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UNCALCULATED IMPACTS OF UNSUSTAINABLE AQUIFER YIELD INCLUDING EVIDENCE OF SUBSURFACE INTERBASIN FLOW[1]

Sydney T. Bacchus[2]

ABSTRACT: Unsustainable withdrawals from regional aquifers have resulted in adverse impacts considerable distances from the point locations of supply wells. In one area of the southeastern (SE) Coastal Plain, conservative estimates for repair/replacement of some residential wells damaged or destroyed by unsustainable yield from the Floridan aquifer system exceeded $4 million. However, a comprehensive assessment of damage/economic loss to private property and public resources due to unsustainable yield from that regional karst aquifer has not been made. Uncalculated direct costs to home-owners from damage attributed to those withdrawals are associated with destruction of homes from increased sinkhole formation, devalued waterfront property, and removal of diseased and dead trees. Examples of other uncalculated economic burdens resulting from unsustainable aquifer yield in the SE Coastal Plain include: (1) irreversible damage to the aquifer matrix and concomitant increased potential for groundwater contamination, (2) large-scale wildfires with subsequent degradation of air quality, debilitation of transportation corridors, and destruction of timber, wildlife habitat and property, and (3) destruction of "protected" natural areas. This paper provides a general background of the regional Floridan aquifer system's karst characteristics, examples of known impacts resulting from ground water mining in the SE Coastal Plain, and examples of additional damage that may be related to unsustainable yield from the Upper Floridan aquifer. Costs of these impacts have not been calculated and are not reflected in the price users pay for ground water. Evidence suggests that the classic watershed management approach must be revised in areas with mined regional karst aquifers to include impacts of induced recharge from the surficial aquifer, and subsurface interbasin flow. Likewise, associated impacts to surface water and interrelated systems must be calculated. The true cost of groundwater mining to this and future generations should be determined using a multidisciplinary approach.
(KEY TERMS: ecosystem management; groundwater hydrology; hydroecology; public resources; water management; watershed management.)

INTRODUCTION

In Florida and the southeastern (SE) Coastal Plain of Georgia, the Upper Floridan aquifer is the major source of ground water. In 1990, the U. S. Geological Survey (USGS) compiled data for a newly defined study area, the Georgia-Florida Coastal Plain, that extended from west-central Florida, north through Georgia's Coastal Plain. Based on estimates and metered withdrawals, ground water use in this area was determined to be approximately 2,888 million gallons per day (mgd), with 91 percent of this ground water withdrawn from the Floridan aquifer. However, water use estimates are the average daily quantities derived from annual data (Marella and Fanning, 1996). For this and other reasons, these estimates should be considered conservative, since withdrawals may vary considerably on a seasonal basis and in response to periods of reduced rainfall.

Water resource specialists involved with the various aspects of ground water production in the SE Coastal Plain generally have maintained a narrow focus. The primary issues of concern have been contamination of the aquifer by pollutants from the surface or from below by saline water, as evidenced by the "Interim Strategy for Managing Salt Water Intrusion in the Upper Floridan Aquifer of Southeast Georgia" (Georgia Environmental Protection Division, 1997).

Little attention has been given to the impacts of groundwater mining on surficial aquifers and living systems supported by those surface/ground water systems. For example, in 1978, the USGS began a regional scale study of the Floridan aquifer system

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[2]Post-Doctorate, Institute of Ecology, University of Georgia, Athens, Georgia 30602-2202 (E-Mail: sbacchus@arches.uga.edu).

under its Regional Aquifer-System Analysis (RASA) program. This was a systematic attempt to study several regional aquifers, without regard to political subdivisions. The selected regional aquifers cover much of the country and provide a significant part of the nation's water supply. The overall objectives of the Floridan aquifer-system study were to provide (1) a complete description of the hydrogeologic framework and geochemistry of the entire aquifer system, (2) an analysis of the groundwater flow through the aquifer system, (3) an assessment of the effects of large withdrawals of ground water on the aquifer, and (4) an appraisal of water-management alternatives (Krause and Randolph, 1989). As was the case for the state of Georgia, referenced above, contaminations of the aquifer by intrusion of saline water have been considered the primary "effects of large withdrawals of ground water on the aquifer." However, "water-management alternatives" cannot be "appraised" without knowledge of the ramifications and costs of the exploited resource. Consequently, RASA is not capable of meeting Objective 4.

Likewise, specialists involved with surface water generally focus on the watershed as the entity governing the response of surface water. Groundwater aspects generally are restricted to infiltration and lateral or base flow, with no consideration given to induced recharge associated with groundwater mining of the underlying regional aquifer.

The first objective of this paper is to provide a general background of the karst characteristics of the regional Floridan aquifer system to increase awareness regarding the interaction between local-scale surficial aquifers and the underlying regional aquifer. Second, examples are provided of recently documented environmental damage in west-central Florida due to induced recharge from the surficial aquifer in response to unsustainable withdrawals from the Floridan aquifer system. Additional examples are provided of similar damage in systems underlain by this regional karst aquifer near groundwater mining centers. These examples include groundwater mining centers associated with the Atlantic coast of northeast Florida and south Georgia, where investigations of hydrologic impacts comparable to those in west-central Florida have not been conducted. Finally, it is suggested that the classic watershed management concept should be revised in areas underlain by a mined regional karst aquifer to include impacts of the induced recharge to underlying aquifers and subsurface interbasin flow. Categories of additional research are suggested to determine the true cost of groundwater mining to this and future generations.

BACKGROUND

Terminology

This paper includes hydrogeologic terms that may not be common vocabulary for those who work with surface water systems or noncarbonate aquifer systems. Additionally, confusion over the use of some terms is encountered routinely in the literature. Unfortunately, there is no single reference source that includes a comprehensive list of terms related to groundwater mining impacts. Definitions of some of the more relevant terms were compiled by Bacchus (1998, 1999c). These include "semiconfined aquifer" (Fetter, 1988; Hantush, 1964; USGS, 1989), where leakage through the semiconfining layers is dynamic and will respond to changes in hydrostatic pressure due to pumping; "subsidence" (Allaby and Allaby, 1990; Challinor, 1986), which encompasses any lowering, sinking, or settling of the ground surface, including sudden collapse; and "sustainable yield." Determining the sustainable yield of an aquifer requires a multidisciplinary approach, including physical, chemical, and ecological responses (Domenico, 1972). Undesired results of excessive extraction include: (1) depletion of groundwater reserves; (2) intrusion of water of undesirable quality; (3) contravention of existing water rights; (4) deterioration of the economic advantages of pumping (Domenico, 1972); (5) excessive depletion of streamflow by induced infiltration; (6) land subsidence (Freeze and Cherry, 1979); (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 groundwater outflow to the ocean, with consequent effect on coastal wetlands and/or nearshore benthic marine habitats (Dingman, 1994). Finally, the distinction is made between "groundwater mining" and "overdraft" (Dingman, 1994) and "fractures," "joints," and "faults."

The current definition of overdraft is inadequate for protecting sensitive ecosystems because sustainable yield is computed from longterm responses and average rates. Irreversible damage to environmental systems and private property can occur following excessive groundwater withdrawals over a short period of time 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. Since environmental damage from unsustainable groundwater withdrawals appears to be comparable to environmental damage from other types of mining, use of the term "overdraft" should be abandoned, and the term "groundwater mining" should be used.

According to strict definition, joints and faults are types of fractures. Faults are fractures or fracture zones along which displacement of the sides has occurred relative to one another. Joints are fractures along which no appreciable movement has occurred (Allaby and Allaby, 1990).

Characteristics of the Floridan Aquifer System

The Floridan aquifer system extends throughout Florida, and north and west into the SE Coastal Plain of South Carolina and Mississippi, respectively. It has been divided into six subregions for analysis and modeling purposes (Figure 1). Vertically, downdip, the aquifer system has been divided into two major permeable zones (the Upper and Lower Floridan

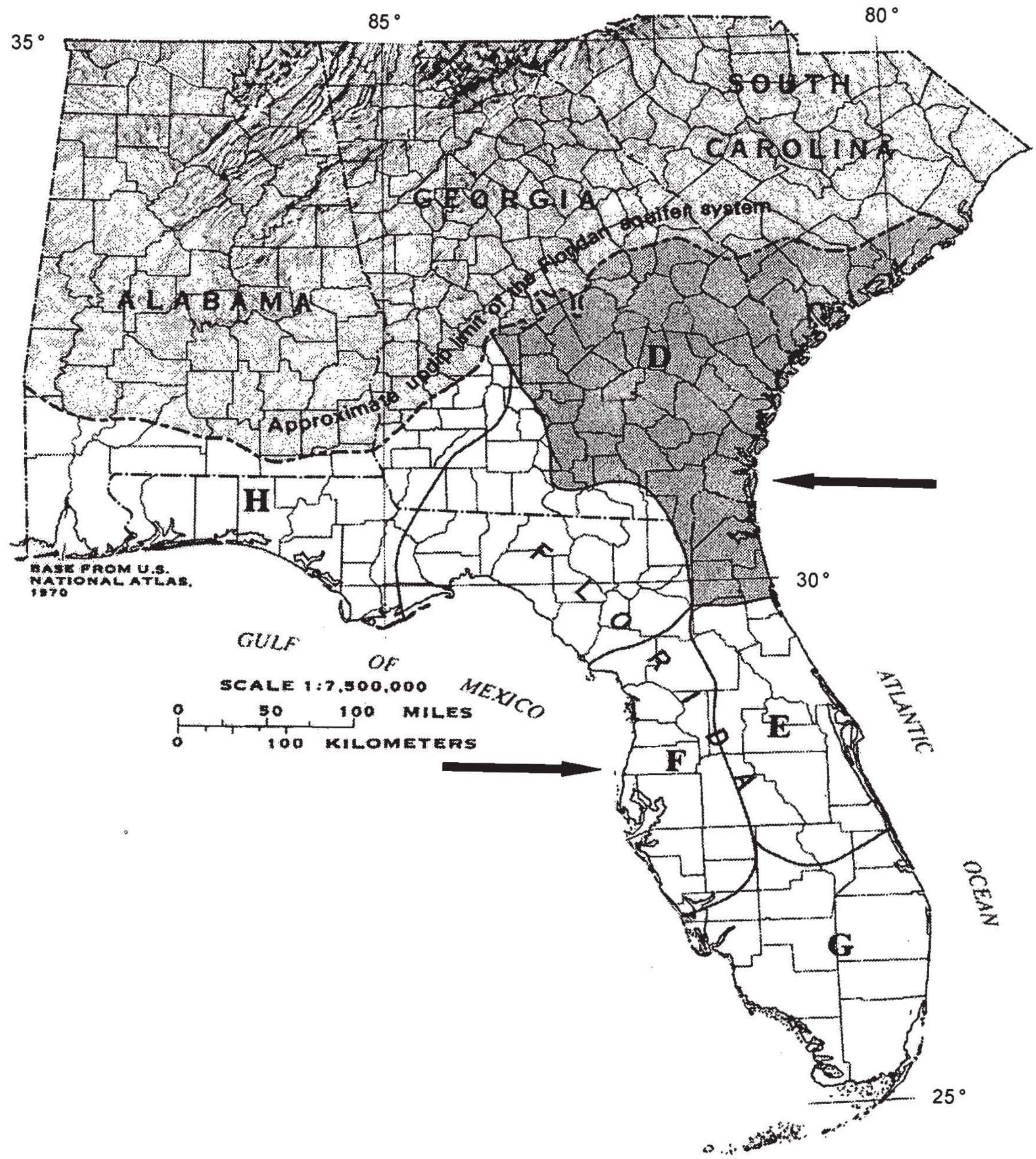

Figure 1. Extent and Six Subregions of the Floridan Aquifer System, USA (from Krause and Randolph, 1989). The west coast arrow indicates the general location of the Northern Tampa Bay Water Use Conservation Area and the east coast arrow indicates the location of Cumberland Island National Seashore.

aquifers), but is hydraulically connected to varying degrees. It is comprised of a thick sequence of carbonate rocks primarily from the Paleocene to early Miocene. Localized cavernous zones occur throughout.

