THE WAKULLA SPRINGS WOODVILLE KARST PLAIN SYMPOSIUM OCTOBER 9, 1998

TRANSACTIONS

COMPILED AND EDITED BY
WALTER SCHMIDT, JACQUELINE M. LLOYD
AND CINDY COLLIER

FLORIDA GEOLOGICAL SURVEY
SPECIAL PUBLICATION NO. 46

STATE OF FLORIDA
DEPARTMENT OF ENVIRONMENTAL PROTECTION
David B. Struhs, *Secretary*

DIVISION OF RESOURCE ASSESSMENT AND MANAGEMENT
Edwin J. Conklin, *Director*

FLORIDA GEOLOGICAL SURVEY
Walter Schmidt, *State Geologist and Chief*

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LETTER OF TRANSMITTAL

FLORIDA GEOLOGICAL SURVEY

April 2000

Governor Jeb Bush
Florida Department of Environmental Protection
Tallahassee, FL 32301

Dear Governor Bush:

The Florida Geological Survey (FGS), Division of Resource Assessment and Management, Department of Environmental Protection, is publishing as our Special Publication No. 46, the *Transactions from the Wakulla Springs – Woodville Karst Plain Symposium*, held at the FSU Center for Professional Development on October 9th, 1998. This conference brought together numerous professionals involved with natural sciences and resources research and land-use planning on the Woodville Karst Plain, located between the Cody Scarp and the Gulf of Mexico coast in the big bend of north Florida. This conference demonstrated the usefulness and need for multidiscipline research expertise to address holistic environmental conservation concerns. This successful gathering also served as the kick-off for Earth Science Week in Florida. We hope this week in the future will serve to highlight other events which demonstrate the importance of understanding applied earth sciences to the future of Florida and our environmental sustainability.

Respectively yours,

Walter Schmidt

Walter Schmidt, Ph.D., P.G.
State Geologist & Chief
Florida Geological Survey

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This collection of papers represents the authors written manuscript of their talk presented at the Wakulla Springs Karst Plain Symposium. The editors have reviewed the submitted texts for basic spelling errors and gross figure irregularity and prepared necessary reformatting of text for consistency. Interpretive concepts, figures, and other professional opinions are clearly the responsibility of the authors and no endorsement by the Florida Geological Survey or the Department of Environmental Protection is intended. Authors who presented their talk but were not able to provide a complete manuscript are represented here by their abstract.

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PREFACE

The first annual ***Earth Science Week*** was celebrated the second full week of October in 1998. This celebration was initially conceived by the American Geological Institute to celebrate their 50th anniversary. The Association of American State Geologists representing the 50 State Geological Surveys immediately supported the concept to raise the visibility and awareness of the Earth Sciences among the public and professional environmental community. Over thirty Governors had signed proclamations designating Earth Science Week within their respective State, Congress adopted a resolution into the Congressional record designating such, and President Clinton saluted the effort by signing a letter recognizing the contributions earth science makes to society and the well being of all Americans. In Florida, Governor Chiles signed a proclamation designating October 11-17, 1998, as Earth Science Week in Florida.

One of the goals of Earth Science Week is to encourage geoscientists to do something in their community to promote earth science understanding and to foster further appreciation for the subject. In Florida, we at the Florida Geological Survey viewed this as a logical and natural means to promote what the Florida Department of Environmental Protection had been endorsing for several years, namely – holistic ecosystem management concepts. This management principle must be based on sound scientific understanding of our natural physical systems and their interconnectedness to be successful. Three activities were organized to kick-off Earth Science Week and to highlight these issues in the Big Bend of Florida. On Friday, October 9, 1998, scientists, land and water managers, and others with an interest in the science behind the Wakulla Springs Basin and its water resources, came together at the **Wakulla Springs Karst Plain Symposium** at the FSU Center for Professional Development, in Tallahassee, FL. Participants included geologists, hydrogeologists, biologists, botanists, cave divers, engineers, land use and resource managers and planners, government officials, and the public. This publication represents a compilation of the papers presented at the symposium on that day. Mr. Kirby Green, the Deputy Secretary of the Department of Environmental Protection provided introductory and welcoming remarks to those in attendance. This was followed by comments from the Honorable Janegale Boyd, Representing District 10 in the Florida House of Representatives (which covers most of the area covered by the symposium presentations). Representative Boyd is an active and dedicated member of the House Water Resources Management Committee.

On Saturday, October 10th, the public was the primary focus at the **Wakulla Springs Earth Science Fair**. Beginning at 10 a.m. at the Wakulla Springs State Park, the Fair gave everyone the chance to enjoy and learn more about this valuable resource. Exhibits explained the importance of karst geology to the springs, the threats to water quality throughout the Wakulla Springs Basin, and how cave divers have mapped the underground cave system that brings water to the Springs. Demonstrations and field trips also were incorporated into the day's activities by the many agencies and various firms participating. The demonstrations covered several aspects of water quality monitoring, the use of satellites for mapping systems such as the network of caves that lead into the springs, how divers negotiated the caves, the damage done to local ecosystems by exotic plants -- and more. Visitors were able to take field trips to see some of the sinkholes and springs that are important components of the Wakulla Springs system and learn how they offer avenues through which pollution can enter the spring system. Visitors also were able to take the river boat and glass-bottom boat tours of the springs to learn more about the waters that bubble up from deep in the earth, and the ecosystems around the spring and river. The park entrance fee was waived during the Fair. The Fair was sponsored and organized by the Florida Department of

Environmental Protection, the Florida Geological Survey, the Florida Association of Professional Geologists and the Wakulla Springs Water Quality Working Group, which is composed of all the federal, regional, state, and local agencies that are working to protect water quality in the springs. Over 1,200 people attended the day's festivities.

On the following Monday, October 12, 1998, the Florida Geological Survey hosted an Open House at the Herman Gunter Building, the headquarters of the FGS in Tallahassee, FL. Geoscience colleagues, environmentalists, government employees, friends, and the public attended to view FGS displays, and learn about our programs and facilities. All in all the first Earth Science Week was a very successful event for the geological community in north Florida. The FGS hopes to orchestrate continuing outreach activities in Florida during Earth Science Week on an annual basis.

Walt Schmidt, Ph.D., P.G.
State Geologist & Chief
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EARTH SYSTEMS UNDERSTANDING: THE FOUNDATION OF ENVIRONMENTAL REGULATORY SUPPORT, LAND-USE PLANNING DECISIONS, NATURAL RESOURCES CONSERVATION, AND THE BASIS OF ECOSYSTEM MANAGEMENT

Walter Schmidt, State Geologist and Chief, Florida Geological Survey, 903 W. Tennessee Street, Tallahassee, FL 32304-7700

ABSTRACT

Each and every environment that exists on the face of the earth, is the cumulative dynamic result of the interactions between four ***Earth Systems****. And without a basic understanding of these Earth Systems there can be no real understanding or predictive capabilities for environmental change, and hence, natural resources conservation or "sustainability" as popularly defined. These systems include:* ***the Geosystem*** *(the solid earth framework of the earth),* ***the Hydrosystem*** *(the hydrologic cycle or the aqueous portion of the earth),* ***the Atmosystem*** *(the meteorological and climate aspects of our planet), and* ***the Ecosystem*** *(the interaction of the biologic assemblages with each other and the physical systems).*

Here, I will champion the need for a greater emphasis on the Geosystem, the solid earth framework. This I believe is critical to our species survival, our societal life style, and indeed all life. Water supply and protection concerns are not isolated issues only involving the study and planning for surface and ground water resources. To fully understand and protect our precious, life sustaining water resources, knowledge of the medium which the water flows through and over must also be considered. The geologic framework serves as the "bucket" that contains the water, and it contributes dissolved minerals and elements which characterizes the ambient water component and is the most critical of the precusor for the soils. Why do I say the solid earth component is the most critical of the systems? Because; we walk on it, we grow our food on and in it, we get our water resources from within it, we dispose of our waste on and within it, we are subject to all the natural hazards it has to offer (such as sinkholes, coastal and fluvial erosion, expansive clays and other soils, if we were from another state I'd mention volcanoes and earthquakes), and we obtain all our mineral resources from it to build our roads, homes, schools, malls, government buildings, cars, computers, clothes, packages, medicines, etc.

We must learn about earth systems, so that we may understand our surroundings. To remain ignorant of geological reality, jeopardizes the future welfare of our society. To quote Dr. Gene Shinn from a recent paper: "No Rocks, No Water, No Ecosystem!"

INTRODUCTION

Earth Systems are commonly thought of as: Volcanoes, Earthquakes, Landslides, and Tsunamis. And a typical response to us in Florida is, we don't have to worry about these things here. Well let me explain to you, that not only are we subject to the dynamic actions of earth systems in Florida, but they clearly are the fundamental aspect of understanding our various environments. For without this awareness, we cannot implement defendable environmental regulations, we cannot conserve or preserve our natural resources, we cannot approach a sustainable society as popularly defined, and we cannot do an adequate job of protecting threatened & endangered species, or degraded habitats.

Viewing a satellite image of hurricane Georges clearly demonstrates a powerful earth system impacting our State. It's the resultant manifestation of land heating, warm ocean circulation, and dynamic atmospheric response. It's forces effect our corner of the earth in: Coastal erosion, inland wind damage to structures and vegetation, coastal flooding, upland flooding, mud slides, sediment build-up at estuaries resulting from increased sediment loading during flood stage events, surficial aquifer loading, changed surface water / groundwater interactions, critical sinkhole development, among many others. Clearly, we are seriously impacted by physical earth systems. When we consider how other parts of the earth must deal with many other geologic hazards, it easy to see why WILL DURANT said: "*Civilization exists by geological consent, subject to change without notice."* And how author H.G. WELLS came to say: *"Human history becomes more and more a race between education and catastrophe."* But we are not here to dwell on the awesome power of earth systems, we are here to nurture an appreciation for the need to understand how they work, for the benefit for society and our co-inhabitants of this earth.

Our society and cultural habits tend to have a great impact on the workings of these earth systems. We must understand the impacts of our actions if we are to conserve our natural environment or minimize our pollution impact. For example: forest fires, logging, road construction, urban development, dam operations, or agricultural draining, all can and do send a rush of sediment into streams and rivers, changing the river's environment and ecological system. Excess sand into a riverine system can degrade fish habitat or increase the potential for flooding. Sediment transport is a function of not only the fluid regime, but the grains lithology, SP gravity, size, roundness, sorting, among other factors.

De-watering an area for development can change the soil type by changing it from a reducing environment to an oxidized environment. The available elements and nutrients which plants depend on would be dramatically altered. The surficial water table may cease being available for the local plant assemblage. It may cease recharging the local aquifer, a spring discharge area could become an aquifer recharge area, sinkholes could be triggered, saltwater intrusion into the local aquifer could contaminate the freshwater resource. These are but a few of the obvious impacts of an apparent simple modification to a local water table for development purposes.

In Florida in 1990, we saw about <u>19 acres per hour</u> of wetlands and agricultural land being developed into urban uses. We have through the P2000 and other programs been able to conserve over 1,000,000 acres of land since then. So significant efforts are being made. But we can't buy everything, nor do we have any business suggesting it. But we must include all the "stakeholders" in the discussion. Science in public policy has rarely been so needed as it is in today's complex political forum. Society demands resources to maintain a standard of living commensurate with people's expectations and a suitable level of environmental quality is inherent to this demand. Tradeoffs are inevitably made between the activities that provide energy, minerals, timber, food, and water, and the need to and desire to preserve ecosystem services and conserve our environment. Such tradeoffs are often highly controversial and politically volatile, and maintaining detachment, not taking sides on issues, is not easy for the scientist or informed citizen. Differences between geological and ecological views may reflect real and inherent tensions arising from the growth of industrialized society, but scientists must seek common ground in order to balance resource and environmental goals. Failure will likely result in alternating extremes of exploitation and preservation. The use of a popular phrase or a current buzz-word can change the course of public opinion, but fundamental geologic and biologic processes are not swayed by polls. We must be careful that true conservation will not be lost in rhetoric and scrambling for dominance of perspective.

LOCAL PERSPECTIVE

The Leon / Wakulla / Jefferson Counties area has increased in human population about 110% the last twenty five years. It now represents over a quarter of a million people. The NWFWMD estimates that the area withdraws about 116 Mgal/day from the aquifers. This area is a great natural laboratory to implement a multidiscipline, multiagency, public / private attempt to mesh our best efforts for the good of the environment, for the conservation of our natural resources, and ultimately to the benefit of us all. We have a growing urban / metropolitan area in Tallahassee. We have several small towns with their own public facilities (such as Perry, Crawfordville, and Woodville), we have widespread areas of rural farms and small homesteads, there are vast unpopulated uplands in timber, pristine uplands and coastal wetlands, a National Refuge and State Parks. There exists a great variety of environmental and geographic landforms in and around the Woodville Karst Plain.

Ecosystem management principals and programs, water shed management; natural resources conservation; environmental regulatory program foundations; land-use, planning, zoning, and management decisions; threatened and endangered species assessment and protection; invasive and exotic species geographic assessment; groundwater and surface water conservation and protection; geologic hazards understanding; minerals resources planning for society's needs; among many other issues, all have at their base, a fundamental need for data and interpretations of the solid earth.

Of course all living things need air, water, and mineral and elemental components to survive. Why do I say the solid earth is the most important from our point of view? It's the substrate to everything we do, we walk on it, we grow our food on and in it, we get our life sustaining water from within it, we dispose of our waste in it, we are subject to all the natural hazards it can dish out, we get all our materials and supplies to build our homes, malls, schools, cars, cloths, etc. from it, and every single square inch of the surface of the earth is a unique environment resulting from the composite dynamic interactions of the solid earth terrain with the hydrosphere and atmosphere, which in turn creates our ecosystems with their associated biologic assemblages. Forested uplands, dry inland ridges, wetlands, and coastal swamps, to name only a few, all owe their existence to the local shallow subsurface geology and hydrogeologic regime. All species exist in the habitat from which they evolved and for which they are best adapted. Why does an area function as a wetland? It is a groundwater discharge area? Is it a low relief karst prairie, or is it flooded as a part of an episodic fluvial system? Is it the result of a perched surficial water table because of an impermeable hard pan or clay bed in the subsoil zone? How does this change seasonally going wet to dry back to wet again? Do these alternating oxidizing and reducing conditions change the available minerals and elemental nutrients? Why do certain species of plants grow in selected defined regions? Are they dependent on the near-surface mineralogical nutrient sources? Are they in need of well drained sediments? Do they require certain groundwater or surface water geochemistry? What accounts for the various types of surface water chemistry we see in Florida? Where do the various elemental and chemical components come from? A clear understanding of the solid earth system is an essential aspect of any successful environmental assessment. I like to say,.....*the solid earth is the "bucket" that contains our precious water resources.*

RESOLVE

So, this is our big picture problem as geoscientists and as environmental scientists from all disciplines, to communicate this to the public, to elected and appointed government officials, to planners, and others. A basic understanding of these concepts is lacking by the general public. Earth Science is not required in our public school systems, so most members of the lay public have never been exposed to these basic earth system concepts. They continue to think of geoscience as the science of mining, oil & gas, and rock and mineral collections from their Boy/Girl Scout days. True natural resource conservation towards a sustainable environment can never be achieved until the general public grasps an overall systems understanding and an appreciation for the interconnectedness of these systems. We must continue and expand our outreach programs to be successful.

