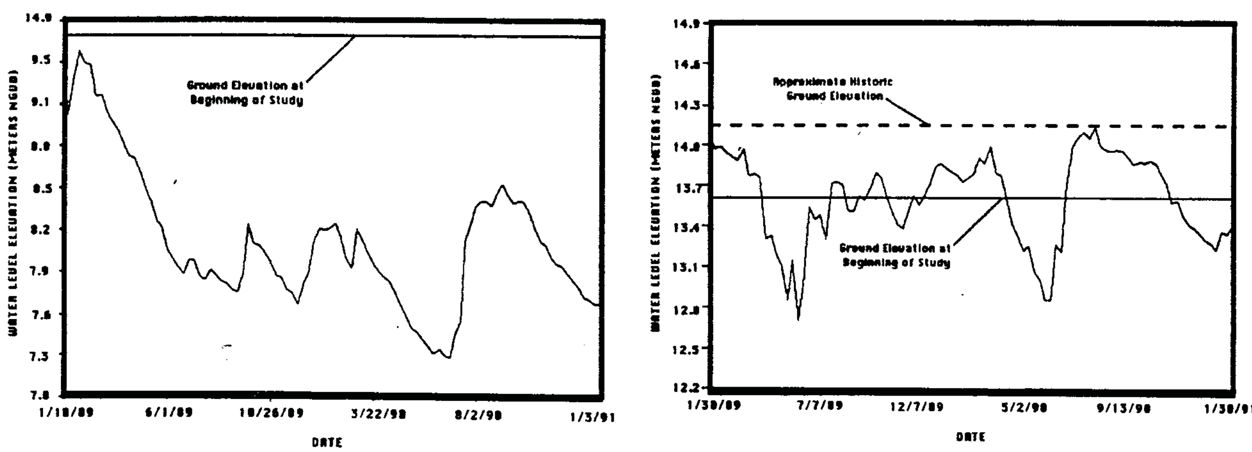
dewatered (Bacchus, 1995a; Bacchus, unpublished data; Rochow and Rhinesmith, 1991).

Rebounding Water Tables

Declines in available water generally are thought to be the cause of water stress in vegetation. However, if the water table rebounds when seasonal pumping is reduced, and subsidence of organic soils or collapse has occurred, vegetation can be subjected to hydroperiods of greater stage and/or duration than normal. Abnormal increases in the stage or duration of natural hydroperiods can result in adverse impacts (e.g., premature decline and death of the trees) similar to those caused by abnormal decreases in stage or duration (Miller and others, 1993; Neufeld, 1984; Penfound, 1952; Stahle and Cleaveland, 1992; Young and others, 1995). Alternating abnormal decreases and abnormal increases in the natural hydroperiod of an area may result in synergistic stresses to the vegetation even in areas where the effects of pumping from the regional aquifer were expected to be buffered by a thick intermediate aquifer beneath depressional wetlands. For example, upland vegetation in the SWUCA, where a thick intermediate aquifer is present, is exhibiting signs of stress and decline similar to that of upland vegetation affected by well fields in the NTB-WUCA, where the thick intermediate aquifer is absent.

Hydrograph Interpretation

An example of another problem associated with current approaches for determining sustainable yield is shown in figure 3, from the west-central Florida case study (Rochow and Rhinesmith, 1991; Watson and others, 1990). Shallow observation wells were constructed in selected depressional wetlands several years after pumping began and hydrographs from these surficial wells were examined to evaluate the hydroperiod of the wetlands. At the Starkey well field site in Pasco county, Florida, the western site (fig. 1*B*) was determined to be affected by ground-water withdrawals because the water table did not rise above the ground elevation that was measured at the beginning of the study (fig. 3*A*).



(*A*) (*B*)

Figure 3. Hydrographs of two depressional pondcypress wetlands in the Starkey well field, Pasco county, Florida. The western site (*A*) was determined to be affected by ground-water withdrawals based on failure of the water table to fluctuate above the ground elevation documented at the beginning of the study. The eastern site (*B*) was determined to be unaffected by ground-water withdrawals based on fluctuations of the water table above the ground elevation documented at the initiation of the study. However, the ground elevation referenced in this study is approximately 0.5 m below the historic ground elevation due to subsidence of organic soils following groundwater withdrawals (modified from Watson and others, 1990).