The Upper Floridan aquifer within this regional aquifer system is composed primarily of the Ocala Limestone and equivalents from the late Eocene. The Ocala is an extremely fossiliferous limestone, particularly in the upper portion, with high effective porosity and permeability. High secondary permeability has developed by the movement of ground water along bedding planes, fractures, and other zones of structural weakness. The enlargement of these features occurs via dissolution of the carbonate matrix of the aquifer. This secondary porosity and permeability in the carbonate rocks, combined with areas of unconfinement, result in the characteristic heterogeneity in the regional aquifer system. Additionally, the preferential orientation of structural features (e.g., fractures) along which ground water may flow freely in some locations, increases the anisotropy of this aquifer system.

Throughout much of its extent, the Upper Floridan aquifer is overlain by the Hawthorn Formation of late and middle Miocene age. The Hawthorn is composed of all strata above the Upper Floridan aquifer and below the surficial aquifer. It includes not only clay of extremely low permeability, but also local sand beds of moderate permeability. It is considered as the upper "confining" zone for the Floridan aquifer system; however, in places it thins to a feather edge and is breached by sinkholes and other solution features. In these cases, semiconfined conditions occur.

The surficial (water table) aquifer functions as a source or sink to the underlying Floridan aquifer system. In areas where the water table in the surficial aquifer is above the potentiometric surface of the Floridan, the surficial aquifer recharges the Floridan by downward leakage through the upper confining unit. Where the head gradient between the surficial aquifer and the Floridan is in the opposite direction, the surficial aquifer receives upward leakage from the Floridan (Krause and Randolph, 1989; Miller, 1986).

Areas of preferential dissolution in the Floridan aquifer system and related karst systems are associated with bedding planes, fracture planes, and the water table. These features provide pathways for preferential flow, and occur from inland to offshore (Beck, 1988; Field *et al.,* 1997; Kindinger *et al.,* 1994; 1997; Krause and Randolph, 1989; Popenoe *et al.,* 1984; Snyder *et al.,* 1989; Spechler, 1994; Spechler and Phelps, 1997; Spechler and Wilson, 1997; Stewart and Stedje, 1990; Warner, 1997; Watson *et al.,* 1990).

Preferential flow in this regional karst aquifer via these discontinuities has been documented on the mainland in Florida and Georgia by numerous researchers. Most have focused on lateral flow within the aquifer system (Brook and Sun, 1982; Brook, 1985; Brook and Allison, 1986; Brook *et al.,* 1988; Warner, 1997) or upward leakage of saline water into the Upper Floridan aquifer from deeper aquifers where semiconfining units are thin or breached by fractures, collapse features, or other structural anomalies (Spechler, 1994; Spechler and Phelps, 1997). Horizontal flow in the Upper Floridan aquifer through these preferential pathways has been measured at approximately 7 to 8 km/day (Beck, 1989; Patten and Klein, 1989) in two major groundwater basins of the Upper Floridan aquifer, as designated by Bush and Johnston (1988).

Considerably less published literature is available regarding increased downward leakage (induced recharge) from the surficial aquifer into the Upper Floridan aquifer. Williams (1985) provides a detailed description of how these depressions represent significant conduits for movement of water vertically from epikarstic (surficial) aquifer systems into the underlying regional aquifer. He describes how the epikarstic water table is drawn down above highly permeable vertical leakage paths underlying these depressions, thus creating "point-recharge depressions." This process is compared to "draw-down depressions" like those associated with wellfields (a group of wells, often linear). The three-dimensional section of an epikarstic aquifer in Figure 2 from Williams (1985) illustrates the characteristic increase in vertical hydraulic conductivity of approximately four orders of magnitude from the perimeter of these depressions to the interior. The contour lines represent an order of magnitude change in vertical hydraulic conductivity, with characteristic values ranging from 10^{-2} m/d at the periphery to 10^{3} m/d in the center of the depressions. This demonstrates the magnitude of point recharge that can occur in the interior of these depressions, resulting in various forms of subsidence (e.g., oxidation/compaction of organic layers, compaction of semiconfining zones, catastrophic collapse of residuum or surrounding karst matrix).

Approximately a half dozen types of sinkholes have been described in the literature (Beck, 1988; Beck and Sayed, 1991; Kindinger *et al.,* 1994; Newton, 1977; Schmidt and Scott, 1984). Sinkholes result primarily from two processes, transport of surficial material downward through solution-enlarged channels, or collapse of the rock roof over large bedrock cavities (Beck and Sayed, 1991). However, the most favored vertical path dissolves more rapidly than the surrounding areas because it carries more water (Kindinger *et al.,* 1994). Therefore, a feedback mechanism exists between these processes. Williams (1985) provides a detailed discussion of the reinforcing factors in the development of these point-recharge features. These processes may occur naturally, or may be induced by anthropogenic activities. Sinclair (1982) explains that although solution of the underlying rocks is the ultimate cause of sinkholes, they also can be induced by abrupt changes in groundwater levels caused by pumping. Newton (1976; 1977) describes how sinkholes also may be induced by construction activities, indicating that damage from induced sinkholes far exceeds damage from naturally formed sinkholes.

The development of sinkholes throughout the SE Coastal Plain generally is associated with northwest-southeast fractures and primarily is due to dissolution of limestone by slightly acidic water. This dissolution is enhanced by water-level fluctuations (Littlefield *et al.*, 1984; Price, 1984; Schmidt and Scott, 1984; Upchurch and Lawrence, 1984). Large numbers of sinkholes have been documented along lineaments and lineament intersections near wellfields (Sinclair, 1982) and areas of groundwater mining for irrigation (Metcalfe and Hall, 1984). The preferred alignments of sinkholes reinforce the concept that these areas of preferential dissolution can form extensive interlinked networks that may extend for considerable distances both vertically (through the semiconfining layer) and horizontally (through horizontal dissolution cavities in fractures and bedding planes).

The original formation of sinkholes throughout the Floridan aquifer system occurred during the Tertiary, as groundwater levels declined with the most dramatic periods of sea-level regression (Pitman, 1978; Popenoe, 1984; Vail and Mitchum, 1978). During the late Oligocene and early Miocene, sea level fell to approximately 80 to 100 m (240 to 300 ft) below the present level (Vail and Hardenbol, 1979). The mechanisms responsible for paleo sinkhole formation during the Tertiary were the same as those described above for the formation of present day sinkholes. However, the paleo sinkholes formed over a geologic time scale during periods of major declines in sea level. Since the 1900s, sinkhole formation has been rapid, due to anthropogenic groundwater drawdowns (Ford and Williams, 1989; Metcalfe and Hall, 1984; Newton, 1977). For example, Ford and Williams (1989) report more than 1700 collapses around five wellfield cones of depression in Alabama in recent decades and predict similar responses to fluid extraction from karst wherever such extraction occurs.

As subsidence continued during the Tertiary Period (approximately 1.8 to 5 million years ago), some individual paleo sinkholes in the same general area coalesced to form larger, elongated depressions. Over thousands of years these relict sinkholes of various sizes filled with sediment, and water levels fluctuated between shallow ground water and shallow surface water. This created the substrate and special hydrologic conditions for colonization by depressional wetland species. Recent geophysical and hydrologic investigations provide additional support for the conclusion that depressional wetlands in the SE Coastal Plain have colonized relict or paleo sinkholes and have more direct contact with the underlying Floridan aquifer system (Blood *et al.*, 1997; Bacchus and Brook, 1996; Stewart and Stedje, 1990; Watson *et al.*, 1990). Figure 2 can be used as a conceptual model of vertical hydraulic conductivity in the depressional wetlands of the SE Coastal Plain.

Forested examples of these depressional wetlands that occupy the elongated systems are known generally as sloughs. Examples of depressional wetlands in Florida and Georgia that are more radially symmetrical are called pond-cypress domes. This name is derived from the dome-like silhouette of the pond-cypress trees due to a gradual increase in height of

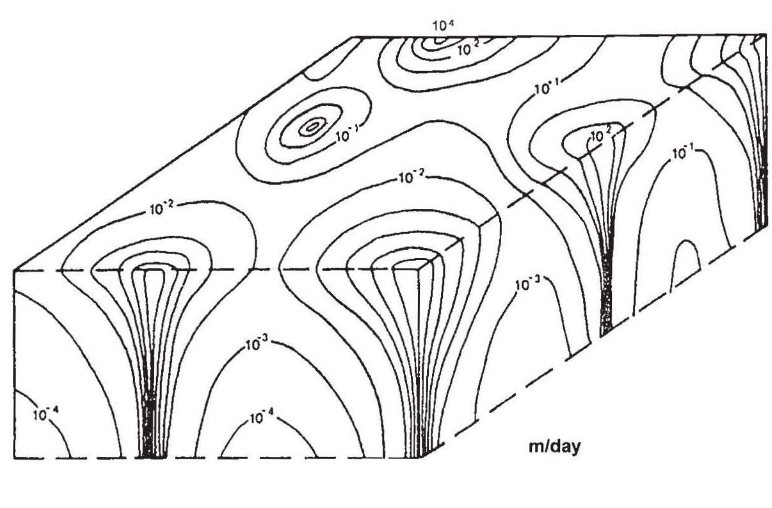

Figure 2. Characteristic Increase in Epikarstic Vertical Hydraulic Conductivity from the Perimeter Toward the Center of Karst Depressions (from Williams, 1985).

the trees from the periphery of the wetland to the center, presumably where the greatest connection with the underlying aquifer occurs. Near the northern range limit for pond-cypress in the SE Coastal Plain, depressional systems with pond-cypress are known as Carolina Bays. Hypothesized origins and orientation of Carolina Bays have included impacts from a large meteor swarm, or comet (Savage, 1982) and wind (Carver and Brook, 1989; Kaczorowski, 1977). Bacchus (1994) found decline characteristics and other indicators of anthropogenic groundwater perturbations in Carolina Bays at a site in South Carolina that were similar to those in depressional pond-cypress in groundwater mining areas of Georgia and Florida. Geophysical evaluations similar to those conducted in Florida have not been performed in the Carolina Bays at the South Carolina site. However, the origin of Carolina Bays may have been structural weaknesses including relict sinkholes in the underlying bedrock that subsequently were eroded and scoured by paleowind. The relict sinkholes with water too deep for colonization by trees such as pond-cypress or other emergent vegetation remained open-water systems. In some cases the centers of cypress domes have subsided to the point where water in the surficial aquifer is too deep during the wet season for the trees to survive. These wetlands are known as donuts because of the "holes" in the center where trees are absent. More attention has been given to the interconnection of these open-water systems with the Floridan aquifer system with increasing groundwater withdrawals from the Floridan aquifer system (Kindinger *et al.*, 1994; Kindinger *et al.*, 1999; Snyder *et al.*, 1989).

A geophysical evaluation of selected wetlands in two west-central Florida wellfields, initiated by the Southwest Florida Water Management District, suggested that individual depressional wetlands may respond differently to groundwater withdrawals due to subsurface structural differences. In conjunction with fracture trace analysis and borings, ground-penetrating radar (GPR) documented differences in geophysical characteristics (reflection free zones and dipping reflectors) of some wetlands that can increase the hydrologic connection between those depressional wetlands and the production aquifer (Watson *et al.*, 1990). Similar evaluations of that complexity have not been conducted in depressional wetlands in other regions of Florida, or in Georgia, where extensive groundwater mining has occurred for agricultural, industrial and municipal uses. However, similar responses to those reported for the north Tampa Bay area were observed in a more wide-ranging GPR study of sites throughout Florida and in the Okefenokee Swamp (Bacchus and Brook, 1996; Bacchus, 1998).

CASE STUDY FROM FLORIDA'S GULF COASTAL LOWLANDS

Regulatory Evolution

Although municipal, agricultural, industrial, and residential uses of ground water have increased in both Florida and Georgia since the early 1900s, monitoring of the impacts of withdrawals from this regional water resource were delayed and have been limited. For example, large volumes of ground water have been extracted from the west-central Florida area for municipal use since the early 1900s. However, the USGS did not begin producing contour maps of the potentiometric surface of the Upper Floridan aquifer in the areas of heavy groundwater mining of the west-central Florida area until 1964. Thus, more than 60 years of groundwater mining had occurred prior to initiation of monitoring in this case.