I thank Dr. Lee C. Gerhard, State Geologist of Kansas, and Dr. Morris W. Leighton (past State Geologist of Illinois) whose many publications and several discussions on this topic provided a basis for these thoughts.

REGIONAL AND LOCAL GEOLOGIC SETTING OF THE WOODVILLE KARST PLAIN

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ABSTRACT

The Woodville Karst Plain (WKP) is situated in the eastern Florida panhandle bordering the Gulf of Mexico. It extends from central Wakulla County, Florida, eastward through southernmost Jefferson County and around the coastal Big Bend region to the Steinhatchee River in southwestern Taylor County. The WKP is characterized as a very-gently-seaward-sloping, sandy, swampy subzone of the Ocala Karst District geomorphic province. It is underlain by shallow, karstic, carbonate bedrock covered by a veneer of undifferentiated sand. Land surface elevations typically vary between 0 and 50 feet. Doline features, such as sinks, collapse depressions, disappearing streams and caves are common throughout the region. The WKP is bounded on the west by an elevationally-higher region of clayey sands with few karst surface features. To the east and south the WKP is bounded by elevationally higher and less karstic zones. The northern boundary of the WKP is a relict Pleistocene marine escarpment named the Cody Scarp, which forms a relatively abrupt transition from the flat, sandy, karst plain into higher clayey sand hills of the Tallahassee and Madison Hills geomorphic zones. The southern edge of the WKP borders the Gulf of Mexico, and the seaward extension of the carbonate plain continues offshore to the edge of the continental shelf.

The origin of the WKP, as well as its underlying stratigraphy, have been significantly influenced by adjacent subsurface structural features. The rocks comprising the shallow bedrock in the WKP are Eocene and younger carbonates. These units dip and thicken to the west-southwest into a broad structural basin named the Apalachicola Embayment. Eocene through Miocene carbonate strata are brought close to the surface in the WKP as the units lap up onto the flank of the Ocala Platform, a broad, southeast-trending, positive structure located to the southeast of the WKP. Eocene Ocala Limestone forms the bedrock adjacent to the crest of the Ocala Platform at the southeast end of the WKP. The Ocala Limestone typically consists of white to pale orange, skeletal, very fossiliferous Eocene (38 Mya [million years ago]) marine limestone and dolostone. It ranges in depth from surface outcrop near the Steinhatchee River in Taylor County to over 400 feet bls at the western edge of the WKP.

Progressively younger geologic units are exposed on the northern and western flanks of the Ocala Platform. Suwannee Limestone unconformably overlies the Ocala Limestone and comprises the shallow bedrock in most of Taylor County and southern Jefferson County. The Suwannee is an Oligocene (33 to 30 Mya) white to gray to pale orange calcarenitic marine limestone and dolostone, comprised largely of foraminiferal tests and small mollusks. In the WKP the top of the unit varies from approximately 150 feet below land surface at the western edge of the plain to surface exposure in the eastern part. A network of large subsurface karst conduits mapped in the WKP are developed in Suwannee Limestone. The Miocene (25-20 Ma) St. Marks Formation unconformably overlies the Suwannee Limestone and forms the shallow bedrock under the western end of the WKP, comprising westernmost Jefferson County, southernmost Leon County, and all of Wakulla County. It is typically a pale orange to light gray to white, calcarenitic limestone, generally very fossiliferous, well indurated, and commonly dolomitic. The St. Marks Formation crops out over much of southern Wakulla County, and many area sinks expose this unit. St. Marks Formation also forms the ledge overhanging the vent in Wakulla Spring, rims the spring pool, and forms the bed of the Wakulla River. The St. Marks Formation and the underlying Suwannee Limestone and Ocala Limestone are components of the Floridan aquifer system.

Variably-thick Pleistocene undifferentiated sands and clayey sands overlie the carbonate bedrock throughout the WKP. These surficial sands are largely reworked marine sediments, deposited by high-standing Pleistocene seas. Relict Pleistocene marine and aeolian features, such as dunes, bars, and beach ridges are common in many areas of the WKP.

INTRODUCTION

The Woodville Karst Plain (WKP) is situated in the eastern Florida panhandle, bordering the Gulf of Mexico (Figure 1). It extends east-southeastward from an approximate line connecting the towns of Panacea and Crawfordville, in Wakulla County, around the Florida Big Bend, encompassing portions of southern Leon, eastern Wakulla, southern Jefferson, and western Taylor Counties. The Steinhatchee River forms the southern boundary of the WKP. The WKP is characterized as a flat-to-gently rolling, seaward-sloping plain, underlain by shallow Tertiary carbonate bedrock. Undifferentiated Quaternary sands thinly blanket the surface, and karst doline features such as

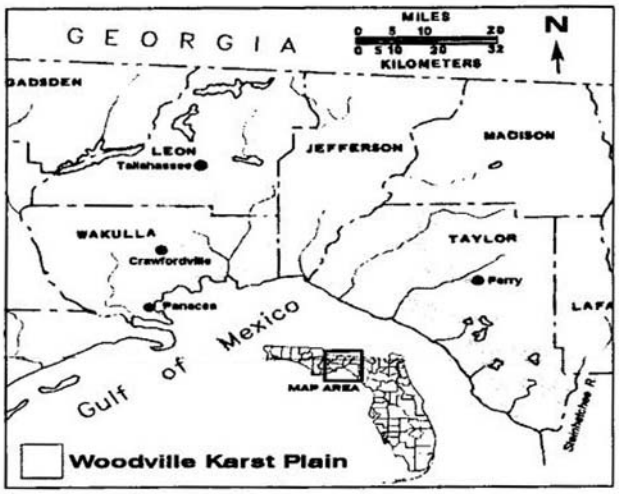

Figure 1. Location of the Woodville karst Plain.

collapse depressions, sinkholes, disappearing streams, springs, and extensive underground caves are common throughtout the area.

PREVIOUS STUDIES

Studies leading to the delineation of the region now called the Woodville Karst Plain have spanned much of the present century. Early descriptions of northern Florida's surface features, completed before detailed topographic maps and extensive subsurface geological data were available, were based on field observations of land forms. The early literature generally recognized differences in elevation and land surface shape between the highlands in the northern part of the panhandle and the lower, flatter coastal plain bordering the Gulf of Mexico. Wilder et al. (1906) noted the topographic differences between the clayey-

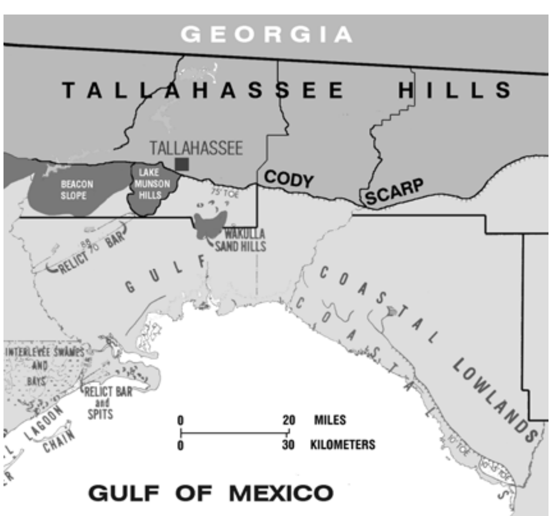

Figure 2. Geomorphic map of the eastern Florida panhandle (modified from White, 1964).

sand highlands of northern Leon County and the low, sandy, undulating plain extending from southern Leon County to the Gulf; these authors correctly attributed the terrain differences to variations in the underlying geology. They also cited the shallow limestone substrate occurring in the region south of Tallahassee noting the numerous sinks and the underground drainage systems.

In his early botanical studies, Roland Harper (1910) took a geomorphic approach to descriptions of the local terrain, dividing the state into geographic regions. Harper (1910) included the Leon County portion of what is now the WKP in his Limesink region, and placed the Wakulla County portion in his Gulf Hammocks region. He also used the term Red Hills to describe the stream-dissected highlands of northern Leon, Jefferson, and Madison Counties, which at that time, he included in his Middle Florida Hammock Belt. Later, Harper (1914) noted that the floral assemblages in the Limesink and Gulf Hammock regions, which correspond to the modern WKP, were distinctly different from surrounding areas and coined the term Tallahassee Red Hills for the highlands in Leon County bordering the northern edge of what would be later named the WKP.

Sellards (1910, 1914) and Sellards and Gunter (1912) broadly described the geomorphology of the counties that would one day contain the Woodville Karst Plain. The only elevation data available for Sellard's studies, however, had been shot along the railroad grades of his day. Therefore, vast expanses of land lay unmapped, and he could not see the geomorphic features which would be used to define the WKP.

The first true regional geomorphic zone encompassing the entire extent of the modern WKP was named the Coastal Lowlands by Cooke (1939). He recognized the Coastal Lowlands as terraced plains representing the sea bottoms of high-standing Pleistocene seas. These were observable as a series of elevational terraces, flat erosional sea floors punctuated by small scarps, approximately paralleling the modern coastline. Cooke also differentiated the broad geomorphic region of stream-dissected highlands between the Apalachicola and Withlacoochee Rivers, extending from Tallahassee north into Georgia, giving it the name Tallahassee Hills.

As topographic map coverage expanded in the panhandle area through the 1950s, and more geologic well data became available, better delineation of geomorphic features was possible. White (1964) produced the first color geomorphic map of the Florida panhandle (Figure 2). In it he incorporated Cooke's (1939) zones and added the important bounding feature known as the Cody Scarp. The Cody Scarp is a relict, east-west-trending marine escarpment representing the shoreline of the Wicomico sea. The escarpment forms a distinct break between the Tallahassee Hills to the north and the Coastal Lowlands stretching from the toe of the scarp southward to the Gulf. It is best developed near the community of Cody in Jefferson County, for which it is named. At Tallahassee, the toe of the Cody Scarp lies at about 50 to 60 feet above mean sea level (msl), with the crest at approximately 150-200 feet above msl. Locally the scarp is modified by dissolution of the underlying carbonates and by erosion to the extent that

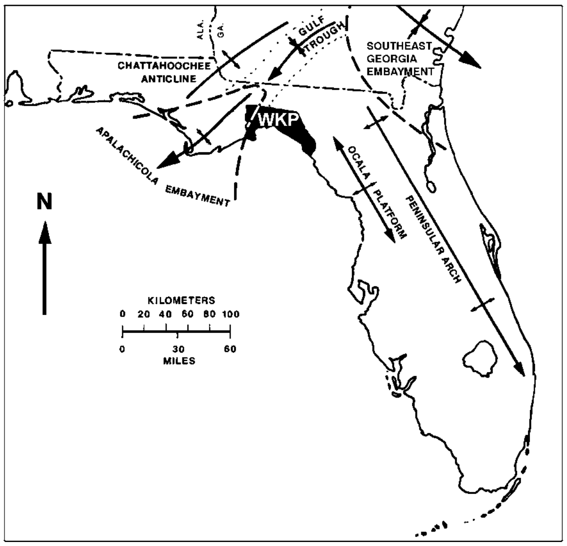

Figure 3. Regional subsurface structures of north Florida.

the scarp face is not as well defined as in areas to the east; here it consists of a series of coalesced sand hills in the transition from highlands to lower karst plain. White also included names for two of the larger relict marine features in the Gulf Coastal Lowlands. At the edge of the Cody Scarp, near Tallahassee, are a series of relict sand bars and dunes associated with the Wicomico sea named the Lake Munson Hills. Crests of the dunes attain elevations of 80-100 feet above msl. Similarly, the Wakulla Sand Hills in southeastern Leon County are a series of Pamlico sea dunes attaining elevations of about 50 feet msl.

In 1966 Hendry and Sproul published a bulletin on the geology of Leon County, in which they further refined existing geomorphic zones and erected several new subdivisions. They proposed the name Woodville Karst Plain (after the town of Woodville, located on the plain in southeastern Leon County) for the gently-sloping, relatively low plain extending from the edge of the Tallahassee Hills south to the Gulf of Mexico, and eastward from the edge of their topographically higher Apalachicola Coastal Lowlands zone into Jefferson County. They characterized the WKP area as "loose quartz sands thinly veneering a limestone substrata that has resulted in a sinkhole and dune topography." Later in 1966, Yon published a bulletin on the geology of Jefferson County and extended the WKP eastward to approximately the Aucilla River. These works established the basic geomorphic boundaries of the WKP, which defined the extent of the zone for most of the last 30 years. In subsequent studies, Lane (1986) illustrated the extent of the WKP in Leon and Wakulla Counties, and Rupert and Spencer (1988) provided a more detailed definition of the WKP in Wakulla County.

Scott (1998a in preparation) has extended the WKP southeastward from its original arbitrary boundar at the Aucilla River, through Taylor County, to the Steinhatchee River. This seems a logical step as karst terrain similar to that mapped by the original WKP authors occurs throughout the coastal Big Bend region.

SUBSURFACE STRUCTURE AND GEOLOGY OF THE WOODVILLE KARST PLAIN

The WKP straddles a transitional area between two major subsurface geologic structures (Figure 3). It is situated along the eastern edge of a broad depositional basin named the Apalachicola Embayment. This basin is filled with approximately 15,000 feet of Jurassic to Quaternary age sediments. Geologic units deepen and thicken to the west-southwest into the trough of the Apalachicola Embayment.

The WKP is also located on the western flank of a large, dome-like structure named the Ocala Platform. This features brings Middle Eocene rocks close to the surface over its crest in Levy County. Progressively younger units lap onto the structure from the west-southwest. The origin of this feature is somewhat uncertain. In early literature it was named the Ocala Uplift (Applin, 1951; Vernon, 1951), assuming that it was the result of structural movement. It was later given the name Ocala "Platform" (Scott, 1988), eliminating the structural connotation to the name. It may simply be a positive region that has undergone less compaction and downwarping than peripheral areas to the west-southwest. The Ocala Platform has had significant influence on the geology of the WKP. Figure 4 illustrates a cutaway view of the Florida Big Bend area, with the different geologic strata shaded for reference. The vertical scale is greatly exaggerated to illustrate the dip of the units. The Ocala Platform brings the oldest rock exposed in Florida, Middle Eocene Avon Park Formation, to the surface over its crest in northwestern Levy County. Younger Upper Eocene Ocala Limestone laps over the structure, forming the shallow bedrock in the central Big Bend region, which encompasses the southern WKP. Still younger Oligocene Suwannee Limestone laps onto the flanks of the structure from the southwest, forming the bedrock from western Jefferson through most of Taylor County before pinching out in southern Taylor County. Lower Miocene St. Marks Formation shallows from the west as it laps over Suwannee Limestone, forming the bedrock in the

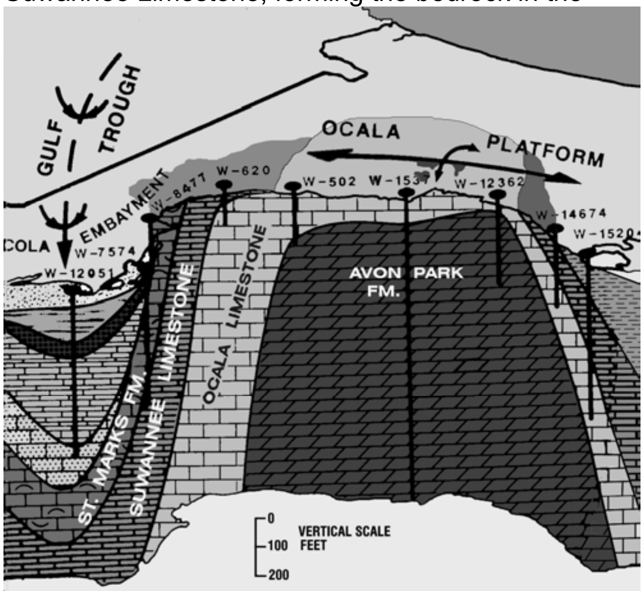

Figure 4. Block diagram of the Florida Big Bend region (from Rupert and Arthur, 1997).

southeastern Leon and Eastern Wakulla Counties. The Ocala Platform has thus helped shape the areal pattern of the shallow bedrock throughout the WKP.