The eastern site at the same well field (geologic cross section not shown) was determined to be unaffected by pumping because the water table rose above the ground elevation that was measured at the beginning of the study (fig. 3*B*). However, examination of the bases of pondcypress trees in the eastern site reveals that approximately 0.5 m of subsidence from oxidation of organic soils had occurred in this wetland prior to construction of the observation wells (Bacchus, 1995b). Similar evidence was observed in other forested depressional wetlands in well fields described in the case study, in wetlands associated with other well fields such as Cypress Creek, and at sites of agricultural withdrawals throughout the SCP. The location of Cypress Creek is shown in figure 4. Subsequent evaluations at the case study sites confirmed that wetlands determined to be "unaffected" contained pondcypress that were dead or in advanced stages of decline. The response of the these trees to pumping apparently were delayed compared with the pondcypress in type 3 settings. The differences in response of pondcypress in type 1 and 2 settings could have been due to a delay in the onset of hydroperiod perturbations or less severe hydrologic impacts in wetlands previously determined to be unaffected. A more detailed discussion of stress responses is presented by Bacchus (1995b).

Water level responses prior to and during the initial period of ground-water withdrawal were not monitored. However, if the approximate historic ground elevation is superimposed on the hydrograph reported for the eastern wetland (fig. 3*B*), the water table at this site also would fail to achieve typical water-level fluctuations associated with these depressional wetlands. Similar subsidence of organic soils was reported for other wetlands in that study after initiation of the study (Rochow and Rhinesmith, 1991). This phenomenon represents another temporal scale problem with a current hydrologic approach for determining the sustainable yield of a karst aquifer.

Hydrologic data collected in wetlands during or after ground-water withdrawals begin, that are not referenced to stable benchmarks, cannot be used to determine whether the hydroperiod of a wetland is being affected by ground-water withdrawals because of potential past and ongoing subsidence caused by the withdrawals (Bacchus, 1995b).

Since prewithdrawal hydrogeologic conditions of the depressional wetlands are unknown in the west-central Florida area, the degree to which long-term ground-water withdrawals may have increased the permeability of or caused the various discontinuities identified by GPR in the case study (e.g., anthropogenic subsidence) cannot be determined. However, evidence of past and ongoing induced recharge from the surficial aquifer to the Floridan is documented in the increasing loss of organic soils of the depressional wetlands. Empirical evidence supports the conclusion that this loss is due to oxidation and compaction from anthropogenic drawdowns of the water table, resulting in subsidence of the organic soils. Although long-term head decline can cause these responses, subsidence is not contingent upon long-term declines in head. Subsidence of organic soils has been observed in wetlands in Florida within one year of hydroperiod perturbation, when long-term head decline was not a factor (Bacchus, unpublished data).

A survey of water-resource managers in Florida, Georgia, South Carolina, and North Carolina revealed that, as in the case study wetlands, prepumping ground surface elevations are not established in depressional wetlands of the SCP where significant ground-water withdrawals occur or will occur. Soil levels prior to anthropogenic drawdowns of the surficial aquifer can be determined by evidence at the bases of long-lived trees, such as pondcypress (Bacchus, 1994, 1995b). However, subsurface subsidence which may have occurred due to ground-water withdrawals cannot be detected in this manner. Subsurface compaction or collapse may occur in the absence of, or in addition to subsidence of organic soils.