Regulation of groundwater withdrawals in Florida did not begin until 1972, with the adoption of Chapter 373, Florida Statutes. Consequently, more detailed monitoring of groundwater response was not initiated until that time. This legislation directed the five regional Water Management Districts to regulate use of the state's water resources. The Southwest Florida Water Management District (1996) regulates groundwater withdrawals in the west-central Florida region, which generally coincides with groundwater subregion "F" in Figure 1. Impacts of groundwater withdrawals in the west-central Florida area will be discussed as a case study since that District has conducted the most extensive and longterm evaluation of interactions between the surficial aquifer in areas of preferential flow (e.g., depressional wetlands) and the underlying Upper Floridan aquifer.

Growth accelerated in west-central Florida from the 1950s, and by the late 1980s damage from groundwater withdrawals was so severe that "Water Use Caution Areas" were established by the Southwest Florida Water Management District. The Northern Tampa Bay Water Use Caution Area (WUCA) includes all of Pinellas County and portions of neighboring Gulf Coastal counties, Hillsborough, Pasco, and Hernando, in addition to Polk, an adjacent inland county. Major metropolitan areas within the Northern Tampa Bay WUCA include Tampa, St. Petersburg, Clearwater, and New Port Richey. The general location of the Northern Tampa Bay WUCA is indicated by the arrow pointing to the west coast of Florida in Figure 1. By 1993, the annual-average quantity of ground water withdrawn for all users in that area was estimated to be 246 mgd. The Northern Tampa Bay Water Resources Assessment Project (WRAP) Report (Southwest Florida Water Management

District, 1996), prepared under the supervision of a Professional Geologist and a Professional Engineer, describes some of the conditions and damage from groundwater mining in the Northern Tampa Bay WUCA (e.g., adverse impacts to lakes, streams, and wetlands; induced sinkholes). Exemplary excerpts are provided by Bacchus (1999c), and include the following:

> ". . . Due to the highly karstic nature of the geologic system, the clay semi-confiner can be absent in one area, but be tens of feet thick a very short distance away. These localized karst features, where the clay semi-confining layer is breached or missing, significantly increase hydraulic connection between the two aquifers" (WRAP, p. 2-39).
>
> "Lowered water levels in surface-water features, including wetlands, lakes, and streams, have resulted in environmental (biological) impacts. These impacts are caused not only by annual-average drawdowns, but also by decreased hydroperiods in wetlands and lakes . . . Environmental impacts to lakes and wetlands observed in the Northern Tampa Bay WRAP area are variable, and include wetland species changes, intrusion of upland species, ground subsidence, rapid and severe desiccation and oxidation of soils, loss of overstory, severe fire damage, wildlife loss, and complete loss of habitat. The spatial magnitude and severity of these impacts can not be attributed to variations in rainfall" (WRAP, p. 6-4).
>
> "With the ground-water withdrawal rates for the existing and proposed future wellfields cut in half, impacts are projected to be reduced in spatial distribution and overall intensity, but not eliminated . . ." (WRAP, p. 6-8).

In 1994 and 1995, numerous legal actions were initiated against the Southwest Florida Water Management District regarding past and proposed regulation of the regional groundwater resource in west-central Florida, in addition to damage to private property and the environment. The ground water withdrawal issues that prompted these legal actions are summarized in the Orders that were issued on March 26, 1997 (Menton, 1997), and May 1997 (Quattlebaum, 1997). Some of the economic losses related to the unsustainable withdrawals that were issues in these cases are described below. A significant legal conclusion was that the major cause of environmental damage in the areas addressed by the cases, including lakes and wetlands, "are related to the withdrawal by the permittees of substantial quantities of water from the Floridan aquifer," rather than to other factors such as recent low levels of rainfall and area drainage projects. This conclusion echoed findings by the Florida House Committee on Natural Resources (HCNR, 1994) and the technical staff of the Southwest Florida Water Management District (1996).

These rulings resulted in the invalidation of some the Southwest Florida Water Management District rules and the withdrawal by the agency of other rules that were environmentally adverse; however, other issues are under appeal. Some of the issues under appeal include minimum flows and levels that must be maintained in environmental systems; whether groundwater withdrawal permittees and applicants can be required to investigate implementation of desalination; and whether water use permits can be denied for failing to meet individual permitting criteria such as adverse environmental impacts.

Economic Losses

Florida's House Committee on Natural Resources (HCNR) concluded that unsustainable groundwater withdrawals from the Floridan aquifer system in a single west-central Florida county had resulted in destruction of approximately 6,880 ha (17,000 ac) of wetlands in addition to private property damage, including failure of private wells. Costs of repairing and replacing private wells damaged from these withdrawals exceeded $4 million at the time of the report (HCNR, 1994). The costs of additional damage to private property have not been determined. Other direct costs to private property owners from damage attributed to unsustainable aquifer withdrawals include damage to homes from increased sinkhole formation, devalued waterfront property as lakes receded and streams ceased to flow, and costs of removing diseased and dead trees, such as oaks and pines (Bacchus, unpub. data; Kenneth Webber, Florida Division of Forestry, pers. comm.). These costs were not included with the costs of failed wells at the time HNRC compiled its report. Notices of impending Class Action suits have been registered in Pinellas County, Florida, a coastal county that is a primary recipient of ground water from rural areas inland. The law suits were on behalf of private property owners in rural areas who have incurred damages due to the groundwater mining in their area primarily conducted to supply the large coastal municipalities.

Other economic burdens to the private sector are associated with these unsustainable aquifer yields, but related costs also remain uncalculated. Groundwater mining can create new sinkholes, and enlarge or "reactivate" relict sinkholes by increasing flow through in-filled sediments and debris, and resulting in preferential subsidence from oxidized/compacted organic sediment and suffosion. Increased sinkhole activity increases the potential for contamination of the Upper Floridan aquifer by surface contaminants. Remediation of contaminated ground water is expensive, when technologically possible. In some cases, remediation technology is not available or is not economically feasible.

Another example of uncalculated economic burdens is increased susceptibility of silvicultural and natural stands to destruction by disease and wildfire, as more surface water becomes induced recharge to compensate for water mined from the Floridan aquifer system. Damage from large-scale wildfires occurring recently in Florida was much more severe in areas of groundwater mining than in other areas (Bacchus, unpub. data). In 1998, approximately 100,000 people, including all residents in the northeast Florida Atlantic Coastal Lowland county of Flagler were forced to evacuate their homes because of catastrophic wildfires. The wildfires started inland, near wellfields that supply municipal water for the Palm Coast development and the Daytona Beach area. In addition to the destruction of homes and silvicultural stands of pines during the 1998 fires in northeast Florida, the Pepsi 400 Stock Car Race was halted. The direct economic loss to businesses and home owners associated with the fires in this area alone was estimated to be in the millions of dollars. Catastrophic wildfires were rekindled in Florida in April 1999, and resulted in the Governor requesting that 67 counties be determined a National Disaster Area to qualify for Federal assistance. In both cases, increases in air pollution and loss of major transportation corridors occurred due to smoke from the wildfires. Cost estimates of damage from the fires in 1998 excluded impaired human health and irreversible environmental damage, because these aspects have not been evaluated.

The loss of property and forest resources in Florida in 1998 was attributed to low rainfall preceding the fires, as was the case for the renewed wildfires in 1999. However, the pattern of destruction for the 1998 fires was coincident with the locations of wellfields (Bacchus, unpub. data). This pattern suggests that perturbations of the water table from excessive withdrawals increase the susceptibility of silvicultural pine stands and natural vegetation to ignition, probably due to lower moisture content in soils, leaf litter, and plant tissues. An evaluation of forested areas that burned during the 1998 wildfires in Florida revealed vigorous resprouting of wetland vegetation in areas not associated with wellfields, but no regrowth in similar areas associated with wellfields (Bacchus, unpub. data). Photographic examples are provided by Bacchus (1999c). Since groundwater mining is known to result in considerable induced recharge from the surface, blaming the fires on low rainfall seems comparable to charging a commoner for bounced checks written against his deposit after bank employees embezzled the deposited funds.

Estimates referenced above also omitted damage to public property and resources by wildfires. For example, the "severe fire damage" referenced in the Southwest Florida Water Management District quotes above (p. 6-4) includes destruction of both wetlands and uplands on publicly-owned land. One large tract of land was conveyed to the Southwest Florida Water Management District by the Starkey family in a purchase Agreement between them dated January 7, 1975. Covenants to run with the lands provided that "all improvements from the natural state . . . shall blend in, and be complementary to, the natural condition of said lands . . .."

Subsequently, the Southwest Florida Water Management District issued permits for construction of a municipal wellfield on the property, which was named the "J. B. Starkey Wellfield and Wilderness Park" (SWP). The groundwater mining in this "Wilderness Park" led to the premature decline and death of pond-cypress trees in depressional wetlands, as well as long leaf pine trees in surrounding uplands throughout that public property and nearby private property. In addition, catastrophic wildfires and declines in wildlife occurred on that site due to the groundwater mining. These adverse impacts are contrary to the original covenants of the Agreement and the covenants, restrictions, and uses of the Warranty Deed signed on October 8, 1982, which stated, "The land shall remain, as nearly as practicable, in its present natural state . . .."

Although 15 mgd of ground water are permitted for withdrawal on SWP, the environmental damage described above occurred from reported withdrawals of only 12 mgd. Similar groundwater mining impacts may be contributing to premature decline and death of longleaf pines in natural flatwoods stands and pond-cypress wetlands in Myakka River State Park (MRSP). Pine flatwoods and depressional wetlands throughout the SE Coastal Plain are adapted to and require frequent fires to reduce competition and release nutrients into their nutrient-poor environment. Historically these fires ignited naturally, via lightning strikes. Now these systems are maintained primarily through prescribed burning. Timber loss from fires was predicted to occur in areas of groundwater mining during attempted prescribed burns of natural pine stands and due to catastrophic wildfires because of induced recharge from the surficial aquifer associated with groundwater mining (Bacchus, 1995a).

Groundwater mining also may prove to be a primary factor responsible for similar wildfires that have resulted in the most recent economic losses in Los

Alamos, New Mexico ($143 million in emergency funding requested by the U.S. Senate Appropriations Committee during the second week of May 2000). Unfortunately, the large-scale impacts of groundwater mining, such as its role in the severity and extent of wildfires, is not being investigated at this time. An example of the current limited scope of view regarding this problem is the National Park Service's longterm, watershed-level studies in national parks (Herrmann *et al.*, 2000). This effort was begun in 1982, before the magnitude of surface ramifications from groundwater mining was realized.

COMPARISON WITH GEORGIA'S ATLANTIC COASTAL LOWLANDS

Hydrologic Responses to Groundwater Mining

Subregional Aquifer Characteristics. Presently, the main source of water for the SE Coastal Plain of Georgia and northeast Florida (subregion D) is ground water from the Upper Floridan aquifer. This is the same regional groundwater resource that supplies water to the area of the case study in west-central Florida. Subregion D is shaded in Figure 1. Callahan (1964) identified three primary areas of recharge for the Floridan aquifer system in its northern extent, as shown in the cross-hatched areas of Figure 3. Krause and Randolph (1989) provide more specific characteristics of this subregion, as summarized by Bacchus (1999c). Some of the most salient points are provided below:

> "The hydrogeology of the Floridan aquifer system in southeast Georgia and in parts of Florida and South Carolina has been investigated extensively in the areas of greatest development. However, these studies are restricted almost entirely to a narrow band between the coastal cities of Savannah, Georgia, and Jacksonville, Florida, which represents less than 15 percent of the area included in this study . . .. The extent of the study area is based on natural hydrologic boundaries. The western and southern boundaries were delineated on the basis of groundwater divides . . ." (p. D5).