Figure 5 shows the Big Bend portion of the geologic map of Florida (from Scott, 1998b, in

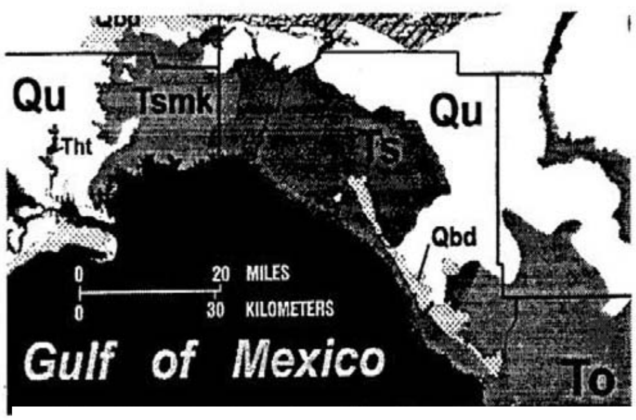

Figure 5. Geologic map of the eastern Florida panhandle (from Scott, 1998a).

preparation). The older-to-the-southeast pattern of shallow rock units imposed on the area by the Ocala Platform is evident. Referring to Figure 5, Miocene St. Marks Limestone (Tsmk) forms the bedrock at the western end of the WKP, the Oligocene Suwannee Limestone (Ts) extends through the central part, and the Eocene Ocala (To) comprises the southernmost portion of the plain. While most of the WKP is covered by variably-thick Quaternary quartz sand, areas covered by sands in excess of 20 feet thick (Qu, Qbd) are mapped in white.

The shallow structure and geomorphology of the WKP is readily observed in cross section. Figure 6 is a west-to-east section across northern Wakulla County. The local bedrock limestone of the St. Marks Formation gently rises from the west to a very shallow position in central and eastern Wakulla County. Here it is mantled by thin porous undifferentiated sands, relicts of the Pleistocene marine transgressions over the area. Surface drainage streams are uncommon; the only major streams in the western part of the WKP are the Wakulla and St. Marks Rivers, both spring-fed and flowing in channels incised in the underlying bedrock. Precipitation falling in this area percolates directly down to the rock. Over thousands of years this meteoric water has dissolved the limestone, forming numerous sinks, underground drainage conduits and other karst features. In the western part of Figure 6, immediately west of the WKP, a major contrast is seen. The land surface is higher, and is underline by thick clayey sands. Three additional geological units, the Pliocene Jackson Bluff and Intracoastal Formations and the Miocene Torreya Formation, pinch out from the west. The thick clayey overburden sediments have served to protect the underlying limestone from dissolution, thus land surface lowering due to dissolution has been reduced, karst features are fewer in number, and the area contains numerous swampy, standing-water bays. Streams following in western Wakulla County, such as Lost Creek, are captured by underground drainage as they flow onto the WKP.

Figure 7 is a section extending from Tallahassee, in Leon County, south to Apalachee Bay. Tallahassee is mostly located above the Cody Scarp, in the Tallahassee Hills geomorphic zone. Hills in this zone locally attain elevations of 200 or more feet above msl. The Tallahassee Hills have a core of Miocene Hawthorn Group sands, clays and carbonates. Capping the hills are the red clayey sands of the Plio-Pleistocene Miccosukee Formation, observable in roadcuts throughout northern Leon County. The Cody Scarp, a former shoreline of the Pleistocene Wicomico sea, forms an abrupt boundary between the Tallahassee Hills and the WKP. The scarp trends east-to-west across the eastern panhandle, passing through Tallahassee just south of the fairgrounds. Shallow St. Marks Formation limestone, overlain by variably-thick undifferentiated sands, forms the bedrock near the scarp and extends under the Tallahassee Hills. High and well-drained relict sand dunes at the northern edge of the WKP support a flora of pines, black-jack, and turkey oak trees. In contrast, wetter areas to the south are populated by cypress and bay trees (Hendry and Sproul, 1966). Harper (1914) described 30 tree species, seven species of woody vines, 30 shrubs, and 109 species of herbs growing within the WKP zone.

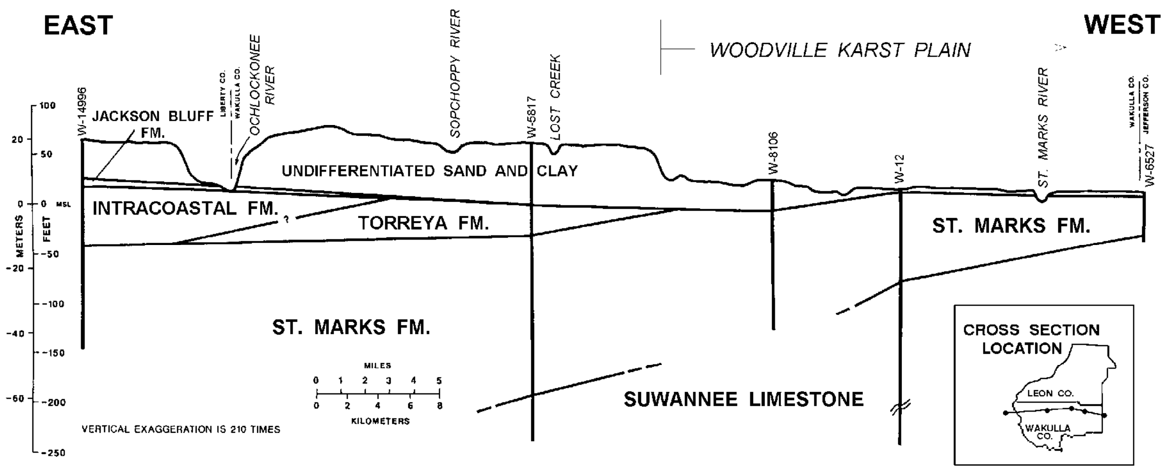

Figure 6. West-to-east geologic cross section in the Woodville Karst Plain (from Rupert and Spencer, 1988).

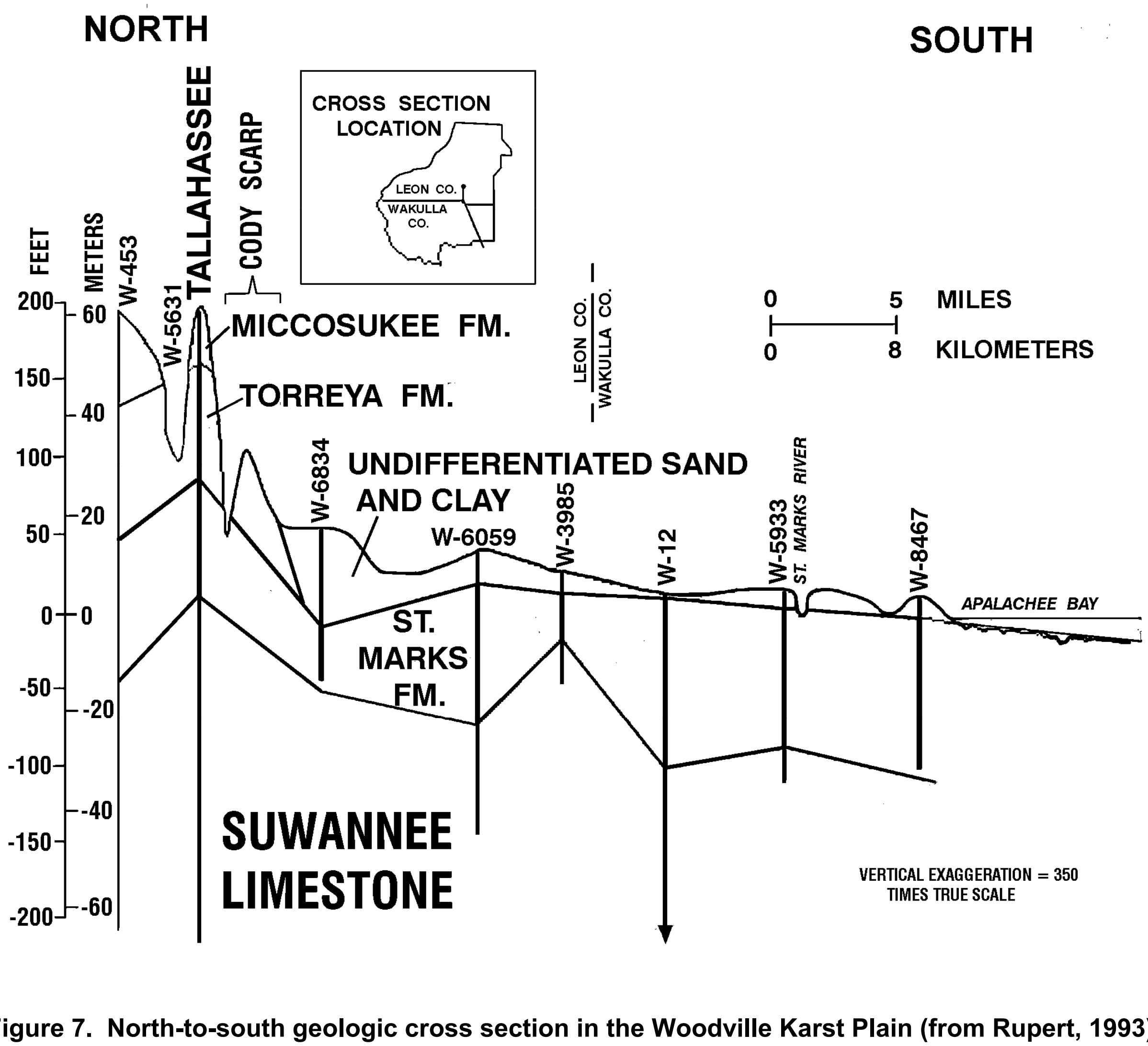

Figure 7. North-to-south geologic cross section in the Woodville Karst Plain (from Rupert, 1993).

At the southern edge of the WKP, the limestone bedrock extends offshore into the Gulf of Mexico and onto the broad Big Bend continental shelf. Boulders and pinnacles of Suwannee Limestone are common in the shallows off the central Big Bend coastline. Extensive salt marshes are developed along most of the coastal portion of the WKP, from Wakulla County eastward through Taylor County. Organic-rich muds and silts, resting on the shallow carbonate substrate, support a marsh flora of predominantly *Juncus* and *Spartina* grasses (Clewell, 1981). Formation of open coastal marshes is attributable to the zero-energy nature of the Big-Bend coast. Sand movement is minimal, and beaches are virtually absent due to a lack of wave activity (Price, 1953; Tanner, 1960).

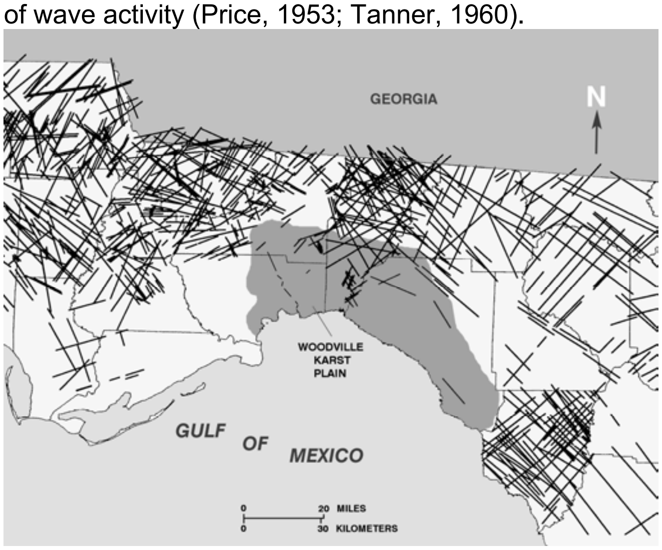

Figure 8. Lineaments in the eastern panhandle-northwestern peninsula area of Florida.

BEDROCK LITHOLOGY

The oldest rock forming near-surface bedrock in the WKP is the Upper Eocene (38 Mya [million years ago]) Ocala Limestone. The Ocala Limestone (Dall and Harris, 1892) is a calcarenitic marine limestone containing abundant microfossils, mollusks, bryozoans, corals, algal fragments, and rare vertebrate fossils. Guide fossils include the pelecypod *Amusium ocalanum*, and the benthic foraminifera *Lepidocyclina ocalana* and *Nummulites* spp. In its type area near Ocala, Marion County, Florida, it is a nearly pure calcium carbonate coquina of large benthic foraminifera and other fossil fragments, cemented with micrite. In the coastal regions of the WKP, it is commonly dolomitized and/or silicified to varying degrees as a result of interactions with groundwater and subaerial exposure. The Ocala Limestone is exposed along the Steinhatchee River and in sinks in the southern end of the WKP. It ranges in depth from surface exposure in southern Taylor County to over 400 feet bls (below land surface) in Wakulla County.

The Oligocene (33 to 30 Mya) Suwannee Limestone (Cooke and Mansfield, 1936) is a white to gray, pale orange, or brown recrystallized calcarenitic limestone, commonly comprised largely of small miliolid foraminifera tests, mollusks, and bryozoans. Guide fossils include the echinoid *Rhyncholampus gouldii* and the benthic foraminifera *Dictyoconus cookei*, *Rotalia mexicana* var. *mecatepecensis*, *Discorinopsis gunteri*, and *Coskinolina floridana*. It also is commonly dolomitized or silicified in the WKP. Chert from the Suwannee provided material for early indian tools and weapons. Many of the underground conduit systems in the WKP are developed in Suwannee Limestone. The Suwannee limestone varies in depth from surface exposure in coastal Taylor and Jefferson Counties to over 150 feet bls along the western edge of the WKP.

The youngest bedrock in the WKP is the Lower Miocene (25-20 Mya) St. Marks Formation (Puri and Vernon, 1964). The St. Marks Formation is a pale orange to light gray, to white, argillaceous, moderately indurated calcarenitic-to-massive limestone and dolostone with abundant casts and molds of mollusks (Mansfield, 1937) and the large benthic foraminifera *Sorites* sp. It commonly crops out along the major streams and sinks in western-most Jefferson County and eastern Wakulla County. The type location for the St. Marks Formation is in a sink named the Swirl, just southeast of Crawfordville in Wakulla County.

All three rock units are components of the Floridan aquifer system. The Floridan aquifer system is the primary freshwater source for the WKP area. Throughout most of the WKP the local water table is the top of the Floridan aquifer system. Recharge to the Floridan aquifer system occurs in areas in Georgia and northern Florida as well as locally by direct percolation of precipitation through the porous sands blanketing the carbonate bedrock. Surface runoff also enters the aquifer through the numerous sinks in the region.