Multibasin and Cumulative Impacts

The standard definition of sustainable yield references "basin" without a distinction between watersheds, which are basins that are relatively easy to delineate by surface drainage, and ground-water basins, which may be applied to local or regional aquifers and are more difficult to delineate. Ground-water withdrawals for municipal, agricultural, and industrial uses often are from regional aquifers that may have considerable lateral extent. Agencies that attempt to manage water resources in the SCP generally focus on drainage basins. Drainage basin boundaries or divides are identified by areas of highest elevations surrounding lower elevational features such as streams. For planning purposes drainage basins generally are treated as distinct entities, with the amount of ground water available for use in the basin considered to be equivalent to the rate of natural recharge from rainfall within the drainage basin boundaries. However, drainage basins are underlain by regional aquifers that extend beyond the basin boundaries.

The previous discussion of equation 1 describes the fallacy of the natural recharge assumption. More specifically, cumulative impacts from numerous large capacity wells in a regional aquifer may influence surficial aquifers across drainage basin boundaries. Therefore, groundwater availability calculated from watershed-specific data may be considerably greater than actual availability of groundwater in the watershed, due to excessive pumping in other drainage basins. This scenario results in drawdown contours extending across basin boundaries, as seen in figure 4, where the 1-ft cumulative drawdown contour predicted for the surficial aquifer extends beyond the Cypress Creek drainage basin and into the Pithlachascotee River drainage basin (Charlotte County et al. v. Southwest Florida Water Management District, 1995, unpublished). Therefore, the individual or cumulative effects of regional aquifer withdrawals from wells constructed in one drainage basin may have significant impacts in other drainage basins where limited withdrawals may be occurring.

ALTERNATIVES FOR DETERMINING SUSTAINABLE YIELD OF KARST AQUIFERS

Considerations for Establishing Reference Systems

An effective means of assessing damage to a natural system (e.g., wetlands, streams, lakes) is to identify one or more unperturbed "reference" systems of the same type as the system of interest in an area where a disturbance, such as a well field, will occur. Responses of the systems of interest then are compared to responses in the selected reference systems over time. Regional water management districts in Florida recently released recommendations for assessing impacts of ground-water withdrawals to natural systems using a drainage basin approach (Lowe, 1994). One recommendation was to subdivide each district or state into regional and local reference areas where extensive pumping does not occur. In districts where extensive ground-water withdrawals have occurred for many years, no true "reference areas" may exist for reasons described above. Pumping large capacity wells in regional aquifers can result in multibasin impacts, and pumping from multiple wells can result in more extensive and severe cumulative impacts (see fig. 4). These impacts can alter ground-water flow divides and cause significant harm to natural systems such as wetlands located far from the pumping wells. Lack of knowledge of the actual extent of the cone of influence from cumulative ground-water withdrawals severely restricts the ability to establish reference systems with "normal" hydro-periods.

Identifying and Monitoring High Risk Depressional Wetlands

Depressional wetlands similar to those described above occur throughout the SCP.

Signs of pondcypress decline similar to declines occurring in Florida have been observed in pondcypress stands throughout the lower SCP of Georgia (e.g., Charlton, Clinch, and Ware counties) and the upper SCP of South Carolina (Bacchus, 1995b). These responses have not been observed in conjunction with natural cycles of low rainfall in the absence of anthropogenic ground-water perturbations and may be useful as indicators of unsustainable ground-water withdrawals. Depressional wetlands in other SCP counties of Georgia with extensive ground-water withdrawals (e.g., Camden, Chatham, Dougherty, Glynn, Liberty, Lowndes, and Wayne) also may be experiencing decline based on field observations of pondcypress wetlands.

Preliminary research suggests that pondcypress is an indicator species that may be used as a sensor for early detection of anthropogenic hydroperiod alterations (Bacchus, 1994; Bacchus, unpublished; Bacchus and Hamazaki, 1996). Consequently, identifying and monitoring pondcypress wetlands that are most vulnerable to ground-water perturbations may provide an indirect mechanism for detecting unsustainable ground-water withdrawals before extensive economic and environmental damage occurs. Identification of high risk pondcypress wetlands using geophysical methods and fracture-trace mapping could reduce the time, extent, and expense of environmental monitoring by eliminating from the monitoring network less sensitive wetlands and uplands that will have a longer response time. This approach could improve attempts to determine sustainable yields from karst aquifers while reducing or eliminating large-scale environmental damage due to hydroperiod perturbations and subsequent damage to private property from unsustainable ground-water withdrawals.