> "Cavities, cavernous zones, and solution channels tens of feet in vertical and horizontal dimensions have been tapped by wells throughout the downgradient part of the Floridan aquifer system in southeast Georgia and northeast Florida . . . faults are believed to be present along the southeast Georgia coast (D. C. Prowell and H. E. Gill, U. S. Geological Survey, written commun., 1983), they have not been mapped by Miller (1985) [sic] . . ." (p. D25).

> "Caliper and sonic televiewer logs and borehole television traverses made in a test well near Brunswick, Georgia, showed extensive caverns through the Floridan aquifer system" (p. D26). . . . The average hydraulic conductivity of the entire upper confining unit is undoubtedly greater than the laboratory-determined values because of the presence of more permeable strata in the unit . . ." (p. D28).

The continental shelf in this region is a drowned continuation of this expansive onshore karst system described above. Specifically, the SE Coastal Plain platform is a mature karst (carbonate/limestone) system characterized by solution/collapse features such as sinkholes, springs, and caverns, in addition to horizontal and vertical fractures, and bedding planes. Similarities of offshore to onshore karst features currently are being used for selection and exploration of submarine anthropologic sites (Faught and Donoghue, 1997). The Floridan aquifer system also extends offshore and under present day barrier islands along the Atlantic and Gulf Coastal Plain. A conceptual model of the system extending offshore is provided in Figure 4, and includes a vertical fracture which extends through all semiconfining units and aquifer units of the Floridan aquifer system.

Groundwater Mining Impacts to the Subregional Aquifer System. Krause and Randolph (1989) report that the first well drilled into the Floridan aquifer system in subregion D was in Savannah, Georgia, in 1885, with no pumping required because the head was approximately 12 m (40 ft) above sea level. By 1900, more than 10 mgd (15 ft^3/s) was being withdrawn for municipal supply and by 1935, industrial use of the Upper Floridan aquifer had begun in the Savannah area. Recently, the impacts to the Floridan aquifer system in this subregion were reported and simulated by Johnston *et al.* (1981) and Krause and Randolph (1989), respectively, based on data from 1980. During 1980, the total estimated groundwater withdrawal from the Floridan aquifer system in this subregion was approximately 625 mgd (970 ft^3/s). The vertical leakage in this subregion was estimated to have reversed from 329 ft^3/sec upward leakage in 1880 to 92 ft^3/sec downward leakage in 1980 (Krause and Randolph, 1989). These figures emphasize the change in the nature of the Floridan aquifer system from supporting the surficial aquifer and surface water systems to draining these systems.

The 1980 potentiometric surface contour map compiled by Johnston *et al.* (1981) depicts dramatic cones of depression along the Atlantic coast in northeast Florida just south of the Georgia state line, and north at Brunswick and Savannah, Georgia. The declines in

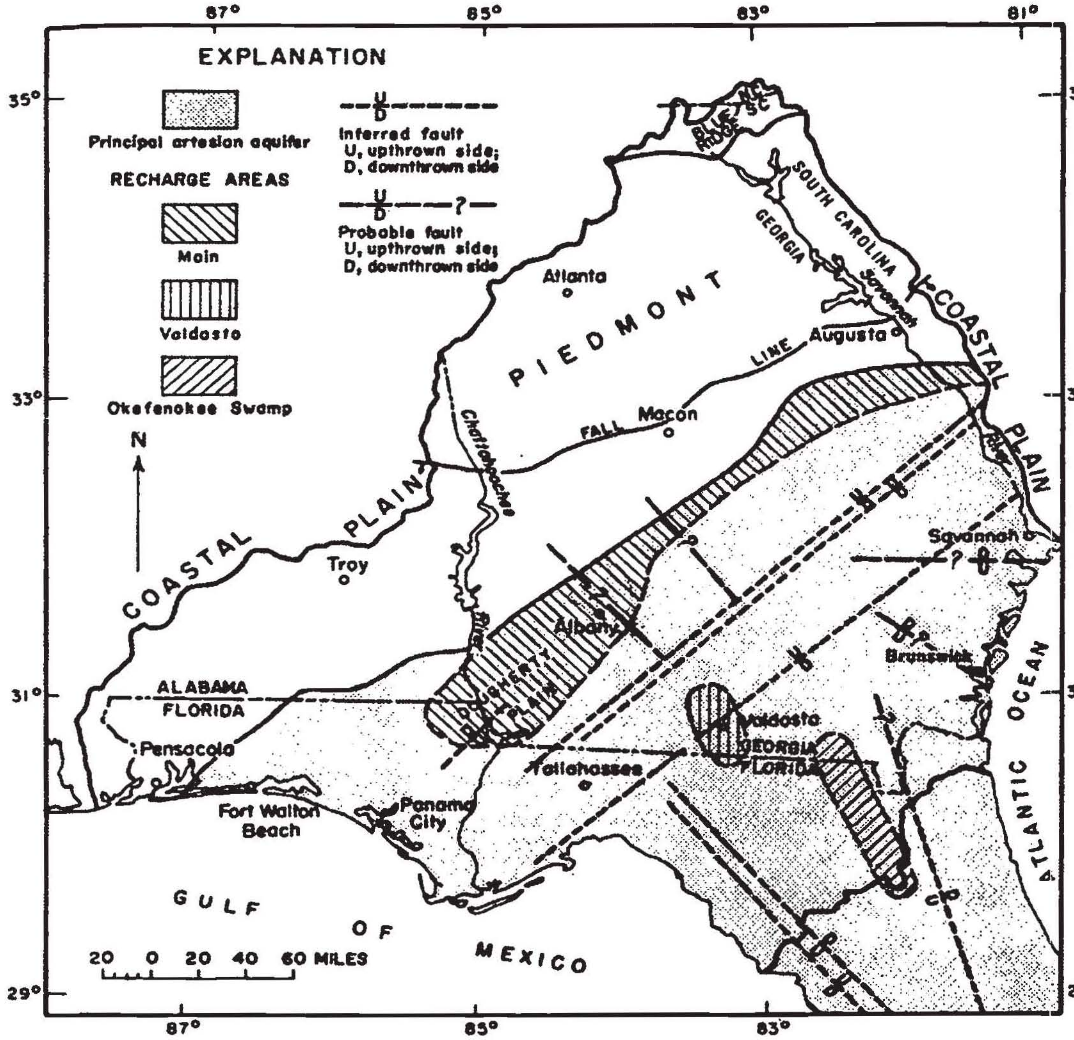

Figure 3. Approximate Extent of the Three Primary Recharge Areas for the Floridan Aquifer System (from Callahan, 1964).

the potentiometric surface at these three locations for 1980, compared with predevelopment (premining) conditions estimated by Johnston *et al.* (1980), were approximately 24 m (80 ft), 23 m (75 ft), and 46 m (150 ft), respectively. However, more severe drawdowns of the potentiometric surface for the Upper Floridan aquifer occurred during some years prior to and following 1980. For example, water levels in Upper Floridan aquifer wells on Fernandina Beach, Florida, were approximately 6 m (20 ft) lower in 1975 and 1976, and approximately 3 m (10 ft) lower in 1979 than levels in those wells in 1980. Lower levels were recorded in Brunswick in 1981. A reversal of high/low water levels for the 1981 growing season, in addition to the lowest "highs" were recorded in well 35P94 in the surficial aquifer near Savannah. The surficial aquifer wells were located in uplands (Krause and Randolph, 1989). More significant responses of the surficial aquifer may have been occurring in freshwater wetlands in that subregion. Bacchus (1999c) provides a synopsis of some of the hydrologic impacts reported by Krause and Randolph (1989) due to groundwater mining in this subregion, with examples listed below:

- Large withdrawal of ground water along the coast has produced large cones of depression, which in places have overlapped, and generally has lowered potentiometric surfaces as far upgradient as the Gulf Trough (p. D36).
- Available water, supplied by lateral or vertical flow, plays a large part in the magnitude of head decline. In Georgia, pumpage at Brunswick is about 30 percent greater than that at Savannah, but higher transmissivity and leakance make more water available at Brunswick, thus producing a much shallower cone of depression (p. D36).
- Head decline in the Upper Floridan along the southwestern boundary of the study area has caused significant lateral flow across the boundary that did not exist before development (p. D39).

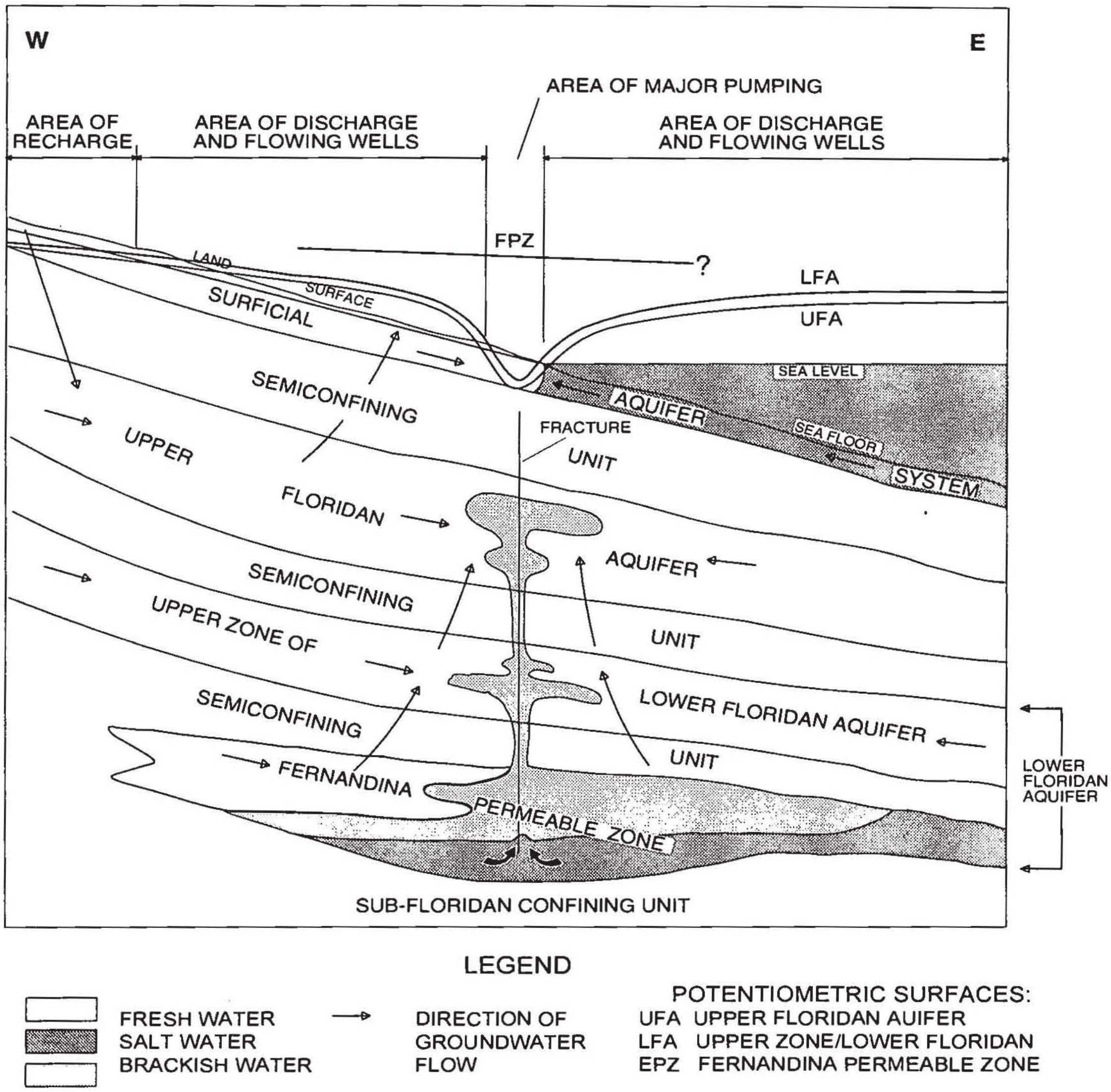

Figure 4. Conceptual Model of the Current Floridan Aquifer System, Inland to Offshore, Along the East Coast (modified from the model developed for northeast Florida by Krause and Randolph, 1989; Spechler, 1994; and Spechler and Phelps, 1997).