A number of surface lineations, primarily in the form of aligned sinkholes, stream courses, and lake and Gulf coastal shorelines are evident on both aerial photographs and topographic maps of the Big Bend Region. Figure 8 is a compliation of lineaments mapped by various authors in county studies as well as additional FGS in-house FGS maps. The map reveals an abundance of linear patterns, thought to possibly reflect joints, fractures, or faults in the limestone bedrock. Two primary directions are prevalent: northwest-southeast and northeast-southwest, with others varying in bearing between these directions. The general directional bearings of the lineaments mirror the alignment of faults in the Mesozoic and older basement rocks of Florida, and may be related. However, research is lacking on this subject. If the lineaments represent fractures, which are commonly observed in dry caves, they would offer paths of least resistance to groundwater flow, and as a result facilitate karst dissolution along their trends. In addition to the obvious linear alignment of sinkholes in the region, many of the underground cave segments mapped by cave divers appear to correspond with these directional trends. Thus fractures may have significant impact on regional and local groundwater flow patterns within the WKP.

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HYDROGEOLOGY OF THE ST. MARKS RIVER BASIN

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ABSTRACT

Understanding the geologic framework of an area and the way that water moves through that framework is fundamental to understanding water quality and biological community health issues. In the St. Marks River Basin, four hydrostratigraphic units are present: the surficial aquifer system, the intermediate aquifer system, the Floridan aquifer system, and the sub-Floridan confining unit. Of the three aquifer systems, the Floridan aquifer is the major carrier of water. Water flow through the Floridan aquifer is ultimately driven by rainfall. Water enters the aquifer through limestone outcrops, sinkholes, lakes, and the thin, sandy soil of the Woodville Karst Plain. Water leaves the aquifer through natural discharges, including Wakulla Springs, and through water well withdrawals. There is a strong connection between surface water and ground water in the St. Marks River Basin.

INTRODUCTION

The St. Marks River Basin is located in the Big Bend Region of Florida (Figure 1). The St. Marks River is approximately 35 miles long and drains 1,161 square miles. Approximately ten percent of the basin area is in Georgia; the remainder is in Florida. Communities within the St. Marks River Basin include portions of Thomasville, Georgia, and Tallahassee, St. Marks, and Crawfordville in Florida.

In the St. Marks River Basin, there is a strong connection between surface water and ground water. An abundance of rainfall has shaped the landforms into river basins and ground water flow systems which carry this water from where it falls to the Gulf of Mexico and the Atlantic Ocean. The flow of water within this combined system is governed by the landforms, or geomorphology, and by the nature of the materials through which the water flows.

GEOMORPHOLOGY

The St. Marks River Basin traverses two regional geomorphic districts in parts of two states. The Florida Geological Survey is currently creating a new geomorphic map of Florida which will maintain continuity of geomorphic names across state borders. In the St. Marks River Basin, Dr. Tom Scott (oral communication) identifies two major geomorphic regions: the Tifton Upland District, which includes the Tifton Upland District of Georgia (Clark and Zisa, 1976) and the Northern Highlands of Florida (Puri and Vernon, 1964); and the Gulf Coastal Lowlands District (Puri and Vernon, 1964). The boundary between the two geomorphic regions is the Cody Scarp, a prominent and extensive east-west trending paleo wave-cut escarpment (Rupert and Spencer, 1988). Displaying up to 150 feet of elevation change in a miles distance (Lane and Rupert, 1996), the Cody Scarp separates a marine terrace below the scarp (the Gulf Coastal Lowlands) from the deltaic deposits of the Tifton Uplands above the Scarp. Figure 2 shows the geomorphic regions and sub-regions in the St. Marks River Basin.

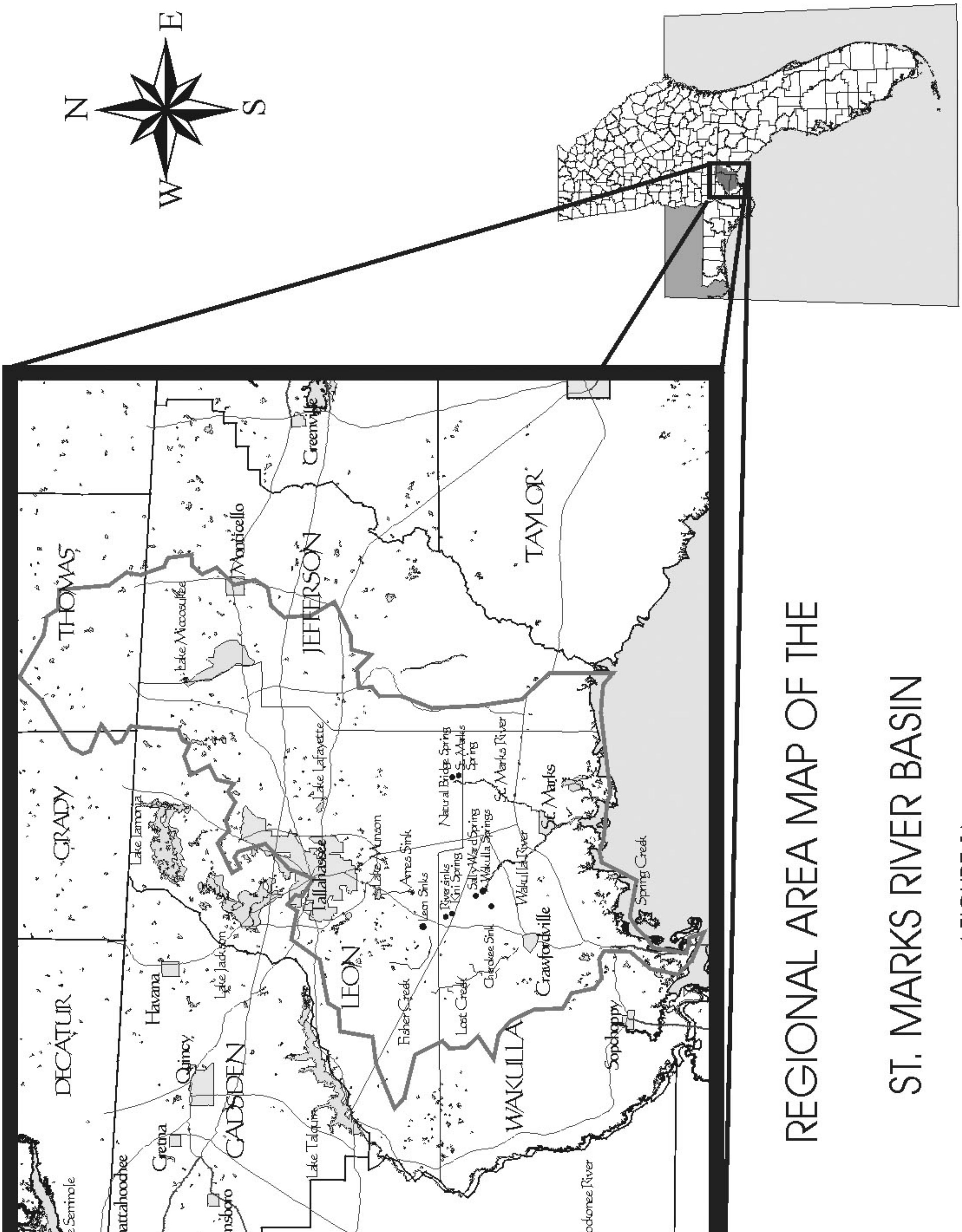
Tifton Upland District

In the St. Marks River Basin, the Tifton Upland District extends from approximately the Cody Scarp northward and comprises the whole northern section of the St. Marks River Basin. Only one geomorphic sub-zone is found in the Tifton Uplands of the St. Marks River Basin:

<u>The Tallahassee Hills</u> subzone consists of a series of topographic highlands extending northward from approximately the Cody Scarp into south Georgia, where it is known as the Red Hills (after Rupert, 1991). In the St. Marks River Basin, the tallest of the Tallahassee Hills is approximately 260 feet above mean sea level (msl). The area was once a deltaic plain and is composed of sands, silts, clays, and gravels eroded from the Appalachian Mountains and carried by rivers to the Gulf of Mexico (Hendry and Sproul, 1966). Erosion of this plain has left a series of gently rolling hills with relief of up to 120 feet.

Gulf Coastal Lowlands District

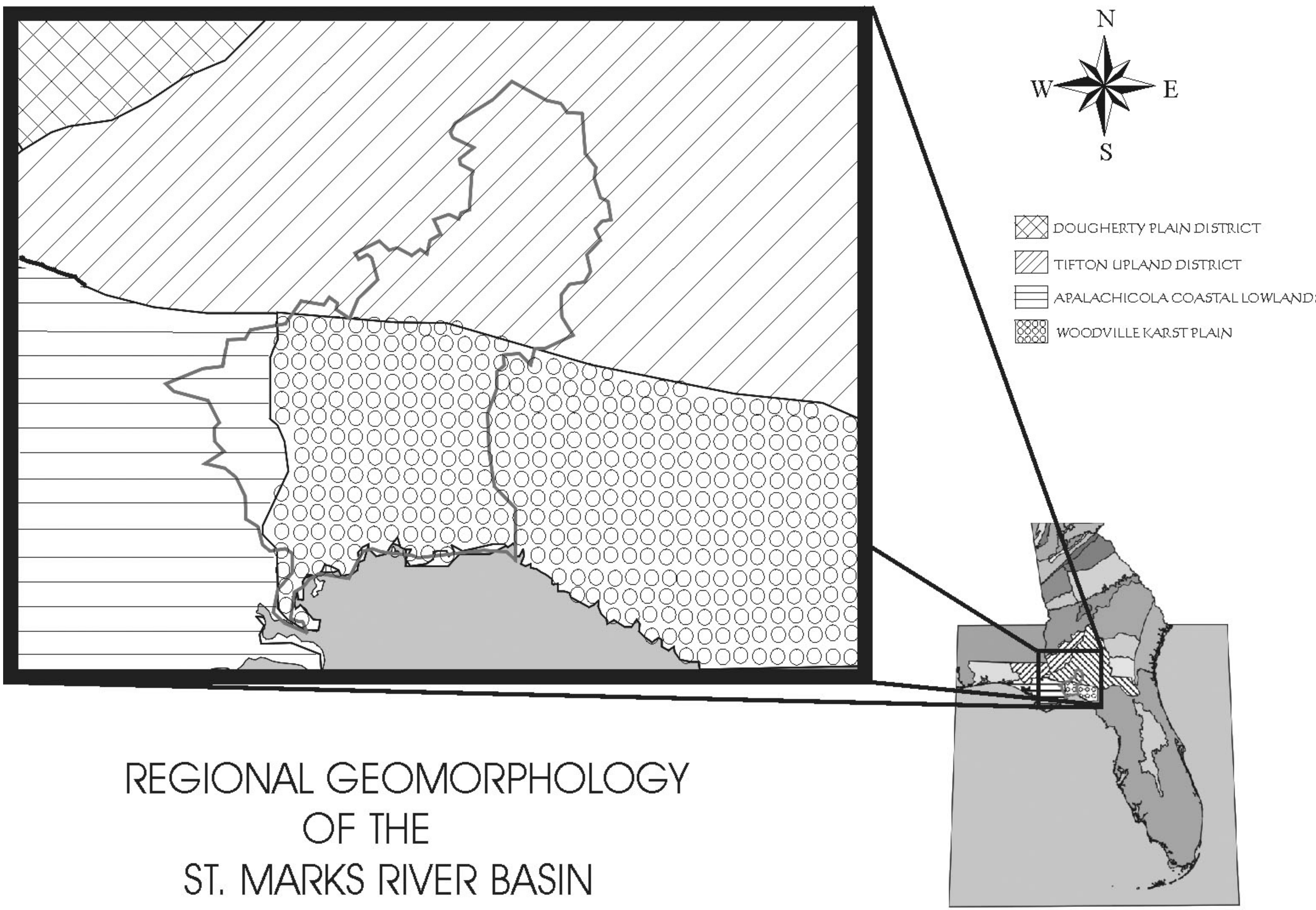
The Gulf Coastal Lowlands District, characterized by generally flat, sandy terrain, extends from the coast inland to the Cody Scarp. Elevation ranges from near sea level to approximately 100 feet above msl. In this area, the deltaic sediments which make up the Tallahassee Hills were removed by erosion during former high sea level stands. Geomorphic sub-zones include:



REGIONAL AREA MAP OF THE

ST. MARKS RIVER BASIN

(FIGURE 1)



REGIONAL GEOMORPHOLOGY
OF THE
ST. MARKS RIVER BASIN

(FIGURE 2)

The Appalachicola Coastal Lowlands are characterized by flat, sandy surfaces marked with shallow "bays" (densely-wooded, swamp-like areas) and poorly-defined creeks (Hendry and Sproul, 1966). The water table is generally close to the land surface and during the rainy season much of the area is swampy.

The Woodville Karst Plain is characterized by elevations of less than 35 feet msl, gentle slopes, and thin, sandy soils lying directly upon a limestone surface. Naturally acidic ground water has dissolved the limestone at or near the land surface into the many karst or solution features that distinguish this area. Sinkholes, springs, caves, and disappearing rivers are all present in the Woodville Karst Plain. In some areas, crests of relict sand dunes rise to 20 feet above the surrounding land. In the Woodville Karst Plain, rain which falls on the land surface tends to soak directly into the ground or to drain into shallow depressions in the land surface.

HYDROSTRATIGRAPHY

Three aquifer systems, or water bearing units, are present in the St. Marks River Basin: the surficial aquifer system, the intermediate aquifer system, and the Floridan aquifer system. These aquifer systems, and the rock formations in which they occur, are shown on Figure 3. The surficial aquifer system and intermediate system aquifers are present mainly in the Tallahassee Hills physiographic region. The Floridan aquifer system is present within the entire St. Marks River Basin. The sub-Floridan confining unit underlies the Floridan aquifer.

Surficial Aquifer System

The surficial aquifer system is predominantly found in the unconsolidated sands and gravels near the land surface in the Tallahassee Hills. Isolated surficial aquifer zones may also occur in the northern portions of the Gulf Coastal Lowlands. The surficial aquifer system is generally less than 50 feet thick and produces only limited amounts of water. Before the widespread use of modern drilling methods, the surficial aquifer was often tapped by hand-dug wells, and used for domestic and farm supply. Water within the surficial aquifer system occurs under unconfined or water-table conditions. Rainfall directly recharges the surficial aquifer system and the water table fluctuates according to the amount of rainfall.

Intermediate Aquifer System

The intermediate aquifer system exists as a group of interlayered clayey sediments, dolostones, and limestone formations, which retard the movement of water between the Floridan aquifer system below and the surficial aquifer system above. Discontinuous water-bearing zones occur within the coarser sediments and carbonate beds. In the Tallahassee Hills, the intermediate aquifer system ranges from about 50 feet to over 150 feet thick. Water reaches the intermediate aquifer system by leakage from the surficial aquifer system and from sinkhole-drained lakes. Water leaves the intermediate aquifer system through downward leakage to the Floridan aquifer system, through baseflow to streams, through ground water flow to sinkholes, and through limited use for domestic water supply.

Floridan Aquifer System

The major carrier of water in the St. Marks River Basin is the Floridan aquifer system, one of the world's most prolific aquifers. The Floridan aquifer system occurs in the thick sequence of carbonate rocks deposited on the Florida Platform and also in parts of Alabama, Georgia, and South Carolina during Paleocene through Middle Miocene time. The aquifer thickens from about 100 feet in south Georgia to over 2,000 feet in southern Wakulla County (Pratt, et al. 1996).

In the St. Marks River Basin, the Floridan aquifer system is comprised of a series of clean, porous, and permeable fossiliferous limestones and dolomites: the Chattahoochee or St. Marks Formations; the Suwannee Limestone; the Ocala Limestone Group; the undifferentiated Claiborne Group; and the hydraulically connected portion of the Wilcox Group (Pratt, et al. 1996). The base of the Floridan aquifer system, the sub-Floridan confining unit, is formed by low permeability sediments, which prevent the downward movement of water.