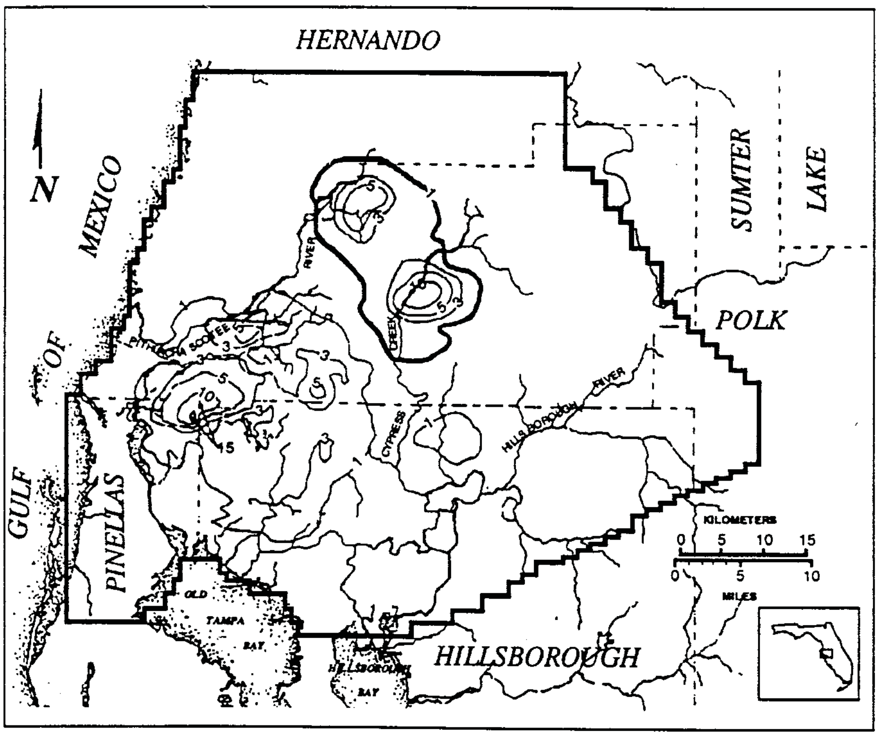


Figure 4. Map showing the extension of the 1-ft drawdown contour (upper center, bold contour) across the Pithlachascotee Creek (upper left) and Cypress Creek (lower center) drainage basins, Pasco county, Florida, based on predicted cumulative surficial aquifer drawdown after 1 year using the 1994 north Tampa Bay Florida (NTB) model, when pumping Pasco county well fields at 1988 permitted average daily rates. The remaining numbered drawdown contours represent additional predicted drawdowns (in feet) of the surficial aquifer due to the pumping, using the NTB model (modified from Charlotte County et al. v. SWFWMD, 1995).

CONCLUSIONS

Noninvasive geophysical techniques such as GPR and fracture-trace analyses have been used to identify apparent structural discontinuities (breaches in lower permeability zones, collapse features, and fracture networks) associated with depressional wetlands in the SCP. Evidence of localized impacts, including subsidence of organic soils and hydroperiod alteration, suggests that these discontinuities are resulting in preferential flow, induced

recharge, and increased rates and magnitude of dissolution and collapse. These conditions can cause unpredicted destruction of natural resources and private property. These conditions also limit the ability of current hydrologic approaches to determine the sustainable yield of a karst aquifer in the SCP. An alternative approach includes (1) avoiding standard designation of reference systems and monitoring locations; (2) evaluating geophysical conditions surrounding ground-water withdrawal areas remotely, using GPR and fracture trace analyses, to identify depressional wetlands that may respond most rapidly and severely to ground-water withdrawals; and (3) concentrating monitoring in and around these high risk wetlands. This approach can promote sound development of groundwater resources in the SCP while simultaneously protecting private property; maintaining valuable wetlands and endangered species habitat; and reducing the time, extent, and expense of monitoring.

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