- Some head decline also occurred along the southern boundary of the study area where water in the Upper and Lower Floridan aquifers flowed out of the study area prior to development (p. D39).
- The prominent cones of head decline at Savannah, Brunswick, and Jesup, Georgia, have overlapped and produced a large area of head decline that encompasses the three pumping centers (p. D39).
- In the area downgradient from the Gulf Trough, flow between the surficial and Upper Floridan aquifers reversed (p. D43).
- The head decline along the southwestern boundary due to groundwater withdrawals created a gradient in the Upper Floridan across what had been a groundwater divide prior to development. This gradient produced a flow of about 201 ft^3/s across that boundary into the study area (p. D43).

Poland *et al.* (1972) defined an aquifer system as "two or more permeable beds separated at least locally by [confining beds] that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system." Krause and Randolph (1989) confirm that this definition applies to the Floridan aquifer system throughout most of its area of occurrence. They further state that, "All components of the flow system within the Floridan aquifer system, as well as hydrologic units that are adjacent to it and that affect it hydrologically are part of the simulation." These statements and the contribution of the surficial aquifer to the underlying aquifer in response to groundwater mining summarized above suggest that the surficial aquifer becomes an integral part of the Floridan aquifer system under groundwater mining conditions. However, the surficial aquifer was treated as an inactive layer, external to the Floridan aquifer system, in model simulations by Krause and Randolph (1989).

The location of the Gulf Trough, oriented northeast/southwest, north of Savannah and extending to the Gulf Coast, impedes the southeasterly flow of water through the Floridan aquifer system from the main recharge area to the west, through Albany, Georgia (Figure 3). Consequently, the primary recharge area for the Georgia/north Florida subregion described above is the Okefenokee Swamp (Figure 3). Conservative estimates of the volume of water that has been pumped from areas down-gradient of this recharge area since groundwater mining was initiated, resulted in the conclusion that induced recharge (both decreased upward leakage and increased downward leakage), in addition to breached groundwater divides would be required to supply the volume of water removed from the regional aquifer. Therefore, the significant decrease in upward leakage and increase in downward leakage (induced recharge) due to groundwater mining along the coast of Georgia and northeast Florida may have had significant adverse environmental impacts on the Okefenokee Swamp, and Okefenokee National Wildlife Refuge. However, as indicated above in the quotes from Krause and Randolph (1989), hydrologic investigations of groundwater mining impacts have been concentrated along the coast, with no evaluation of impacts that may have occurred to the internationally-renowned federal natural area.

In the past, groundwater resource specialists evaluating impacts of groundwater mining have been concerned with water quality only, such as contamination of the Floridan aquifer by intrusion of saline water (lateral encroachment/landward migration from the sea, vertical intrusion, upconing). No consideration has been given to water quantity impacts such as potential impacts of groundwater mining on the ecosystems that the surficial aquifer supports.

The response of the Floridan aquifer system described in the quotes above suggest that environmental impacts comparable to those described in the west-central Florida case study should be expected in this subregion, including the ecosystems located offshore. For example, Cumberland Island was within the estimated potentiometric contours of 9 to 12 m (30 to 40 ft) above mean sea level for 1980 (Johnston *et al.*, 1981). However, the estimated potentiometric contours for the same area prior to excavation of wells into the Floridan aquifer was 18 to 21 m (60 and 70 ft) above mean sea level (Johnston *et al.*, 1980). These estimates suggest a decline of at least 9 m (30 ft) for Cumberland Island in 1980 due to groundwater mining primarily on the mainland.

Although monitoring of the Floridan aquifer system in the SE Coastal Plain of Georgia is similar to that in west-central Florida, a monitoring program for the surficial aquifer comparable to that established by the Southwest Florida Water Management District in Florida has not been established in Georgia. Specifically, longterm monitoring of the surficial aquifer via observation wells located in wetlands, in addition to monitoring of vegetation sensitive to hydroperiod alterations, has not been implemented in the SE Coastal Plain of Georgia at this time.

Damage on Cumberland Island National Seashore

General Background. Cumberland Island is Georgia's largest and most southerly barrier island, indicated by the arrow pointing to the east coast of Georgia in Figure 1. Its southern terminus is located within the combined cone of depression of St. Marys, Georgia, and Fernandina Beach, Florida. Its northern terminus is located approximately 10 km (6 mi) southeast of the combined cones of depression for Brunswick, Jesup, and Savannah, Georgia. These cones of depression were established in the 1930s. Reduced diffuse upward leakage from the Floridan aquifer system has been estimated at 85 percent for Cumberland Island due to induced recharge from groundwater mining (Johnston *et al.*, 1980; 1981). This estimate was based on comparisons of approximated conditions in 1880 with 1980 data. However, the total volume of ground water withdrawn from this regional aquifer is not known because self-supplied domestic uses and agricultural uses are not metered and must be estimated. Additionally, not all users in the remaining categories (public supply, commercial, industrial, mining, and power generation) are metered (Marella and Fanning, 1996).

The National Park Service purchased much of this barrier island in 1972, designating it as a National Seashore. Ten years later, Congress designated 3,600 ha (9,000 ac) of this 14,560 ha (36,400 ac) tract as a "Wilderness Area," to "preserve the scenic, scientific, and historical values" of this natural resource. However, no record could be found of government-sponsored attempts to assess any structural damage to the aquifer matrix or environmental damage that might be occurring to the National Seashore and Wilderness Area due to the large declines in potentiometric surface of the regional Floridan aquifer, as described above.

In 1997, a ground reconnaissance was conducted in the portion of the Wilderness Area where hydrologic perturbations of the surficial aquifer from groundwater mining was predicted to be most apparent, if present. The focus of the reconnaissance was the area surrounding an extensive freshwater wetland system oriented in a general north/south direction in the interior of the Wilderness Area in the north central portion of Cumberland Island (Bacchus, 1999a).

Numerous characteristics were observed in the reconnaissance area that were similar to surface expressions of groundwater mining from the Floridan aquifer system documented in other areas of the SE Coastal Plain, including the case study described in west-central Florida. These characteristics included a drop in the level of the surface water for the interior wetland, premature death and decline of both canopy and subcanopy trees in the uplands surrounding the freshwater wetland, soil subsidence evident at the bases of trees, and shallow sinkhole-like depressions in the uplands near the freshwater wetland. The sinkhole-like depressions were similar to those in SWP and throughout the NTBWUCA in west-central Florida, with the apparent rim of the largest depression observed in the Wilderness Area approximately 7 m (23 ft) in diameter. Vegetative indicators suggest that the permanent decline in the water level occurred in two-stages (Bacchus, 1999a). The vegetative characteristics in the Wilderness Area also were similar to vegetative responses observed in depressional wetlands and uplands in other areas of Georgia (Bacchus, 1997) and Florida (Bacchus, 1998; Menton, 1997; Rochow, 1994; Rochow and Rhinesmith, 1991), where perturbations of the surficial aquifer and associated surface water have occurred as a result of unsustainable withdrawals from the Floridan aquifer system. The hydrologic and vegetative responses at similar sites and a more detailed discussion of the reconnaissance area characteristics and mechanisms are provided by Bacchus (1999a).

Potential Causal Factors. Four factors were considered by Bacchus (1999a) as possible causes for the environmental destruction, two-phased water-level declines in the wetland, soil subsidence and sinkhole-like depressions observed in the Wilderness Area of Cumberland Island. The potential causal factors, summarized below, included (1) periods of below-average rainfall, (2) ditching, (3) widening and deepening of the ship channel separating the western shoreline of Cumberland Island from the mainland, and (4) groundwater mining on the mainland.

Pollution was not considered as a causal factor because the "symptoms" were not consistent with pollution, and pollution would not have accounted for the two-phased water-level declines in the wetland, the soil subsidence, or the sinkhole-like depressions. Likewise, climatic changes other than "drought" were not considered because the distribution of the damaged and undamaged vegetation was not consistent with climatic change as a causal factor. The population on the island has decreased over time; however, recreational use of the Wilderness Area may have increased during the recent past. The actual use of that area cannot be determined because use of the "back country" is tracked only for those who camp in designated sites within the Wilderness Area (no camping is or has been allowed in the area that was damaged since public purchase). No special passes are required for day hikers or island residents who may use the area. Conversely, those camping in the "back country" may do so, and hike extensively, without coming in contact with the described damaged area. It is unlikely that the ecological damage in the Wilderness Area is related to recreational use of that area since the same species of trees that are dead in the Wilderness Area occur in the heavily used area near Sea Camp, but the latter exhibit few symptoms of adverse impacts.

Drought was eliminated as a potential causal factor because the occurrence of premature decline and death of canopy and subcanopy trees is not homogeneous throughout the barrier island. Instead, this destruction is associated with the depressional wetland system in the interior of the Wilderness Area. This area is most protected from damaging salt spray and mechanical disturbance from the limited vehicle and foot traffic on the barrier island. Therefore, it would be less likely to experience adverse impacts from limited rainfall than vegetation in peripheral areas of the barrier island. Additionally, natural vegetation is adapted to the cyclical periods of below-average rainfall that occur in their region. Conversely, many commercial agricultural crops must be irrigated during periods of low rainfall to prevent crop damage and loss. Long-lived trees, such as live oaks (dead and dying in the Wilderness Area), can thrive for hundreds of years and survive countless droughts in the absence of significant anthropogenic interference. Finally, below-average rainfall alone (in the absence of groundwater mining) would not explain the two-phased water-level decline or sinkhole-like depressions associated with the large interior wetland.

Ditching of the interior wetland also was eliminated as a potential causal factor because the ditches were well-established in 1953 aerial photographs. Hillestad *et al.* (1975) suggest the ditches were present in 1946. Drainage via the ditches would not have resulted in such a prolonged lag time prior to the two-phased decline of water levels in the interior wetland, the appearance of the sinkhole-like depressions within approximately the past 10 years, or the relatively recent initiation of premature decline and death of trees. Current evidence suggests that the latter occurs over a period of approximately 20 years for mature trees subjected to hydroperiod perturbations. Finally, the topographic gradient where the ditches were excavated is nominal, particularly compared to the conservative estimate of vertical decline in the potentiometric surface of 10 m (30 ft) for 1980.

Insufficient information was available to evaluate the role of the excavated ship channel in the damage within the Wilderness Area described above. Evaluations were conducted prior to the deepening, widening and lengthening of the channel in the mid-1970s for Trident submarines. However, the focus of these studies was the potential impact to groundwater quality, rather than hydroperiod perturbations. Additionally, no observation wells or other boreholes were excavated in the vicinity of the interior wetland by Yankee Paradise trail where the damage has occurred.

Groundwater mining from the mainland was the second factor that could not be eliminated as the potential cause of the damage observed in the Wilderness Area of the Cumberland Island National Seashore. This factor includes catastrophic fires and predisposition to disease (e.g., fungal pathogens) due to water stress, both of which are linked to groundwater mining. The damage in the Wilderness Area of the Cumberland Island National Seashore is consistent with areas of groundwater mining in Florida, where the quantity of water extracted from the regional aquifer is less, and the decline in the potentiometric surface of the aquifer is approximately one-third the estimated decline in the potentiometric surface of the Floridan aquifer for Cumberland Island in 1980.