The Floridan aquifer system is generally an excellent transmitter of water, allowing huge amounts of water to flow through it. Transmissivities in the Floridan aquifer system in the St. Marks River Basin range from as low as 5,000 feet squared per day in a small area near the coast to over 125,000 feet squared per day in the highest zones (Pratt, et al. 1996). Sever (1966) indicates that similar high transmissivity values were found in tests at the Thomasville, Georgia municipal well field. Transmissivity, the capacity of an aquifer to transmit water, is a function of the total thickness of the aquifer and the permeability of the rocks which comprise it.

GROUNDWATER FLOW WITHIN THE ST. MARKS RIVER BASIN

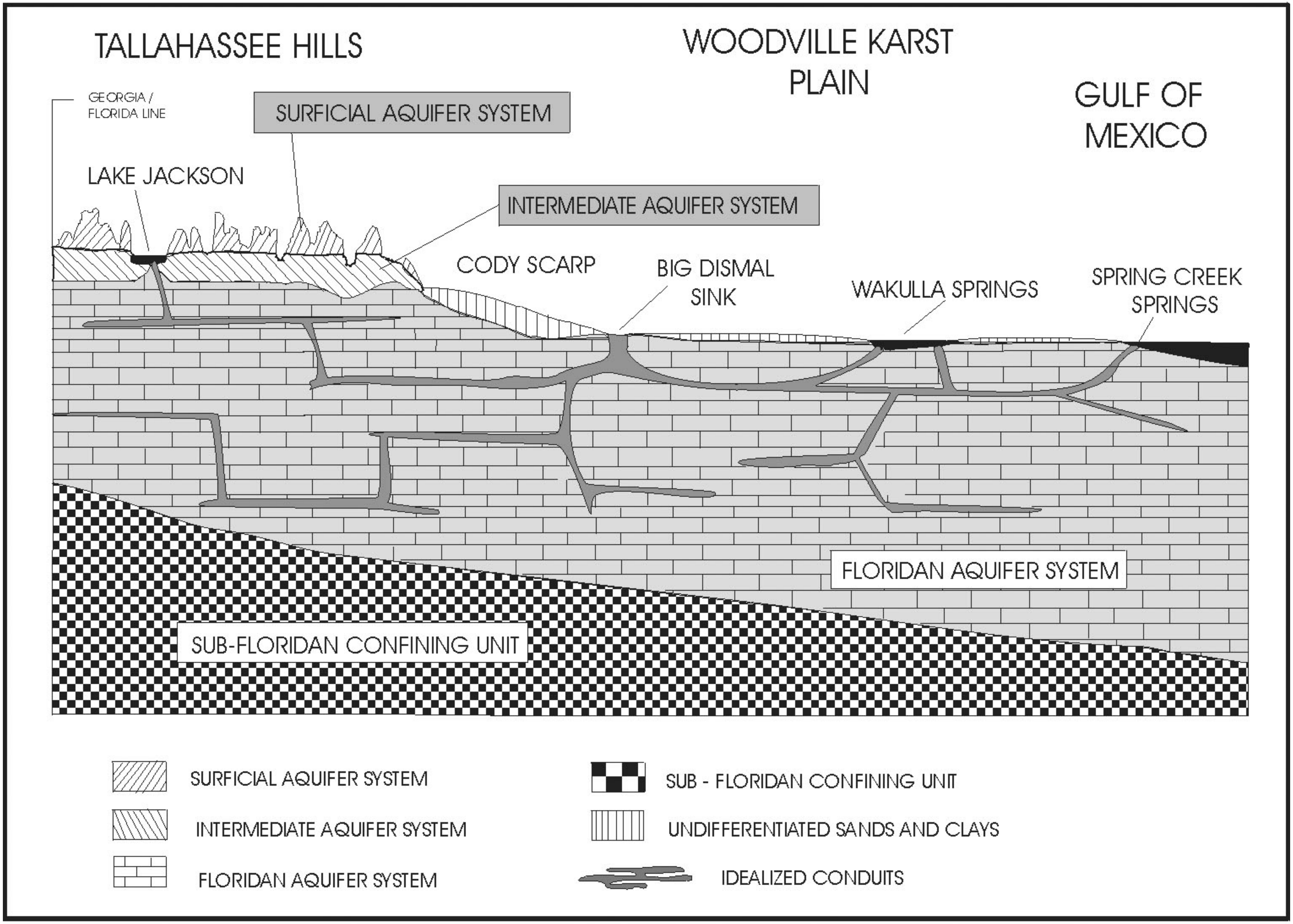
Water moves downward from the surficial aquifer system or the land surface where the Intermediate system is absent, thin, or as in Leon County, breached by sinkholes. This movement of naturally acidic rain and surface water has allowed the limestone within the Floridan aquifer system to dissolve, creating a very permeable, cavernous aquifer with rapid and dynamic movement of groundwater. Water within the Floridan aquifer system in the St. Marks River Basin generally flows from north to south.

NORTH - SOUTH STRATIGRAPHIC SECTION FOR THE ST. MARKS RIVER BASIN

				SOUTH GEORGIA BASIN AREA			PANHANDLE FLORIDA BASIN AREA		
	SYSTEM	SERIES	AGE MY	STRAGRAPHIC UNIT	LITHOLOGIC DESCRIPTION	HYDROSTRATI-GRAPHIC UNIT	STRAGRAPHIC UNIT	LITHOLOGIC DESCRIPTION	HYDRO STRATI-GRAPHIC UNIT
CENOZOIC ERATHEM	QUATERNARY	HOLOCENE	<10,000 YEARS	UNDIFFERENTIATED HOLOCENE/	Sediments comprised of undifferentiated quartz sands, clays, clayey sands, and gravels.	SURFICIAL AQUIFER SYSTEM	UNDIFFERENTIATED HOLOCENE /	Sediments comprised of undifferentiated quartz sands, clays, clayey sands, and gravels.	SURFICIAL AQUIFER SYSTEM
		PLEISTOCENE	2 MY	PLEISTOCENE Sediments	These are the surficial sediments found in several locations in the study area.		PLEISTOCENE Sediments	These are the surficial sediments found in several locations in the study area.	
	TERTIARY	PLIOCENE	5 MY	CITRONELLE FORMATION MICCOSUKEE FORMATION	Cross-bedded sands, gravels and clays deposited by streams and rivers Moderately sorted to poorly sorted coarse to fine-grained, varicolored, clayey, quartz sand; and kaolinitic, montmorillinitic sandy clays.		MICCOSUKEE FORMATION JACKSON BLUFF FORMATION	Moderately sorted to poorly sorted coarse to fine-grained, varicolored, clayey, quartz sand; and kaolinitic, montmorillinitic sandy clays. Poorly consolidated, clayey quartz sands and sandy shell beds	
		MIOCENE		HAWTHORN GROUP - TORREYA FORMATION	A silicaclastic unit consisting of fine to medium-grained, clayey sands to sandy, silty clays, containing varying amounts of limestone, dolomite and minor amounts of phosphate.	INTERMEDIATE AQUIFER SYSTEM	INTRACOASTAL FORMATION HAWTHORN GROUP - TORREYA FORMATION	Olive-gray, Sandy, highly micro-fossiliferous, poorly consolidated calcarenitic marine limestone. A silicaclastic unit consisting of fine to medium-grained, clayey sands to silty clays; minor amounts of phosphate, and quartz-sandy, clayey limestone.	INTERMEDIATE AQUIFER SYSTEM
			23.5 MY	CHATTAHOOCHEE FORMATION	Terriginous and shallow water sediments comprised of silts, clays, and dolomite.	FLORIDAN AQUIFER SYSTEM	ST. MARKS FORMATION	Pale to graysh-orange, fine to medium-grained, partly recrystallized silty to sandy limestones; dolomitized in differing amounts.	FLORIDAN AQUIFER SYSTEM
		OLIGOCENE	36 MY	SUWANNEE LIMESTONE	White to light-gray, coarse to fine grained well indurated fossiliferous marine limestone, containing nodules of clastic limestone, and chert.		SUWANNEE LIMESTONE	White to light-gray, coarse to fine grained well indurated fossiliferous marine limestone, containing some dolomite, with sand as a minor component.	
		EOCENE		OCALA LIMESTONE	Pinkish-white finely crystalline, oolitic, fossiliferous limestone, grading downward into an interlayered dark-brown recrystallized, dolomitic limestone.		Ocala Limestone	Light-brown, slightly glauconitic, fossiliferous limestone, grading downward into a saccharoidal fine crystalline dolomite.	
			56 MY	CLAIBORNE GROUP	Deltaic and marine clastics; cross bedded sandstones; calcareous, carbonaceous, and fossiliferous shales	SUB - FLORIDAN CONFINING UNIT	CLAIBORNE GROUP	Fossiferous limestones; and glauconitic, argillaceous limestones	SUB - FLORIDAN CONFINING UNIT
		PALEOCENE	65 MY	WILCOX GROUP	Coarse-grained sands with clay clasts, laminated clays, and massive micaceous, fine-grained sands		WILCOX GROUP	Pale orange argillaceous calciluitie containing dolomite gypsum, chert, and glauconite	
	CRETACEOUS AND OLDER			UNDIFFERENTIATED			UNDIFFERENTIATED		

(FIGURE 3)

HYDROGEOLOGY OF THE ST. MARKS RIVER BASIN



(FIGURE 4)

However, because of the well developed conduit system within the aquifer rocks, localized flow may be in any direction.

Inflows

To the north of the St. Marks River Basin, water enters the Floridan aquifer system where limestones of the aquifer are exposed at land surface in Georgia (Davis, et al., 1989). Recharge to the Floridan aquifer system occurs in the Tallahassee Hills physiographic region, through minor downward leakage from the intermediate system aquifers, or through sinkholes (Hendry and Sproul, 1966). Large lakes in this region have periodically drained because of loss of water through active sinkholes. The Woodville Karst Plain acts as another major recharge area for the Floridan aquifer system, where the aquifer receives rainfall through the overlying sands or from runoff or stream flow into sinkholes (Scott, et al., 1991).

Disappearing Streams

At least four streams in the St. Marks River Basin flow underground into sinkholes, including the St. Marks River at Natural Bridge, Fisher Creek, Munson Slough at Ames Sink and Lost Creek near Crawfordville. Fisher Creek, Lost Creek, and Munson Slough at Ames Sink all flow under ground through sinkholes and "disappear." The St. Marks River at Natural Bridge also goes underground, but re-emerges, augmented by additional Floridan aquifer system water, at St. Mark Springs.

Lakes

Many lakes are found within the study area, ranging in size from a few acres to hundreds of acres. Lakes in the St. Marks River Basin are either small and deep, created by sinkholes extending into the underlying rock, or they are large, elongated, and shallow. The large lakes are only found in the Tallahassee Hills and were formed by the dissolution of large areas of limestone, either along stream valleys or in the underlying rock in fractured areas (Hendry and Sproul, 1966). These large lakes naturally drain periodically, through a combination of low rainfall, high evaporation, and flow through sinkholes in the lake bottoms.

Lake Miccosukee is located along the Leon and Jefferson County line in the Tallahassee Hills province of the Tifton Upland District. A large sinkhole in the northwestern part of the lake formerly allowed water to drain from the lake, but the sinkhole is now surrounded by a dam to prevent this from occurring (Swanson, et al. 1988). Lake Lafayette, located in east central Leon County, is another of the shallow, sinkhole drained lakes of the Tallahassee Hills. Lake Munson is a shallow, 255-acre impounded lake on the south side of the City of Tallahassee (Ryan and Hemmert, 1997). Munson Slough flows into Lake Munson and from Lake Munson to Ames Sink, where it goes underground into the Floridan aquifer system.

Sinkholes

Sinkholes are closed depressions found on land surfaces underlain by limestone, formed either by the collapse of a cave roof or by solution as descending water enlarges a crack in limestone. If a sinkhole is deep enough, it intercepts the water table and fills with water, forming a pond or a lake. A sinkhole can also form in an aquifer conduit, creating a "karst window." The water continues to flow through the conduit, and is briefly exposed at the land surface through the sinkhole "window."

The St. Marks River Basin area contains numerous sinkholes of various surface areas and depths. Examination of aerial photos shows a linear pattern to the arrangement of many of these sinkholes, which may be due to fractures existing in the sub-surface limestone units. Many ongoing studies are attempting to show subsurface connections between these sinks by tracing the movement of ground water as it flows south toward the Gulf of Mexico. There are far too many sinkholes in the study area to name individually, but more prominent sinkhole areas or sinkholes include: The Leon Sinks State Geological Area (including Big Dismal Sink and many others), the Riversinks, Cherokee Sink, Bream Fountain in Crawfordville, and Ames Sink, which drains Lake Munson.

Outflows

Major discharges for the Floridan aquifer system in the St. Marks River Basin include springs and seeps within the St. Marks and Wakulla Rivers; Wakulla, Spring Creek, and other springs; and the submarine springs and underwater exposures of the limestones of the Floridan aquifer system in the Gulf of Mexico. Water is also withdrawn from wells in various amounts for various uses.

Springs

A spring is water that leaks from an aquifer, or water-bearing formation, through a natural hole in the ground. Springs are abundant in the St. Marks River Basin. According to Rosenau, et al. (1977) six of Florida's twenty-seven first magnitude springs, or springs with flows greater than 100 cubic feet per second, are located in the St. Marks River Basin. Nine other named springs and countless unnamed smaller springs and seeps are also found here. Table 1 shows the names, county location, and discharges of springs found in the St. Marks River Basin.

Table 1: Springs in the St. Marks River Basin

Name	County	Discharge (cfs)	Comments
Horn Springs	Leon	29	
Natural Bridge Spring*	Leon	106	see note 1
Rhodes Springs	Leon	14 to 22	4 small springs
St. Marks Spring*	Leon	519	avg. 1958-73
Indian Springs	Wakulla	0.11	
Newport Spring	Wakulla	8.24	
Kini Spring*	Wakulla	176	see note 1
Panacea Mineral Springs	Wakulla	0.11	several small springs
River Sink Spring*	Wakulla	165	see note 1
Spring Creek Springs*	Wakulla	2,000	see note 2
Wakulla Springs*	Wakulla	390	
Mc Bride Spring	Wakulla	**	
Sally Ward Spring	Wakulla	**	
Shepherd Spring	Wakulla	no data	

Source: Rosenau, et al., 1977
** First Magnitude Springs listed by Rosenau, et al., 1977*
*** Very minor flow generally combined with Wakulla Springs discharge*
Note 1: These springs have been reclassified (Wilson and Skiles, 1989) as karst windows. They are now considered to be aquifer conduits, temporarily exposed to the surface because of collapse of the conduit roof. Although the water is exposed at the land surface, it remains within its conduit and continues its flow through the aquifer.
Note 2: Flow at Spring Creek Springs has been measured twice: on 05/30/74 at 2,000 cfs and again on 11/01/91 at 307 cfs (Davis, 1996).

WATER USE IN THE ST. MARKS RIVER BASIN

Most of the water used in the St. Marks River Basin is derived from ground water, primarily from the Floridan aquifer system. Water use data from 1990, the most recent year available, is provided by US Environmental Protection Agency (1998). A total of 39.17 million gallon per day (mgd) of water was withdrawn for use in the St. Marks River Basin. A total of 97.7 percent , or 38.27 mgd, was supplied by ground water; the remaining 2.3 percent, or 0.90 mgd, is drawn from surface water sources.