Conceptual Model. A model illustrating diagnostic solution and collapse features of the Floridan aquifer system was prepared by Kindinger *et al.* (1999) to illustrate processes in north Florida, where groundwater mining is occurring. For example, they observed individual sinkholes ranging from < 1 m to > 100 m (3 ft to 300 ft) both in depth and diameter. Their model (Figure 5) is included as a conceptual model of features that may be underlying Cumberland Island and could explain the structural, hydrologic and vegetative damage that was observed in the Wilderness Area by Bacchus (1999a). Their model could explain delayed multiple and intensified perturbations consistent with the pattern of damage

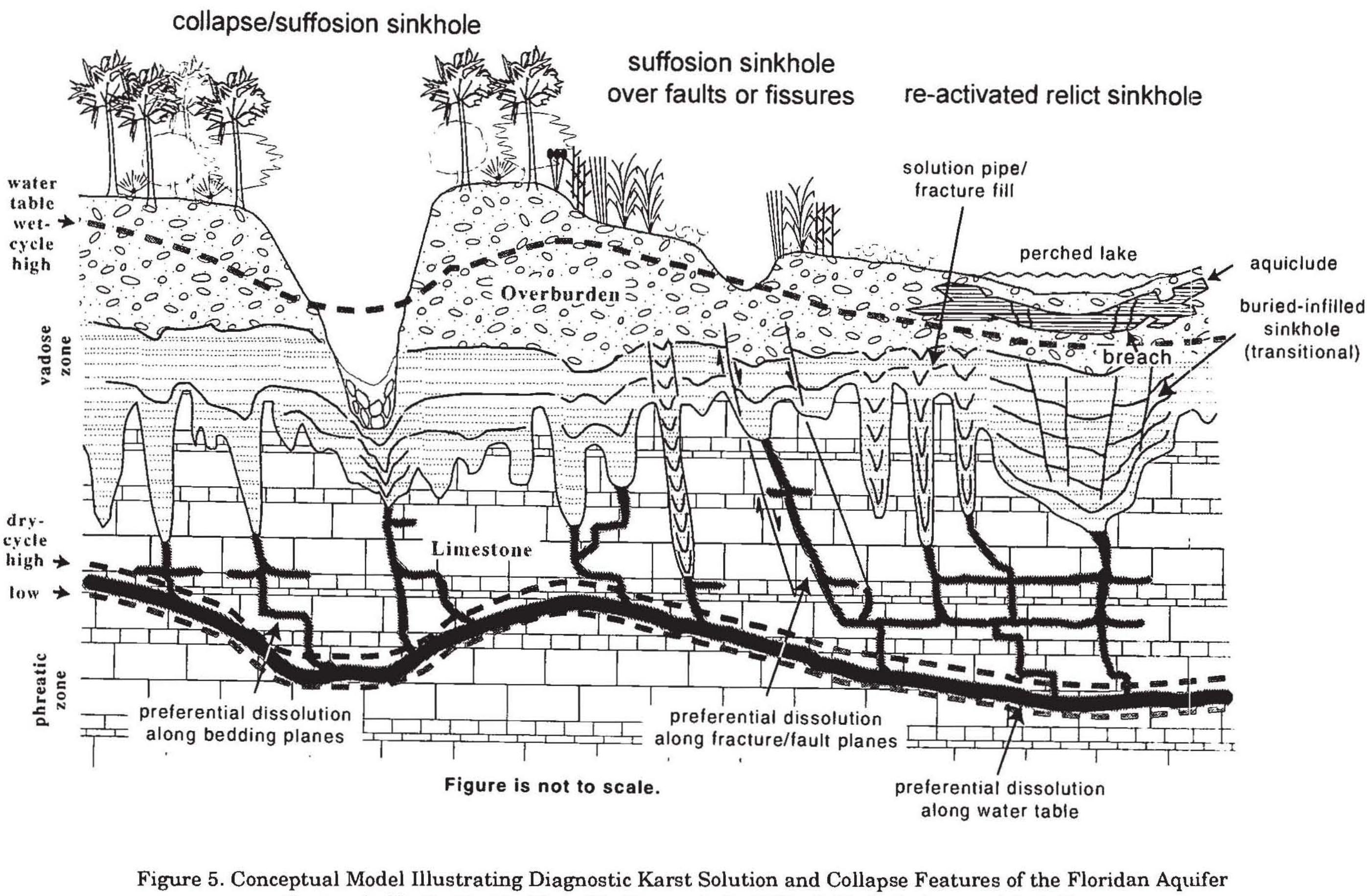

Figure 5. Conceptual Model Illustrating Diagnostic Karst Solution and Collapse Features of the Floridan Aquifer System in North Florida (from Kindinger *et al.*, 1999, sinkhole features relabeled).

observed in the Cumberland Island Wilderness Area. In this conceptual model, the preferential dissolution along the horizontal bedding planes and vertical fracture planes is interconnected with sinkhole features that breach the Hawthorn. This creates a leaky, semiconfining zone rather than the "impermeable confining" unit referenced extensively throughout the literature. The horizontally extensive bedding planes and associated fractures also could link the barrier island system to the excavated channel between the barrier island and the mainland, and sites of groundwater mining, such as those on the mainland described previously.

The model developed by Kindinger *et al.* (1999) labels the lower permeability zone under the "perched lake" as an "aquiclude" (Figure 5). This term is synonymous with "confining unit" (USGS, 1989). In the absence of groundwater mining, this could be accurate. However, as groundwater mining increases downward leakage from the overlying surficial aquifer, the aquiclude becomes an aquitard, or "leaky confining bed" (terminology from USGS, 1989), yielding more and more water to induced recharge. The thickness of the Hawthorn formation (semiconfining unit overlying the Upper Floridan aquifer system) at the site where Kindinger *et al.* (1999) developed their conceptual model is approximately 50 m, which is less than the thickness of the same system underlying Cumberland Island. However, if breaches in the semiconfining zones at Cumberland Island were subjected to longterm groundwater mining, similar surface expressions might result. For example, the "buried-infilled sinkhole" and overlying breached aquitard on the far right of the conceptual model developed by Kindinger *et al.*, could represent the interior wetland in the Wilderness Area, where the water table has been depressed in multiple stages. An expansive area of increased permeability, such as that resulting from an underlying infilled sinkhole, could be functioning as a large area of "point-recharge" for the ongoing groundwater mining north and south of Cumberland Island. The depressed water table extending landward from this wetland into the surrounding uplands also could impose sufficient stress on canopy and subcanopy vegetation to result in the premature death and decline, windthrow, and soil subsidence observed by Bacchus (1999a). The "solution pipe/fracture fill" features to the left of the "perched lake" could explain the small sinkhole-like depressions associated with the interior wetland. Finally, the sinkhole on the far left of the conceptual model by Kindinger *et al.*, that has experienced collapse with fill (suffosion) could explain the loss of emergent vegetation in Johnson pond, as surface water levels deepened following the "point-recharge" collapse. Although the model developed by Kindinger *et al.* (1999) could be one explanation for the responses in the Cumberland Island Wilderness Area, some of these responses also might result from other mechanisms such as dissolution of shallow shell beds.

Additional Evidence Suggesting Anthropogenic Perturbations of the Surficial Aquifer

Fire on Cumberland Island. Hillestad *et al.* (1975) reported that a severe fire occurred near Johnson pond in approximately 1965. Johnson pond is located less than 1.5 km (1 mi) north of the interior wetland and surrounding upland in the Wilderness Area where the damage described above was observed. Johnson pond reportedly was a marsh that apparently was converted to open water following the fire. This characteristically occurs in wetlands where groundwater mining depresses surface water (via induced recharge), making both wetland vegetation and organic substrate susceptible to consumption by fire (Quattlebaum, 1997; Bacchus, unpub. data). When a thick organic layer is consumed, the water levels during periods of reduced pumping are too deep for emergent wetland vegetation to become reestablished because of the new, lower "bottom" elevation. The same end result can occur due to subsidence of the organic layer due to oxidation associated with depressed water levels, in the absence of fire. For example, the bottom elevation was lowered approximately 0.5 m (1.5 ft) in one year in a SWP wetland due to soil subsidence from groundwater mining (Rochow and Rhinesmith, 1991). Windthrow, premature decline and death of trees, and sinkhole-like depressions were associated with these areas of groundwater mining in Florida with less than 3 m (10 ft) drawdown in the Upper Floridan aquifer (Bacchus, unpub. data).

The evidence that water levels in the interior wetland of the Cumberland Island Wilderness Area have been lowered in two stages, and have not recovered (see Bacchus, 1999a for discussion), suggests that the Johnson pond area burned as the result of an anthropogenically depressed water table rather than simply abnormally low rainfall. The longterm precipitation record for the area north of Cumberland Island reported the highest rainfall on record during the period of approximately 1963 through 1968 (Krause and Randolph, 1989). These data provide additional support for anthropogenic perturbations of the surficial aquifer on Cumberland Island. The timing of a depressed water table in approximately 1965 would be more consistent with the indicators of lowered water levels observed by Bacchus (1999a) in the damaged area, than the timing of ditching in the 1940s.

The timing of the fire also would be consistent with the onset of premature decline for the canopy trees that have died in the Wilderness Area. Trees in other areas of groundwater perturbations in Florida and Georgia have died approximately 20 years after the onset of physical evidence of the perturbation (e.g., subsidence), as summarized by Bacchus (1999a). Opportunistic fungal pathogens appear to infect trees subjected to these hydroperiod perturbations, causing root and basal decay of the susceptible trees, which is presumed to lead to windthrow.

Other Barrier Islands – Wetland Losses, Fractures, and Subsidence. Alkaff (1997) determined that a significant loss of both perimeter and interior wetlands has occurred for the Sapelo Island complex since 1920. Sapelo Island is a barrier island similar to Cumberland Island, with the northern two-thirds of the island included in the R. J. Reynolds Wildlife Management Area. Sapelo Island is located approximately 8 km (5 mi) off the Georgia coast, and north of Brunswick approximately the same distance as Cumberland Island is located south of Brunswick. The loss of wetlands on Sapelo Island was attributed to rising sea level (Alkaff, 1997), as is generally the case for the loss of coastal wetlands not destroyed by developments. In reality, these wetland losses may be the result of induced recharge and subsidence from groundwater mining on the mainland.

Tectonic fracture sets and associated vertical joints/joint sets recently have been identified in the late Pleistocene strata along Sapelo Sound, suggesting broad uplift in this area (Bartholomew *et al.,* 1999). These features could function as "point-recharge" locations on Sapelo Island, where induced recharge from the surficial aquifer is more intense than in other areas where the surficial aquifer has been monitored.

South of Cumberland Island, seismic data and natural gamma logs from wells have been analyzed (Kindinger *et al.,* 1997). The data were collected onshore and offshore of the Atlantic Coast of central Florida, in the Indian River Lagoon and barrier island near Vero Beach. That analysis revealed a southeast dipping of the Hawthorn Group in response to subsidence or dissolution in the underlying Floridan aquifer system. Fluid migration, rock movement, and dissolution along a deeper fault zone were identified as possible mechanisms for the subsidence. That study confirmed the presence of structural features on barrier islands that could serve as "point-recharge" locations for induced recharge. That study was located in the vicinity of the Indian River Aquatic Reserve and Pelican National Wildlife Refuge.

In the Savannah area, 10 cm (0.33 ft) of land-mass subsidence occurred from approximately 1933 to 1955. By 1975, an additional 7 cm (0.23 ft) of land-mass subsidence had occurred in Savannah. The land-mass subsidence was attributed to gradual dewatering of the semiconfining layer (marl, clay, silt, and find sand) separating the Upper Floridan aquifer from the surficial aquifer. The dewatering continued at comparable rates even after water-level declines in the Upper Floridan aquifer slowed (Davis *et al.,* 1976). Similar land-surface subsidence has been described associated with Texas and the Gulf of Mexico (Germiat and Sharp, Jr., 1990; Sharp, Jr. *et al.,* 1991).

Additional evidence of apparent subsidence comparable to subsidence in wetlands in SWP has been documented in the center of Seagrove Lake in the Okefenokee National Wildlife Refuge using ground-penetrating radar. Seagrove Lake reportedly was a cypress wetland prior to a catastrophic wildfire in 1932 (Bacchus and Brook, 1996). The Okefenokee Swamp is the primary recharge area for the Atlantic Coastal Lowlands where previously described groundwater mining has occurred since the late 1880s (Callahan, 1964; Krause and Randolph, 1989). This recharge area has experienced a decline in the potentiometric surface of the Upper Floridan aquifer of approximately 20 m (60 ft) based on the conservative comparison of estimated predevelopment levels and 1980 levels. Induced recharge from the Okefenokee Swamp to the Upper Floridan aquifer was suggested by Krause and Randolph (1989), based on 1980 withdrawals. Hydraulic evidence also suggests that vertical flow is occurring from the Okefenokee Swamp to the underlying Upper Floridan aquifer in southeast Georgia. The magnitude of this induced recharge may have resulted in preferential subsidence in some of the wetlands in this federally "protected" property, including wetlands in the Wilderness Area of the Refuge. Kitchens and Rasmussen (1995) also suggest that the observed pH and water-level changes, and increased heavy metal accumulations in the wildlife of that area may be related to induced recharge in some areas of the Okefenokee Swamp (e.g., from exposure and oxidation of organic deposits and associated chemical changes).