The major water use in the St. Marks River Basin is for public water supply, comprising about 63 percent of total use. Irrigation and self supplied domestic use follow, making up 17.5 and 15 percent of the total use, respectively. Remaining uses (commercial, industrial, power generation and livestock) account for less than 5 percent of total use.

SUMMARY

Understanding the way that water moves through a natural system is essential to understanding how that system functions. Figure 4 provides a summary of the hydrogeology of the St. Marls River Basin. Important features include the following:

- In the St. Marks River Basin, there is a strong connection between surface water and groundwater. Springs contribute groundwater to surface water bodies; surface water streams flow underground to become groundwater.
- There are two distinct geomorphic districts in the St. Marks River Basin. The Tifton Uplands District is a deltaic plain with gently rolling hills of sands, silts, clays and gravels in various thicknesses covering the underlying limestone. In the Gulf Coastal Lowlands, these clastic materials have been removed by the erosive action of higher sea levels and the limestone is exposed at the land surface, or covered with a thin layer of sandy soil. The two regions are separated by the Cody Scarp, a wave cut escarpment, which displays an elevation change of up to 150 feet change in elevation in a mile's distance (Lane and Rupert, 1996).
- Four hydrostratigraphic units are present in the St. Marks River Basin: the surficial aquifer system, the intermediate aquifer system, the Floridan aquifer system, and the sub-Floridan confining unit. The surficial aquifer system is found primarily in the Tifton Uplands, the intermediate aquifer system occurs only in the Tifton Uplands, and the Floridan aquifer system and the sub-Floridan confining unit underlie the entire St. Marks River Basin.
- The Floridan aquifer is the main source of water supply in the area. It is a very productive aquifer of regional extent which supplies abundant water. It is the source of the large springs in the St. Marks River Basin.
- Water flows into the Floridan Aquifer through recharge areas in southern Georgia, through leakage from the surficial and intermediate aquifer systems, where present, through sinkholes, and through the thin, sandy soils of the Woodville Karst Plain.
- Water flows out of the Floridan aquifer system through discharge to springs and seeps, through water well withdrawals, and through offshore discharge to the Gulf of Mexico.

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REGIONAL HYDROLOGY OF THE UPPER FLORIDAN AQUIFER OF NORTH-CENTRAL FLORIDA AND SOUTHWESTERN GEORGIA

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ABSTRACT

Within north-central Florida and southwestern Georgia (referred to as the study area) the Upper Floridan aquifer includes all or parts of the Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone, St. Marks Formation, and Chattahoochee Formation. The altitude of the top of the Upper Floridan aquifer ranges from about 200 ft above sea level in the Dougherty Plain to greater than 400 ft below sea level in parts of the Apalachicola Delta District and Tifton Uplands. The altitude of the base of the aquifer ranges from 100 ft above sea level in the northern part of the study area to greater than 2,200 ft below sea level in the south. The aquifer thickens from about 100 ft in the north to greater than 2,000 ft in the southwest.

The ultimate source of recharge to the Upper Floridan aquifer is precipitation. Recharge rates are relatively high in the karst areas because the aquifer is exposed at land surface or covered only by a thin veneer of sediments. Precipitation falling in these areas can rapidly infiltrate through the overlying sediments or directly enter the aquifer through sinkholes and sumps. Outside the karst areas, the aquifer is overlain by low-permeability sediments. Recharge rates in these areas are less than in the karst areas because the low-permeability sediments cause a large proportion of precipitation to become overland runoff to streams.

In areas where the overlying low-permeability sediments confine the Upper Floridan aquifer, the rate of recharge (leakage downward) is dependent on: (1) the difference in head between the water table and the potentiometric surface of the Upper Floridan aquifer, and (2) the thickness and vertical hydraulic conductivity of the low-permeability sediments. In the Barwick Arch area (a subsurface feature located in extreme southern Georgia), the Upper Floridan aquifer is unconfined but overlain by low-permeability sediments. Here, the rate of leakage is not dependent on the head in the Upper Floridan aquifer so fluctuations in the Upper Floridan aquifer water levels do not effect the rate of recharge through the overlying sediments. The base of the Upper Floridan aquifer is formed by low-permeability marine sediments that are at least two orders of magnitude lower in hydraulic conductivity than sediments of the Upper Floridan aquifer.

The transmissivity of the Upper Floridan aquifer varies greatly, ranging from 1,300 ft^2/d to 1,300,000 ft^2/d. The highest transmissivity values generally occur within the karst areas of the Dougherty Plain, the Ocala Uplift, and the Tifton Uplands where the overlying low-permeability sediments are thinnest or absent. The lowest transmissivity values occur within the Apalachicola Embayment - Gulf Trough where the overlying low-permeability sediments are thickest.

Discharge of ground water from the Upper Floridan aquifer occurs as spring flow, seepage into rivers and the Gulf of Mexico, and withdrawals from wells. Rivers within the karst areas are hydraulically connected to the Upper Floridan aquifer, but rivers (or reaches of rivers) not in the karst areas are generally separated from the aquifer by low-permeability sediments. Major springs draining the Upper Floridan aquifer in the study area are the Spring Creek Spring group, Wakulla Spring, St. Marks Spring group, and the Wacissa Spring group. These four springs are among the eight largest springs in Florida. Discharges measured on November 1, 1991, were: Spring Creek Spring group (307 ft^3/s), Wakulla Spring (350 ft^3/s), St. Marks Spring group (602 ft^3/s), and Wacissa Spring group (319 ft^3/s). Some discharge also occurs in smaller springs along the coast and directly from the aquifer to the Gulf of Mexico.

A BURIED KARST PLAIN ON THE NORTHEASTERN GULF OF MEXICO SHELF, NW FLORIDA: ORIGIN AND RELATION TO ONSHORE KARST

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ABSTRACT

More than 800 km of high-resolution seismic surveys, vibracoring, and sea-floor sediment sampling have revealed the buried topography and geology of the offshore component of the Woodville Karst Plain on the NW Florida coast of the Gulf of Mexico. Detailed seismic interpretation and correlation with vibracores and boreholes have outlined the geographic distribution of the offshore karst plain, which covers approximately 3,000 km^2 of inner continental shelf, trending south-southeastward from the present day Ochlockonee River mouth. The submarine karst plain is distinguished by high freshwater seepage rates, extensive dissolution of the near-surface Tertiary limestones, isolated paleofluvial channels, sinkholes, and submarine springs. Based on the array of available information it can be postulated that a significant part of the karst plain has developed since 9,000 yr BP--a time when global climate was considerably wetter than during the present--and that at least some of the karst was developed in a submarine setting. The development and evolution of the karst plain both onshore and offshore was assured by a relatively stable tectonic setting, and was predominantly controlled by climate-induced fluctuations of the regional fluvial and groundwater systems of the coastal plain and shelf.

INTRODUCTION

General

The Florida carbonate platform has been subject to extensive karstification due to its relatively stable tectonic setting, large-scale limestone aquifer systems, high precipitation rates, and numerous rivers and springs. However, the majority of karst investigations both in Florida and elsewhere have been, and still are, conducted in terrestrial settings. Most karst features, such as sinkholes, are still believed to be the result of exclusively subaerial exposure (Esteban and Wilson, 1993). Paleokarst unconformities are widely considered as a sea-level indicator (e.g., Schlanger and Silva, 1986).

Not until recently has the importance of offshore karst processes and antecedent topography to coastal development been fully realized. Among others, Hine et al. (1988) documented the extremely irregular Paleogene bedrock on the inner continental shelf and broad coastline in an area of the northwest Florida coast. They postulated that the antecedent topography, a product of karstification and dissolution processes, not only controls coastal stratigraphic development, but also strongly influences the structure and preservation potential of coastal bioherms.

Further south, along the Florida Gulf peninsula coast, Evans et al. (1989) and Evans and Hine (1991) described the extensive isolated karst depressions and fracture-controlled elongated limestone troughs within the Charlotte Harbor lagoonal and estuarine system. They linked the karst effects imprinted upon the early- to middle Pleistocene seismic unconformities to the repeated sea-level fluctuations and coastal migrations that have recurred in southwest Florida throughout Quaternary time.

Using seismic and side-scan sonar imagery techniques, Land et al. (1995) provided a hydrogeologic mechanism for the formation of offshore sinkholes. They argued that sinkhole and other karst features may not reflect exclusively a subaerial exposure condition. Rather, they may be an indicator of the pattern and intensity of ground-water circulation beneath continental margins.

Faught and Donoghue (1997) described the discontinuous nature of the offshore karst drainage system on the northeastern Gulf of Mexico inner continental shelf off northwest Florida. They linked the karstification process to complex groundwater flow, which directly or indirectly discharges through the seafloor of the continental shelf and outer margin at places where coastal aquifers crop out on the sea floor. Interestingly, these outcrops, identified as offshore karst depressions and paleofluvial features, are often the ideal spot for conducting underwater geoarchaeological research, and hunting for Paleoindian and Early to Middle Archaic artifacts.

Hypotheses

In this study, the following hypotheses were tested. The first is that the terrestrial Woodville Karst Plain has an offshore equivalent. Its existence is not obvious, due to burial beneath Quaternary sediments, but shallow seismic profiling can be used to delineate its extent. A second hypothesis involves the general belief that the karst plain was a product of the long-term Quaternary sea-level and coastal environmental change (Lane, 1986). However, the observations made in this study imply another possibility: the onset of the major part of the karst may not have occurred until approximately 10,000-9,000 yr BP, when global climate finally entered a pluvial post-glacial stage (Jacobson et al., 1987), with precipitation in the southeastern U.S. reaching levels 30% greater than during the present day (Kutzbach, 1987; Kutzbach et al., 1998). A final hypothesis involves the prevalent belief in traditional karst investigations that, because the meteoric water of continental interiors is the primary agent of dissolution (e.g., Palmer, 1990), *subaerial exposure* is considered to be necessary for karst development (Esteban and Wilson, 1993). Based on the evidence from this study and others' observations, it is reasonable to hypothesize that karst features and especially the aligned sinkholes and depressions in the offshore submarine environment may be related to subaqueous karst processes. In this view karst development is carried out mainly by groundwater seepage through the shelf seafloor along structural or tectonic zones of high permeability, such as regional joint systems, aided by the migration of coastal fluvial systems along the shoreline, and by the advance and retreat of coastal fluvial systems back and forth across the shelf.

Study Area

As part of an interdisciplinary cooperative program between Florida State University and the Florida Geological Survey, we examined the distribution, stratigraphy and topography of the subsurface karst features on the upper continental shelf of the northwest Florida coast of the Gulf of Mexico. Included in the investigation were seismic profiles, vibracores and sediment sampling. The purpose of this investigation was to document the stratigraphic expression of the shallow karst structure, to examine the role that karst development has played in the hydrogeologic evolution of this portion of the continental shelf, and to determine what these features can reveal about sedimentary processes and paleoclimatologic and paleohydrogeologic changes that have occurred within the region. Figure 1 shows the study area and the grid of seismic lines generated in this study. An additional goal of the work was to provide a framework for re-evaluating the role that the karst-influenced offshore groundwater flow has played in water balance and budget calculations for nutrients and dissolved constituents -- such as ^{222}Rn and CH_4, to the Gulf of Mexico and the world ocean.

Background Geology

Rupert (this volume) describes in detail the background geology of the study area. Rupert and Spencer (1988) and Rupert (1993) detailed the geomorphology, stratigraphy, and hydrogeology of the Woodville Karst Plain. They documented a number of karst features, such as karst springs, sinks, dissolution depressions, natural bridges, and subaqueous conduits. They described the complex regional hydrogeologic processes that participate in the regional karst drainage system. The Woodville Karst Plain--whose offshore extension is the subject of this study--has an area of approximately 1,000 km^2 (Lane, 1986). However, when combined with its offshore counterpart, its total area exceeds 4,000 km^2.

Rate of Freshwater Seepage Through the Shelf Seafloor

Groundwater is believed to be an important source of nutrients and other dissolved constituents to the coastal marine and continental shelf environments, particularly when the concentrations of these dissolved components are elevated in groundwater relative to seawater (Johnannes,1980). Furthermore, changes in quality (e.g., the nutrient and pollutant load) and quantity of groundwater transport may have a significant influence on coastal water ecology and human activity (Snyder et al., 1995). For instance, the groundwater seepage through nearshore sediments into Great South Bay, New York, is estimated to be as much as 15-20% of the total freshwater discharge to the Bay (Bokuniewicz, 1980). Moore (1996) found a similar result for the coastline of the Atlantic Bight: groundwater seepage through the seafloor was equivalent to approximately 40% of freshwater riverine input.

Similar to the Snyder et al. (1995) study on the nutrient-rich margins of the North Carolina continental shelf, Young et al. (1995) and Cable et al. (1996) attempted to quantify the coastal groundwater seepage on the NW Florida Gulf coast. Young and colleagues utilized the trace gas ^{222}Rn to construct a conservative, advection/diffusion model, cross-checked by the qualitative groundwater tracer, methane (CH_4). The ^{222}Rn sources in this system include benthic sediment-water exchange, water column production of ^{226}Ra, and groundwater seepage. The sinks include radon decay and atmospheric exchange. Cable et al. (1996) measured the concentrations of the trace gases (^{222}Rn and CH_4) and thus calculated freshwater discharge rates to coastal waters. By comparing with average sea water ^{222}Rn concentration in the offshore area (less than 10 dpm m^{-2} d^{-1} (disintegrations per minute per square meter per day)), and locating and quantifying sources of freshwater seepage, they discovered that, compared with the diffusion rate through the seafloor (178 $\pm$ 56 dpm m^{-2} d^{-1}), other sources, such as direct injection via submarine spring flow (5,200$\pm$1,800 dpm m^{-2} d^{-1}) play a more significant role in groundwater discharge to the coastal ocean. Their data confirmed a long-held belief that dissolution of carbonate bedrock in the coastal zone, shelf, and even continental margin (e.g., Land et al., 1995), may create direct groundwater conduits for supporting offshore freshwater seepage and spring flow.

Using similar techniques, Cable et al. (1997) determined the magnitude and variations of groundwater seepage along the NW Florida shoreline. They found that groundwater seepage through sediments into the ocean in the study area occurs at a flow rate up to 4.4 m^3 sec^{-1}. They further determined that the main control on temporal variations of groundwater flow in the region is precipitation, not tidal height nor barometric pressure, because recharge is governed largely by precipitation levels and the size of the recharge area. Employing Cable et al's (1997) mid-range measured seepage rate, Faught and Donoghue (1997) calculated that the inner shelf seafloor of Florida discharges freshwater at a rate of more than 64,000 cfs (or 1,812 m^3 sec^{-1}), nearly equal to the combined flow of Florida's 20 largest rivers.