The rate of inundation from sea-level rise due to global warming has been estimated at 0.3 m (1 ft) over the next 50 years, with increases along the coast of Georgia reported as 1.7-2.4 mm/yr from 1940 to 1972 (Hicks and Crosby, 1974). However, this rate of inundation should be compared to the documented rates of soil subsidence due to groundwater mining in the SWP referenced above (0.5 m/yr). This comparison can provide a perspective of the potential magnitude of the groundwater mining problem in the SE Coastal Plain. The global relevance of this problem was recognized by Sahagian *et al.* (1994) in their statement that the contributions of glacial melting and ocean thermal expansion are smaller than previously thought, but that increased rates of groundwater mining from large aquifers could have important implications for sea-level rise in the 21st century.

Investigations for Harbor Deepening. Currently a proposal by the Port Authority is being considered to expand and deepen the Savannah Harbor and entrance channel at the boundary between Georgia and South Carolina. In response to that proposal, two clusters of observation wells were constructed in the uplands along the Atlantic coast at Fort Pulaski and Tybee Island, eastern Chatham County, Georgia. The wells were monitored by the USGS from December 1997 through January 1998. The purpose of this study was to evaluate aquifer interconnection. Water-level data were from wells extending into the surficial aquifer, the underlying low permeability sediments that are the stratigraphic equivalents of the upper Brunswick aquifer, and the Upper and Lower Floridan aquifers. Data collected during this period showed that the hydraulic head decreased with depth at both sites, indicating potential downward leakage of water from the surficial aquifer to the Upper Floridan. Water levels in the Upper Floridan at these sites have been lowered because of pumpage from the aquifer in the Savannah area, resulting in a downward hydraulic gradient at these sites. More specifically, the water level in the sediments underlying the surficial aquifer at Fort Pulaski on January 22, 1998, was approximately 0.5 m (2.1 ft) below sea level, suggesting a possible leakage in response to pumping from the Upper Floridan aquifer (Clarke *et al.*, 1999).

The wells for this USGS investigation were constructed in uplands, as was the case with investigations on Cumberland Island prior to harbor excavations adjacent to that barrier island (Herndon, 1991; Herndon and Cofer-Shabico, 1991; Wilson, 1990; Wilson *et al.*, 1991a; 1991b). More pronounced interaction between the surficial and Upper Floridan aquifers may be observed in wells constructed in freshwater wetlands within that area. Similar water chemistry in the surficial aquifer and underlying upper Brunswick equivalents at Tybee Island suggests mixing of water from the two aquifers (Clarke *et al.*, 1999). The Tybee Island site is approximately 2.5 km (1.6 mi) east of the Fort Pulaski site, and provides additional evidence that adverse environmental impacts may be occurring to ecosystems supported by the surficial aquifer on these barrier islands.

Some of the natural areas in the vicinity of this area proposed for harbor deepening include the Savannah National Wildlife Refuge and Tybee National Wildlife Refuge to the north, and the Wassaw National Wildlife Refuge and Ossabaw Island Heritage Preserve to the south. Additional coastal and barrier island natural areas lying between Savannah and Brunswick, Georgia, within the combined cones of depression established many years ago include Harris Neck National Wildlife Refuge, Sea Beard National Wildlife Refuge, Blackbeard Island Wilderness Area, R. J. Reynolds State Wildlife Refuge, Sapelo Natural Area, Sapelo Island National Estuarine Research Reserve, and Wolf Island National Wildlife Refuge and Wilderness Area.

The Savannah National Wildlife Refuge has experienced dramatic declines in the number of ducks and striped bass in the Refuge since the previous harbor excavation activities; however, no causal relationship has been established (Sam Drake Jr., Refuge Manager, pers. comm.). Additional anthropogenic perturbations in the area of the Refuge include the severe cone of depression from groundwater mining associated with Savannah and a constructed tide gate which has been inactivated. Current modeling studies of the area attempting to simulate impacts to the Refuge from the proposed harbor deepening were presented by Applied Technology and Management at the 1999 Georgia Water Resources Conference on March 31, 1999. However, only surface water components were included. Evidence supporting the influence of groundwater mining in that area on the surficial aquifer and surface water systems can be found in data from one of the few surficial aquifer wells being monitored in that subregion. A comparison of water-level fluctuations in the surficial aquifer and cumulative departure of precipitation in the Savannah area between 1943-1981 reveals that surficial aquifer fluctuations were relatively constant through the "drought" of the late 1950s and peak rainfall of the late 1960s (Krause and Randolph, 1989).

Interactions between groundwater mining in the Savannah area and excavations in the harbor may be occurring, or may occur in the future if the harbor is deepened. Since the two primary causal factors for the damage in the Cumberland Island National Seashore Wilderness area appear to be harbor excavations and groundwater mining on the mainland, and interactions between these two factors may be occurring, it seems imperative that more detailed investigations of both potential causes and potential interactions between these two factors be initiated prior to additional harbor deepening activities at the Savannah site. A detailed investigation also is needed to identify the cause of the damage in the Cumberland Island National Seashore Wilderness Area to determine what action is necessary to prevent similar damage in the future.

ADJUSTING THE COURSE

Assessments of All Impacts Needed

Recently, National Geographic featured an article on America's Wilderness Areas, describing various threats to maintaining these crown jewels owned by the public. The Cumberland Island Wilderness Area was included in the article, but the potential threat of groundwater perturbations to this and other "protected" lands in the SE Coastal Plain was not recognized (Mitchell, 1998). An increase in public awareness is needed regarding the potential for damage to these natural areas from groundwater mining and other groundwater perturbations.

Attempts are being made by water resource agencies in Florida to evaluate the costs of various water supply alternatives to ground water. These attempts are being made without information regarding the ultimate costs of adverse impacts from the extraction of ground water, or alternative sources. In fact, no concerted effort is underway to identify and assess the adverse impacts of groundwater withdrawals in the SE Coastal Plain, or to determine the costs of these impacts. For example, the "Water Resources Management Plan" for Glynn County, Georgia, where Brunswick is located, recently abandoned analysis of desalination options because "the costs of desalination were so great" (Ashley, 1999). First-year cost estimates for the Tampa Bay seawater desalination facility from four different companies were 0.2¢/gallon, based on the Tampa Bay Water press release dated February 22, 1999. This represents a fraction of the cost of the damage already attributed to groundwater mining in that area. Although desalination of seawater also will have associated adverse impacts, identifying and resolving those impacts will be simpler and less expensive than attempting to resolve the large-scale impacts of groundwater mining from a regional aquifer.

The USGS is the most logical agency to initiate an evaluation of the adverse impacts of groundwater mining since it operates on a regional scale and houses a multidisciplinary staff. The Regional Aquifer-System Analysis program within USGS laid the ground work for what is needed. An expansion of that program could address the final objective that the initial RASA program did not address, providing the scientific foundation required to "assess water-management alternatives." The remaining task is to determine the costs of all impacts associated with groundwater use, and alternative water sources.

Evaluation of damages within the USGS' purview would fall under five ecosystem types: (1) depressional wetland systems, (2) lacustrine systems, (3) riverine systems, (4) associated uplands, and (5) estuarine/marine systems. For example, a detailed investigation of the damage to the Wilderness Area in the Cumberland Island National Seashore could provide considerable insight into the impact that groundwater mining may have on depressional wetland systems and associated uplands offshore, in addition to the degree to which channel excavations and groundwater mining interact to influence these systems. Similar investigations in the Savannah area could provide insight into the impact of groundwater perturbations on riverine and estuarine/marine systems. Examples of damages that would not be within the USGS' purview would include human health impacts from aspects such as degradation of air quality from catastrophic wildfires, and the concomitant economic costs of individual impacts.

Ramifications for the Classic Watershed Management Concept

Upward Leakage and Induced Recharge. The classic watershed model, such as the one described by Freeze and Cherry (1979), considers a drainage basin an entity in which water enters the basin as precipitation (rainfall/snowmelt); may be retained as storage (unsaturated soil moisture storage/saturated groundwater storage/channel storage); or may exit the basin from the surface (interception/evapotranspiration/overland flow (aka runoff)/stream flow) or from the subsurface (baseflow/streamflow/groundwater recharge). Accuracy and precision are primary concerns for the various approaches used to measure or estimate the amount of water entering and leaving a watershed from the surface or as baseflow. However, little attention is given to water entering or leaving a watershed via discharge to, or recharge from, the underlying regional aquifer. In fact, this classic watershed model does not even recognize water contributed to the watershed via upward leakage from the underlying regional aquifer (see also Sun *et al.* 1998a, 1998b).

In the SE Coastal Plain and similar karst systems, the strongest influence of upward leakage will be associated with discontinuities in the semiconfining layer between the regional groundwater system and the overlying surficial aquifer, as described in previous sections. For example, upward leakage from the underlying regional aquifer is the sole factor maintaining spring flow from deep aquifers, and can be a significant factor in maintaining ecosystems in streams, lakes, depressional wetlands, and estuaries, particularly during periods of low rainfall (refer to the preceding discussions of hydrology). Prior to initiation of groundwater mining from the Floridan aquifer system, the high potentiometric levels probably were the major factor in maintaining the water tables in perched lakes and wetlands, with upward leakage occurring very slowly through semi-confining layers. After initiation of groundwater mining, rapidly fluctuating groundwater levels in lakes and depressional wetlands could jeopardize the integrity of the semi-confining layers underlying these perched systems.

Holzer (1995) describes the aquitard-drainage model, which attributes land subsidence associated with mining of underground fluids to nonrecoverable compaction of slowly draining clay layers. This model applies to withdrawals of ground water, oil, and gas, and has been used to explain land-mass subsidence in California and Texas (see Germiat and Sharp, Jr., 1990; and Sharp *et al.,* 1991, for more detailed discussion of subsidence in Texas). Although this model also appears to be applicable to the land-mass subsidence in Savannah, Georgia, described by Davis *et al.* (1976) above, it does not appear to be given consideration in the SE Coastal Plain region, where the clays in the semi-confining unit between the surficial and Floridan aquifer systems could be affected.

In addition to nonrecoverable compaction of large-scale clay units, localized clay lenses (e.g., underlying depressional wetlands and lakes) could crack during dewatering and not regain their integrity if/when water levels rebound. This could result in significant chemical changes in depressional systems where the integrity of the semi-confining layers has been breached and the exchange of water between the two aquifers is increased in magnitude and velocity. This potential problem does not appear to have been investigated in detail. However, increases in pH from 4.5 to 6.5 and resistivity concentrations on order of magnitude greater than surrounding water have been documented in the center of one depressional wetland in central Florida where pond-cypress trees were exhibiting significant symptoms of premature decline and some trees were dying. A nearby depressional wetland where pond-cypress trees were healthy did not exhibit these chemical anomalies (Bacchus, unpub. data). The chemical anomalies in the former wetland were attributed to more direct upward leakage from the Floridan aquifer system (Todd Rasmussen, pers. comm.).

Laboratory tests often are used to determine characteristics such as permeability, porosity, and compressibility of a zone of lower hydraulic conductivity ("confining" zone) separating a regional aquifer from a surficial aquifer. Small samples taken from these zones are used for the laboratory determinations. Values for these characteristics determined by laboratory analysis are of limited use for regional karst aquifers because primary flow occurs through landscape-scale features of secondary permeability (including breaches in the "confining" zone) rather than through the small-scale pore spaces of the sample evaluated in the laboratory.

In some cases, these characteristics are determined by short-term field tests, observing fluctuations of water levels in wells constructed in the uplands. This approach also poses problems. For example, Krause and Randolph (1989) reported that the transmissivity values derived from some of the aquifer tests in subregion D (described previously) were considerably lower than those simulated. The suggested probable causes of the discrepancy were aquifer tests that were too short, or were conducted on wells that partially penetrated the aquifer or that tapped parts of the aquifer lacking fractures or solution conduits that control flow on the regional scale. Although field-determined values for these characteristics using pumping tests are an improvement over laboratory-determined values, this approach poses significant problems in karst aquifers subjected to groundwater mining, beyond problems referenced by Krause and Randolph (1989). The first is that the observation wells routinely are not constructed in areas that may be "point-charge" locations (e.g., depressional wetlands), where the greatest response to the pump tests may occur. The second problem is that karst aquifers are not static and their characteristics change over time. In the past, these changes have occurred over geologic time. However, intensive, prolonged groundwater mining has compressed these changes to the span of one or two human generations. Consequently, a pump test conducted prior to groundwater mining, for a period of several days, will not represent the characteristics of the aquifer after groundwater mining is initiated and has occurred for a period of years.

Likewise, conditions of the surficial aquifer that support wetlands, streams, and lakes also change over time in response to groundwater mining from regional karst aquifers. Therefore, conditions of these systems documented in the period of record cannot be assumed to reflect the typical conditions for these natural systems. Considerable induced recharge may have occurred prior to initiation of the period of record due to regional groundwater mining. For example, the effects of antecedent rainfall on stream discharge in Georgia's Coastal Plain recently were evaluated for the period of record (1948-1994). The conclusion reached was that stream discharge returned to "normal" between one and two years following a drought if normal rainfall conditions returned (Rose, 1999). Groundwater mining in this subregion had been occurring for more than 50 years before initiation of data collection in the streams used in this evaluation. Therefore, the assumption that the period of record reflects "normal" wet and dry conditions in these streams is invalid.

Subsurface Interbasin Flow and Watershed Model Constraints. The concept of subsurface interbasin flow is not new. Approximately three decades ago Toth (1963) described a flow model in which water from a local drainage basin (watershed) recharged a regional groundwater system, which in turn discharged the water to another local watershed, far removed from the first. Prominent hydrology texts (e.g., Freeze and Cherry, 1979) even include discussions of groundwater recharge and discharge as components of a hydrologic budget. However, this component is minimized, ignoring the significant impacts of both upward leakage to, and induced recharge from, the surficial aquifer.

Most recently, Thyne *et al.* (1999) described hydrogeological, geochemical and isotopic evidence of interbasin flow of ground water in the southeastern Sierra Nevada, proposing bedrock fractures as the flow paths. They acknowledge that fractures often are the only pathways with significant permeability in hard rocks and limestone. The bedrock in their study supplies recharge to the San Joaquin Valley (site of extensive groundwater mining) to the west. Previous research suggested that fracturing had created a high-permeability zone that funnels recharge from the Sacramento Mountains at least 80 km (49.7 mi) southeastward to aquifer discharge points (Mayer, 1996), representing approximately twice the distance described in the Sierra Nevada study. Issar and Gilad (1982) note that the direction of flow through fractures may be different than the regional gradient if the permeable fracture zones are not oriented parallel to the topographic gradient.

Based on 1980 conditions in the Floridan aquifer system, Krause and Randolph (1989) found that the head decline along the southwestern boundary of the subregion created a gradient in the Upper Floridan across what had been a groundwater divide prior to development. This suggests that flow across groundwater divides, in the form of induced subsurface transfer of water from one watershed to another may be initiated by groundwater mining. The legal ramifications of induced subsurface interbasin flow has not been addressed yet.

An example of constraints associated with typical watershed models is provided in the recent introduction and application of the "FLATWOODS" model developed by Sun *et al.* (1998a, 1998b) for use in the Coastal Plain. In theory, the "FLATWOODS" model offers distinct advantages over other options available for forested areas of the SE Coastal Plain, a significant portion of which was pine flatwoods. Unfortunately, the Gator National Forest site selected for development of the model is in close proximity to the Murphree wellfield, the municipal water supply for Gainesville, Florida. Many of the pond-cypress wetlands on the site exhibit the typical symptoms of hydroperiod perturbation (e.g., soil subsidence, premature decline of pond-cypress). However, without additional information it is difficult to determine how much of the perturbations can be attributed to the municipal withdrawals and how much, if any, can be attributed to hydroperiod perturbations from the conversion of the former pine flatwoods stand to the pine plantation stand. Canopy conversion factors alone, in the absence of influences from municipal supply wells, suggest that application of this model should be restricted to pine plantations, with trees of the same species and comparable age as those in the stand where the model was developed. A more detailed discussion of reductions in infiltration and recharge that may be associated with conversions of natural pine flatwoods to pine plantations in the SE Coastal Plain is provided by Bacchus (1995b, 1999b).

Pumping from the municipal wellfield near the Gator National Forest site began in 1968 and 1969 for eight wells, with the final three wells coming on-line in 1990. The permitted production capacity of the wellfield is 57.8 mgd, but the actual amount withdrawn is not documented (Gainesville Regional Utilities, 1991), and may be considerably less. Collection of groundwater data for development of the "FLATWOODS" model occurred only from 1992 through 1995. Consequently, significant alteration of the natural hydroperiod of the former pine flatwoods site may have occurred years prior to the collection of groundwater data. The impact of pumping on aquifer characteristics is seen in the increase in transmissivity from 129,000 gpd/ft, at the time an initial well was drilled in December 1968, to 229,000 gpd/ft in 1991 (Gainesville Regional Utilities, 1991). The statement by Sun *et al.* (1998a) that little overland flow occurs on the site corroborates observations of subsidence and premature decline of pond-cypress on this site (Bacchus, unpub. data). This provides additional support for the hypothesis that significant anthropogenic alteration of the hydroperiod has occurred. Following rainfall events of various magnitudes and durations, considerable overland flow has been observed in pine flatwoods located throughout the state of Florida, but not associated with major supply wells (Bacchus, unpub. data). The "FLATWOODS" model was unable to predict peaks of overland flow in the "control" watershed located in Bradford Forest, and produced low Pearson Coefficients (0.61 and 0.62) for the wet years tested by Sun *et al.* (1998a). Induced recharge at the Gator National Forest site due to groundwater withdrawals from the municipal wellfield may be responsible for these performance problems with the model. Until additional work has been done to evaluate the influence of groundwater withdrawals at the Gator National Forest site and the influence of cover-type conversion, assumptions cannot be made that the "FLATWOODS" model represents typical responses in natural pine flatwoods stands, or in pine plantations planted on sites of former pine flatwoods that are not influenced by groundwater withdrawals.

Widespread Lack of Recognition. Evidence that similar interactions between contiguous aquifers apply to regional aquifers other than the Floridan aquifer system was provided recently by Boyd (1998). He found that interaction between an alluvial and underlying bedrock aquifer in Cedar Rapids, Iowa, occurs where (1) the confining layer between the two aquifers is discontinuous, (2) the bedrock aquifer is fractured, or (3) pumping of supply wells induces the flow of water between aquifers. However, current literature attempting to address forest hydrology issues for the 21st century fails to acknowledge this problem, referencing only forested watersheds manipulated for supply of surface water (Swanson, 1998). Equally as pressing is the issue of regions relying primarily on ground water, and what impact unsustainable withdrawals from a regional aquifer in one watershed will have on forest resources (and other natural resources) in that watershed, as well as in neighboring watersheds.

Black (1998) produced a broader, more comprehensive discussion of the most pressing needs and research issues in forest hydrology, identifying five levels, including watershed function. Despite the recognition of many important inadequacies that need to be addressed, his paper also neglected to address the problem of induced recharge and subsurface interbasin diversion of water. For example, he stated that the influence of gravity on watershed function and stream discharge can be described largely by the topography of the watershed. Although that statement is not false, the influence of topography can be superseded by the influence of induced recharge for watersheds underlain by a mined regional karst aquifer (and possibly other types of regional aquifers). He also concluded that, given sufficient records of flood peaks on a series of watersheds, we can construct a reliable regional model of flood behavior on a geographically similar ungaged watershed. This is not the case for watersheds where water is being mined from the underlying regional aquifer. Finally, he quoted McCleese (1996), indicating that the hydrologic environment "must consider the interrelationships between the terrestrial, riparian, and aquatic ecosystems." The missing component in this interrelationship is the regional groundwater system and any anthropogenic perturbations to which that regional groundwater system is being subjected. This ignored component can have profound impacts on the remaining triad. A recommended substitute for McCleese's triad is the dynamic interrelationship between (1) regional groundwater systems, (2) local surface water and groundwater systems, and (3) the living systems supported by these hydrologic systems.

Finally, Baker (1998) lists the important components of forest hydrological science as flooding, water quality, or land-use impacts as general phenomena that are well-explained. This list implicitly excludes the influence of groundwater mining, because the impact of this land-use currently is not well-explained. However, he makes the quantum leap by proselytizing the need to use observational components to test and calibrate models, because of the ability of landscapes and sediments to provide indices of real processes. Specifically, he recommends that more concern be given to the science of what the world says to us, incorporating observational components into hydrological science. He reminds us that although true controlled experimentation is impossible in nearly all environmental science, "these sciences serve for hypothesis generation according to retroductive reasoning processes that complement the more heralded inductive/deductive dichotomy of scientific inference."

CONCLUSIONS

Based on the documented and potential impacts associated with groundwater mining described above, the most critical needs and research issues for water resource specialists to address in the 21st century will be on a scale beyond the watershed/drainage basin level currently being addressed. Although the focus of this paper has been on problems initiated at a regional scale, the adverse impacts may extend beyond the regional scale because of the widespread nature of groundwater problems throughout the continental United States, and the rest of the world (refer to previously referenced conclusions of Sahagian *et al.*, 1994).

At the regional scale, water resource specialists must determine the true cost of using ground water, before comparisons can be made with use of other sources such as desalination of seawater. These costs must include both direct and indirect short and longterm impacts. One category of these impacts is the irreversible damage to the aquifer matrix and semiconfining layers (dissolution, collapse, compaction/compression). This category would include the concomitant degradation of groundwater quality, and damage to private and public property (homes and other buildings, roads, and depressional wetlands – including those theoretically "protected"). A second category is the reductions in regional groundwater contributions to surface water systems as both spring discharge and diffuse leakage/seepage. This category would include resulting physicochemical changes in surface water systems (streams, lakes, wetlands, estuaries) such as pH, salinity, and temperature changes. This category also would include water quantity changes such as alterations in flow regimes and stages during each season. Finally, this second category also would include all of the adverse impacts of these water quality and water quantity changes on the living organisms (plants and animals) supported by these systems. A third category is the reductions in regional groundwater contributions to the subsurface portion of the surficial aquifer. This category would include reductions in soil moisture during individual seasons that can result in catastrophic wildfires and predisposition of trees to pathogens. It would include concomitant losses of commercial, silvicultural stands of trees, as well as natural stands of vegetation on private and public property, including "protected" areas. This category also would include concomitant disruption of transportation flow and degradation of air quality from particulates associated with smoke from these wildfires.

Four years ago, Black (1996) mused over the irony that water, our most valuable and essential resource, literally was cheaper than dirt. He quoted prices for a cubic yard of soil at $50, while an equivalent quantity of water cost approximately 10¢. The reason for this great disparity in price is that we have not been paying for the actual cost of our water. Recent generations have been using water under a balloon mortgage. The final payment will be served on future generations and it will be a financial burden that they are incapable of meeting. Determining and assessing the actual cost of the water we use now may ameliorate that final payment by resulting in shifts to less damaging alternatives and more conservative use of our most valuable resource. The time has come for a true multidisciplinary approach to hydrology. Regional and local surface and groundwater systems must be treated as linked entities, and the responses of the ecological components of these linked systems must be evaluated in conjunction with the standard physical components. This holistic approach is required before options of water supply can be evaluated intelligently.

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