Rate of Carbonate Platform Surface Degradation

The lowering of the land surface on a regional scale is thought to be inherent in the formation of karst terrain. Regional land surface lowering is the cumulative effects of local karst processes. Since Sellards' (1909) attempt, many investigations have sought to calculate the lowering rate or the "surficial degradation rate". The rate calculated varies widely, ranging from 2 to 10 cm/1,000 yr in Florida, depending on carbonate rock properties and hydrogeologic processes (Lane, 1986). In his study of the structural geology and hydrologic features on the Woodville Karst Plain and adjacent areas, Fennell (1969) reported surface-lowering rates of 1.3 cm/1,000 yr (in Rainbow Springs), 2.1 cm/1,000 yr (in Itchetuknee Springs) and 3.5 cm/1,000 yr (in Silver Springs). However, another study of the same three sites showed somewhat larger surface-lowering rates of 2.0, 3.1 and 5.3 cm/1,000 yr respectively (Lane, 1986). Other reported estimates of surface-lowering rates by karst processes in Florida include 3.0-5.2 cm/1,000 yr in the Suwannee river drainage basin (Brooks, 1967), and 17.8 cm/1,000 yr in Tampa (Sinclair, 1982)

Based on the occurrence of marine fossils of Pleistocene age in the high (42-49 m) terrace deposits of the northern Florida peninsula, Opdyke et al. (1984) postulated a lowering rate of approximately 1 m in 38,000 yr, or 2.6 cm/1,000 yr. They calculated an isostatic uplift rate of 1 m per 41,000 yr, or 2.4 cm/1,000 yr, due to compensation at depth for the removed mass of carbonate rock. They argued that the northern Florida peninsula was at or near sea level during the deposition of Miocene and Pliocene sediments, and that karst development began during the late Miocene and fluctuated during the Pleistocene as global glaciation intensified. The elevated marine terraces that contain Pleistocene marine fossils were attributed to compensating isostatic uplift of the carbonate platform by approximately 40 meters in response to karstification and the resultant dissolution of the carbonate bedrock.

Recent studies (Wilson et al., 1987; Wilson and Beck, 1992; Wilson and Shock, 1996, among others) have indicated that previous estimates of the intensity and frequency of karst activities in Florida are probably conservative. This would imply that karst processes exert a much stronger influence on the Florida platform's hydrology and geology -- both onshore and offshore. Thus the inner continental shelf -- the drowned lower portions of the coastal plain -- has been heavily influenced by karst processes during Quaternary time.

METHODS

Approximately 800 km of high-resolution seismic survey lines were collected in a multi-year survey on the inner shelf of northwest Florida, from East Bay eastward to a longitude of 83°55' (Figure 1). Seismic data were acquired primarily with a Geopulse 3.5 KHz high-resolution sub-bottom profiling system. Some lines were also profiled using a Uniboom system. A velocity of 1500 m/s, calibrated by correlation with borehole records (Schnable and Goodell, 1968; Schmidt, 1984; Donoghue, 1992), was used to convert acoustic travel time to sediment depth. The seismic data were analyzed using the methods of Vail et al. (1977) and Donoghue (1992).

Taking advantage of long and continuous seismic track lines enabled identification of prominent reflectors by continuously tracking similar seismic patterns throughout most of the profiles. Navigational fixes were obtained approximately every five minutes, and at all course changes. Navigation utilized a GPS system or, in estuaries, fixed reference points such as channel. Subbottom lithologic control of the seismic data was established using borehole records and vibracores from Schnable(1966), Donoghue (1992), and Chen et al. (1996; 1998). Cores were logged and described using standard methods (Chen, unpub. data; Ladner et al., 1995, 1996, and 1997).

RESULTS

A typical subbottom seismic profile of the near-surface offshore karst plain is shown in Figure 2. All of the seismic profiles from the offshore extension of the karst plain show a first-order, distinctive, and very irregular reflector ranging in depth from 20 to 50 milliseconds (two-way travel time), or at approximate depths of 15 to 38 m below MSL. Deepening westward, this seismic reflector represents the fundamental building baseline of sedimentary successions, namely, the surface of the offshore extension of the Woodville Karst Plain. We interpret it as a regional unconformity, the top of the St. Marks Limestone of early Miocene age.

Immediately above this reflector, the seismic expression of overlying sedimentary units is usually characterized by a weakly reflective to reflection-free pattern in the western part of the study area, indicating subaerial exposure and erosion, and a rapid and homogeneous infilling (Evans et al., 1994). In the central area, however, the seismic expression of the overlying units is dominated by wavy-parallel to subparallel patterns (Figure 2), which reflects generally a gradual sedimentation process, accompanied by sedimentary deformation during the dissolution of the underlying St. Marks Formation of early Miocene age.

In the western portions of the study area, west of Turkey Point (approximately 84^{o}30'), an additional seismic reflector is often observed, approximately 0.5-3 m above the strong and irregular reflector disscussed above. We interpret this seismic unit as being the early Neogene -- but post-St. Marks -- sedimentary units that are observed in boreholes in the western part of the study area (Scott, 1992; Rupert and Spencer, 1988). Toward the east, this unit pinches out or becomes too thin to be detectable as a discrete seismic unit.

The paleokarst -- as well as ongoing karstification -- can be readily observed (e.g., Figure 2). The features have a vertical relief averaging 6-9 m, and a width ranging from 50 to 250 m. They are densely distributed throughout the far-western subsurface St. Marks Formation.

Figure 2 shows the active karstification in the western portion of the study area, characterized by an irregular upper surface and densely developed sinkholes of 10-50 m in diameter and 3 m in average depth. These sinkholes can be described as "buried dissolution sinkholes" using Wilson and Shock's (1996) classification. They form a highly irregular pattern in the seismic profiles, and are widely distributed throughout the region. Many other morphologies of sinkholes can be found in the offshore sub-bottom carbonate units as well, such as the "karst depression", elongate "karst trough", and collapse structure in offshore subbottom seismic records.

Figure 3 shows an isolated paleofluvial channel or a paleokarst trough (here presented in multiple traverses of the same buried feature -- labeled F-3 in Figure 1), in which dissolution of the carbonate bedrock and subsequent subsidence and perhaps collapse of the infilling sediments can be observed. This feature is comparable in morphology and scale to what Wilson and Shock (1996) have observed in subsurface radar images onshore at Champney Sinkhole, Orange County, Florida.

Although karst processes act on both the St. Marks Formation and the overlying younger units, the St. Marks Formation has undergone more severe karstification. Besides the greater age of the St. Marks, this has occurred because the St. Marks has a lithology more conducive to karstification. The unit is composed of moderately indurated moldic calcilutite and dolomite. The overlying units are composed primarily of poorly indurated sandy/clayey calcilutite or clayey quartz sand (Rupert and Spencer, 1988). This explains in part why karst features are not readily observed in the upper seismic unit. In this study, therefore, the designation "offshore Woodville Karst Plain" refers predominantly to the karstified inner-shelf components of the St. Marks Formation.

Figure 4 shows the distribution of the major geomorphologic divisions of the offshore Woodville Karst Plain. These include: 1) the western region of intensive karst, where the St. Marks Formation not only lies deeply beneath the Intracoastal Formation and recent sediments (Table 1), but also has been karstified; 2) the central transitional region where the St. Marks Formation is overlain by the thinning Intracoastal Formation and/or the Quaternary sediments; 3) the eastern karst region where the offshore karst plain is best developed, contiguous to the traditional onshore Woodville Karst Plain; 4) the outcrop region where the St. Marks Formation is exposed in many places on the seafloor, and where the karst process is primarily influenced by the magnitude and variation of local groundwater seepage.

DISCUSSION

Resting upon the stable foundation of the Paleogene Florida Platform throughout the study area (Figure 1), the St. Marks Limestone has served as a basis for the development and evolution of the late Cenozoic geology -- and especially the Quaternary stratigraphy and sedimentology -- of the northeastern Gulf shelf (Rupert and Spencer, 1988; Donoghue, 1993). With its karst-enhancing lithology and petrology, along with changes in regional tectonics, the St. Marks Limestone has passed through various stages of deformation and alteration. Among the most striking changes to affect this sedimentary unit have been dissolution and karstification.

Age of the Offshore Karst Plain

Although the process of karstification may have occurred as early as Early Neogene, shortly after the formation of the St. Marks Limestone, the notable karst features of the present day may have had a much later origin, perhaps as late as Wisconsinian time. This would be the case if we accept the assumption that the dominant, strong, and irregular seismic reflector in most of the study area (e.g., Figures 2 and 3) is the upper surface of the St. Marks Formation, which has experienced multiple episodes of subaerial erosion since early Miocene time.

During the approximately 15 million years since the St. Marks formed, it could have experienced various events of dissolution and karstification. However, due to weathering, the surficial karst features of earlier times may not be evident today. It is possible, in fact, that any pre-Wisconsinan karst may not have survived recognizably through the lengthy periods of subaerial weathering during the Quaternary.

There is support for the hypothesis that, beginning in the Late Paleogene, the Mississippi River significantly diminished its sedimentological influence on this part of the Gulf Basin (Bouma et al., 1978; Perlmutter, 1985). The Paleo-Apalachicola River system (Figure 1) gradually became the major player in refabricating and constructing the geological environments of the northeastern Gulf coast during the intervening time (Donoghue, 1993).

During the Wisconsinian sea-level low stand, the Apalachicola River and the smaller coastal rivers of the NE Gulf of Mexico region incised a dense network of paleofluvial channels on the present-day continental shelf (Donoghue, 1993; Faught and Donoghue, 1997). As a result, a complex hydrologic system was established, incorporating the paleochannel network and paleokarst features. Along with the dramatic change of coastal landscapes, the freshwater hydraulic head might have dropped by as much as 80-100 meters in response to sea level change (Anderson and Thomas, 1991). A new episode of karstification would have begun to act upon the St. Marks Limestone, superimposed upon older Late Neogene erosion surfaces.

In the western region of the study area (see Figure 4), both the St. Marks and the Intracoastal Formations can be traced in the seismic records. However, the lower reflector (top of St. Marks) is more "irregular", distinctive, and broadly traceable throughout the rest of the study area. The Intracoastal/Torreya Formations are not present in the eastern half of the study area, with the result that the St. Marks Formation is the uppermost carbonate unit in that region. It is noteworthy that the topographic relief of the St. Marks Formation in the western region (see Figure 4) is much greater than that in the other regions (Figures 2-4). In the western region, the relief of the buried karst features is generally 10 m or greater; in the rest of the regions, the relief is approximately 3 m or less.

The St. Marks Limestone surface in the western region exhibits a different style of karstification than that in the east. In the west, no dissolution features are observed that cut through the overlying Intracoastal Formation and reach the St. Marks surface. The karstic rim on the limestone surface possesses approximately the same thickness--there are no V-shaped dissolution features or sinkholes observed on the topographic lows or the paleofluvial valleys on the St. Marks surface.

This evidence implies that, although there may be multiple generations of karstification imprinted on the St. Marks Formation, it appears that the youngest and most distinct karst features on the St. Marks surface were developed during relatively recent geological time via a major hydrogeologic event. This event not only modified the older St. Marks surface, but also imprinted its new evidence of karstification onto the St. Marks surface. That surface appears in high relief in the west region of the study area, but gradually becomes more subdued in the rest of the regions, where the St. Marks surface has been exposed to multiple Quaternary episodes of subaerial erosion (Figures 2 and 3).

Regional Paleoclimatic Background

Based on a convergence of glacial lake data (Hu et al., 1997), paleofluvial information (Leigh and Feeney, 1995), GCM modeling (Kutzbach, 1987; Kutzbach et al., 1998), pollen analyses (Watts, 1969, 1971, and 1975; Grimm, et al., 1993), granulometric data (Tanner, 1992; Chen et al., 1998), and paleo-environmental index studies (Chen et al., 1996; Chen et al., 1998), a wetter than present-day climate (10-30% greater precipitation) has widely been inferred for parts of the Holocene for the southeastern United States. This wetter climate occurred worldwide beginning in the early Holocene (9,000-8,500 yr BP), extending to approximately 5,500 yr BP (Leigh and Feeney, 1995). This event corresponds to a major change in the seasonal solar-radiation cycle, which took place 9,000-6,000 yr BP (Kutzbach, 1987), and to the possible final step in Wisconsinan deglaciation at 8,000-6,000 yr BP (Jacobson et al., 1987).

As a result, the onset of much of the karstification of the Woodville Karst Plain and its offshore counterpart may have occured approximately 9,000 yr BP. The pluvial conditions may have enhanced the process of karst development and the consequent lowering of the surface. The karst-induced surface lowering rate for the coastal plain during that time could easily have exceeded 2.6 cm / 1,000 yr--an average rate Opdyke et al. (1984) calculated for the northern Florida peninsula during the past 1.5 Ma. The rate might even have reached as high as 17.8 cm/1,000 yr--a surface lowering rate Sinclair (1982) calculated for the present-day karst-rich Tampa area.

After the pluvial period, a dryer and perhaps warmer climate followed (Baker et al., 1992; Webb et al., 1993; Yu et al., 1997). The dry climate was initiated earlier in the north and later in the south. For instance, it began between 8,000-5,000 yr BP in Minnesota (Webb et al., 1983; Web et al., 1993), and 5,500-3,000 yr BP in southern Ontario, eastern Iowa and southern Wisconsin (Yu et al., 1997; Winkler et al., 1986; Baker et al.,1992). In the southeast, a few dry swings occurred 6,000 - 1,500 yr BP, with a final shift to dryer climate beginning at approximately 1,500 yr BP (Watts, 1971). During the dryer periods, karst development might be expected to have slowed down and surface subsidence rates would have been significantly reduced.

The offshore karst features, as revealed in the subsurface seismic data, provide some insight into the paleoclimatic changes that have dominated the topography of the region. Figure 3 shows the multiple subsidence and collapse structures of infilling sediments in a feature that appears to be a paleofluvial-paleokarst trough or sinkhole. The subsidence/collapse unit is highly recognizable by its distinctive seismic reflection pattern. In detailed examination of the unit, a number of sub-layers can be recognized, indicating that the paleochannel or karst trough may have gone through a number of dissolution and subsidence stages.

A possible scenario to explain the karst features observed in the eastern karst region of the study area is as follows: starting with the onset of wet conditions in the southeast approximately 9,000 yr BP, karstification accelerated on the exposed St. Marks surface. Most of the karst development could have occurred during the subsequent few millenia; thereafter, with the continuing post-glacial sea-level rise and inundation of the karst field, infilling and collapse commenced.

Other studies in the same offshore region have revealed similar features of subsidence and collapse. Donoghue et al. (1995) described Ray Hole Spring, a sub-bottom paleosinkhole spring in the southeastern corner of the study area (see Figure 1). According to Donoghue et al. (1995, and unpubl. data), Ray Hole is characterized by two asymmetric, irregularly-shaped dissolution crevices. Each is approximately 10 m deep below the modern seafloor and with a total diameter of approximately 50 m. Both of the dissolution features narrow downward, and are filled with a sedimentary sequence from brackish (?) shell-rich sediments to marine sands, implying a relatively rapid filling of the karst features.

Faught and Donoghue (1997) described the J&J Hunt paleosinkhole on the eastern border of the study area. A string of filled or partly filled dissolution features ranging 50 to 100 m in diameter, including the Fitch Site and the J&J Hunt paleosink system, defines the paleo-Aucilla River fluvial channel in an intensely karstified zone of the NE Gulf of Mexico. These paleokarst features are located offshore from the modern Aucilla River mouth in the NE portion of Figure 1.

Implications of Dynamic Offshore Groundwater Seepage

Relatively acidic freshwater dissolution has long proven to be the most significant agent in karstification (Brooks, 1967). As described above, fresh and acidic groundwater seepage through the floor of the inner shelf accounts for a significant amount (ranging from 10 to 36%) of coastal water budgets (Brock et al. 1982; Lane, 1986; Shaw et al., 1990; Lee and Hollyday, 1993; Cable et al., 1996; Cable et al., 1997).

The seismic expression of the upper contact of the St. Marks Formation is commonly characterized by an impressive irregular reflector. The strong seismic reflector reveals a ragged surface that is characterized by densely distributed buried sinkholes. Similar sub-bottom karst features can be observed immediately offshore from the modern Carrabelle River, a small coastal river adjacent to the Apalachicola River system (Figure 1). Similar extensive karst features can also be observed in several other submarine environments. An example is the central transitional region (Figure 4), in which the Ochlockonee, St. Marks, Aucilla and Econfina Rivers converge, and a number of karst structures, such as paleochannels, submarine sinkholes, and offshore freshwater springs are present (Figure 1) (Donoghue et al., 1995; Faught and Donoghue, 1997).

It is quite clear that, despite the distance (several to several tens of kilometers) between the present-day shoreline and these offshore sites of heavy karst development (Figure 1), the sub-bottom karst development at these sites appears very similar in terms of their density and karst topography (Figures 2 and 3). This implies that the St. Marks Formation at these sites has experienced a similar degree of dissolution through most of late Wisconsinian and Holocene time.

It can be observed that in the western deep-karst region of the study area (Area I in Figure 4), the St. Marks Limestone surface is buried to a greater depth, and shows evidence of more robust weathering. However, among these deeply incised, subaerial erosional paleochannel deposits, no funnel-shaped dissolution sinkholes nor infilled collapse structures were found. This implies that in the far west area, the groundwater seepage and dissolution front may move primarily in a lateral fashion, along the heavily weathered paleoerosional surface. Alternatively, the dissolution front may follow a joint system or paleofluvial network, rather than vertically percolating through the clayey/sandy layered sediment overlying the St. Marks Limestone surface.

The explanation for this phenomenon may lie in the fact that the St. Marks Limestone surface in this study area dips westward at a slope of approximately 1:1,000 (Hendry and Sproul, 1966; Cable et al., 1997), which is steeper than that of the modern continental shelf, and, arguably should exert a greater hydraulic head. This perhaps was especially effective during sea-level lowstands. Recent studies (Cable et al., 1996; Cable et al., 1997) have clearly demonstrated that the groundwater seepage rates at an offshore submarine spring (Lanark Spring, approximately 10 km west of Turkey Point on Figure 1) is significantly greater than that of the surrounding seafloor (60 vs. 20 mL m^{-2} min^{-1}).

The environmental significance of this effect is that the localized salinity at the offshore spring drops by as much as 2 ^{o}/oo (from 32 to 30 ^{o}/oo), and the nutrients and other dissolved constituents, such as CH_4 and Rn^{222}, are elevated by several orders of magnitude relative to the surrounding seawater (1,500 vs. 0.0 nM for CH_4; and 100 vs. 0.0 dpm L^{-1} for ^{222}Rn). The fresher and more nutrient-rich water at these sites can enhance not only the chemical dissolution of the seafloor carbonate bed, but also the biochemical weathering process.

Fluvial Migration, Groundwater Seepage, and Geomorphological Development

Dissolution and karstification have played a significant role in re-fabricating the enormous (350,000 km^2), flooded, broad, flat carbonate platform (Hine et al., 1988), re-shaping the antecedent topography, and controlling the distribution of subsequent sedimentation in the northeastern Gulf of Mexico coast. It is reasonable to hypothesize that at the initial stage, the fluvial systems and groundwater transport systems of NW Florida were developed along structural or tectonic zones of preferential dissolution, such as regional joint systems. The structural zone would subsequently undergo mechanical, chemical and biological weathering, forming topographic lows, where not only the fluvial system transports and removes sediments, but also where geochemical processes begin the development of karst. Faught (1996), Faught and Donoghue (1997) and Chen et al. (1998) have reported this type of phenomenon in the paleo-Aucilla river in the southeastern portion of this study.

We relate the isolated sinkholes and especially the aligned sinkholes/ depressions in the offshore submarine environment to subaqueous karst developments, which are carried out mainly by either groundwater seepage in zones of weakness or dynamic intrusion of a fluvial system. It is interesting to note the case of the modern Carrabelle River, a small distributary stream in the Ochlockonee River watershed. The river mouth has migrated in recent times from west to east. The result appears to be a consequent shift of karst development from west to east. Similar features are observed along the modern Ochlockonee River, where the river mouth has undergone several stages of migration from west to east.

This and other evidence implies that rapid development of karstification not only has etched the upper contact of the St. Marks into a high relief (Figure 3), but also has set the architectural framework for the subsequent topography in the northeastern Gulf coast and shelf. Hine et al. (1988), in an investigation immediately east of the study area, reported the intense karstification of what they called "marsh archipelago" (in their Figure 5) which appears almost to be a modern analog of the buried karst topography observed in the western region of the present study area. They define "marsh archipelago" as an area that is dominated by numerous marsh islands, and has an elevated, irregular, rocky surface, flanked by adjacent broad "shelf embayments" or topographic lows. They postulated that a subaerial stage plays a significant role in the development of these karst features.

It can be inferred, however, that a *subaerial* stage is not absolutely necessary for the development of such features because there is no fundamental difference between the "marsh archipelagoes" and the topographic lows in terms of spring/seepage density and local groundwater discharge systems over spatial scales of 100's of meters, as in the study by Hine et al. (1988). Instead, based on the present study, it can be inferred that the migration of coastal fluvial systems along the shoreline, the advance and retreat of coastal fluvial systems back and forth on the shelf, and the seepage of groundwater through the shelf floor, can create an architecture similar to a "marsh archipelago" and associated topographic lows on the NE Gulf shelf.

Investigations of the lower continental slope offshore New Jersey (Robb, 1982) and of the Straits of Florida (Jordan, 1954, 1964; Malloy and Hurley, 1970; Land et al., 1995) have also demonstrated that karst processes are not restricted to subaerial conditions, and can take place over a broad range of water depth—hundreds and even thousands of meters below the sea level (Land et al., 1995)

Possible Mechanisms for Development of the Karst Plain

Postulating an explanation for the occurrence of the high elevation (42-49 m above MSL) marine beach ridges of Pleistocene age near the border of northern Florida and southern Georgia, Opdyke et al. (1984) proposed an epeirogenic uplift mechanism to explain the occurrence of the raised terraces, the karst development of the Florida Platform, and the evolution of the Florida Platform from Late Neogene to Holocene time. Noting that the sedimentary wedges and any resulting isostatic changes are present mainly on the fringe of the Florida platform, and that there is little tectonic influence and no significant fault displacement, they concluded that the robust surficial or near-surficial karst processes have removed mass at a minimum rate of 1.2 x 106 m^3 / yr. They calculated that this mass loss may have resulted in lowering of the karst surface by approximately 2.6 cm/1,000 yr and a compensating epeirogenic uplift of the north Florida Platform by approximately 2.4 cm/1,000 yr. Their speculation pointed out a largely unpursued line of research in this field, and quantified in a simple format the magnitude of post-Miocene karstification in Florida.

However, the epeirogenic uplift mechanism contrasts with other regional geophysical observations, with the result that alternative mechanisms need to be considered. For example, Meade (1971) contoured crustal movement rates for the eastern United States, and categorized the region of the northern Florida peninsula between Pensacola and Fernandina west to east, and between Savannah, Georgia, and Cedar Keys north to south, as primarily a stable region (vertical crustal movement rate of approximately 0 mm/yr). Using precise releveling and mareography data, Holdahl and Morrison (1974) likewise found that the northern Florida peninsula principally lies in a stable or slightly subsiding zone at a vertical elevation change rate of -2 to 0 mm/yr.

These geophysical observations may be a reflection of the long-term tectonic history of this region. The closing of the Suwannee Straits in the Mid-Cenozoic (Chen, 1965; Schmidt, 1984; Scott, 1992) would have led to thickening of the lithosphere due to infilling of sediments, and to cooling of the underlying aesthenosphere (McKenzie, 1978; Royden et al., 1980). As a consequence, this part of the Florida Platform would undergo long-term subsidence.

These observations indicate that an epeirogenic uplifting mechanism may not be the sole candidate for explaining the origin of the elevated terraces of NE Florida. Other processes may also participate in the development and evolution of both the onshore and offshore karst plains. As mentioned above, post-Miocene tectonic movement in this region has been primarily in a stable or a subsidence mode due to the thickening of the lithosphere and cooling of the underlying asthenosphere. This region of the Gulf coast is marked by a low energy level and sediment starvation, removing the likelihood of isostatic change due to sediment loading (Tanner, 1960; Hine et al., 1988; Donoghue and Tanner, 1992). Evidence for reactivation of pre-Pleistocene faults is lacking (Opdyke et al., 1984; Nunn, 1985). The influence of glacial ice and meltwater on the Florida Platform is relatively insignificant in comparison with more northern regions, because the ice-induced hydro-isostasy is generally considered to be proportional to the proximity of deep water (Bloom, 1967). The wide, shallow shelf of the northern Gulf of Mexico therefore makes this factor less important.

As a consequence, we postulate that the coastal and offshore groundwater system and the coastal river systems in this area (Figure 1) have been the primary agents controlling the development and evolution of both the onshore and offshore Woodville Karst Plain. In particular the potentially high rate of groundwater flux to the shelf--via springs and seepage--may have played a major role in development of the regional karst. This would be especially true during wet periods, such as the mid-Holocene, when seepage rates might be expected to have been even greater than at present.

SUMMARY

One can observe the relentless processes of dissolution and karstification over a broad geographical range of both onshore and offshore environments in the northeastern Gulf coast of northwest Florida. By tracing the seismic sequence boundary of the top of the St. Marks Formation, the areal extent of the offshore Woodville Karst Plain--more than 3,000 km^2 -- can be delineated on the inner Gulf of Mexico shelf.

Based on the array of available information it can be postulated that the onset of a significant part of the Woodville Karst Plain may have occurred approximately 9,000 yr BP, a time when global climate was considerably wetter than today. The development and evolution of the karst plain both onshore and offshore were assured by a relatively stable tectonic setting, and predominantly controlled by the temporal-spatial variations of the fluvial system on the coastal plain and shelf. The geographic distribution and volumetric quantity of the groundwater seepage to this part of Gulf probably have been significantly underestimated previously, because prior to this study there was no systematic documentation of the geomorphology, sub-bottom stratigraphy, and spatial variation of the sub-bottom karst in this offshore region. Based on the sub-bottom features, submarine environments, and geographic extent of the offshore karst features, four geomorphologic regions of the offshore karst plain have been established.

It appears that the older subaerial erosion surface--the upper contact of the St. Marks Formation--may have served as a surface conduit for groundwater seepage. This may be especially true in the western region of the study area where the St. Marks Limestone surface is characterized by high relief (10 m and greater). Paleofluvial systems often co-exist with the present-day springs or sinkholes or karst troughs both onshore and offshore, implying a similar controlling influence on the development of such features. The development of the Woodville Karst Plain -- both onshore and offshore -- appears to have been closely associated with regional structural geology, sea-level fluctuation, climatic change, and the magnitude and variations of groundwater seepage.

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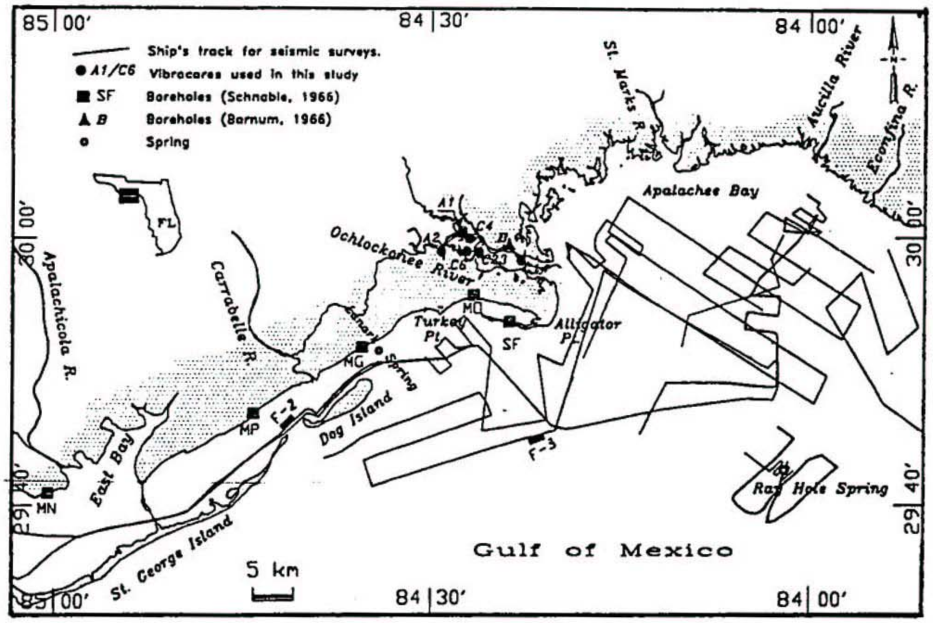

Figure 1. Study area in NE Gulf of Mexico off northwest Florida. Inset map shows location in NW Florida. Offshore grid of high-resolution seismic lines is shown. The solid bars on the seismic survey lines labeled "F-" denote the location of the subbottom profiles shown in the corresponding figures.

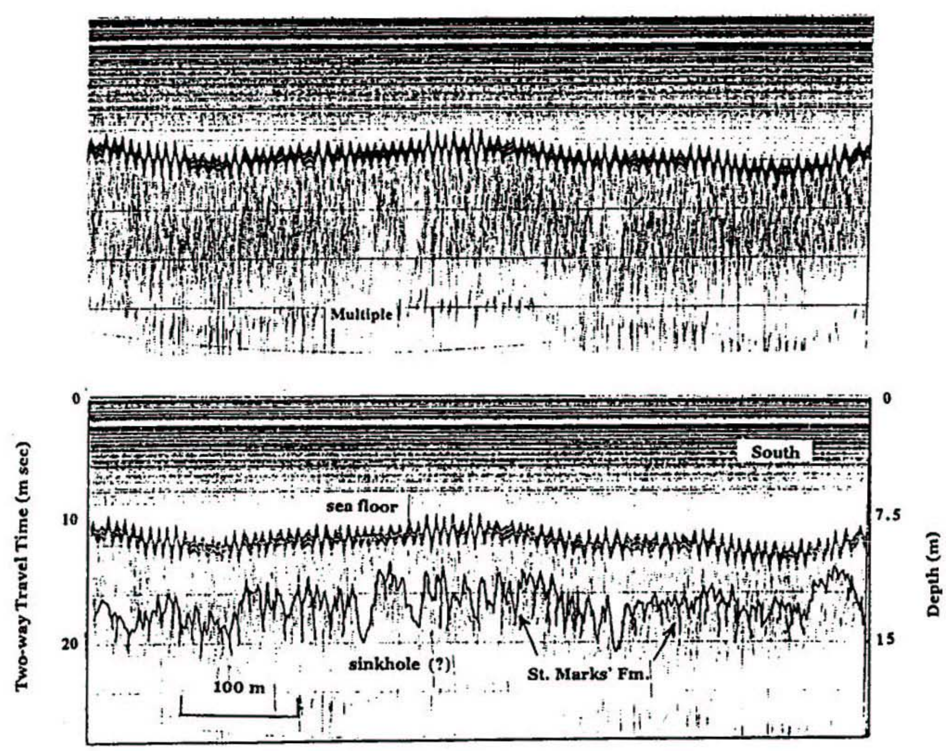

Figure 2. Seismic profile of karst features in the central transitional region of the study area. Relief on the upper surface of the St. Marks Formation is 3-5 m. See Figure 1 for location of the profile.

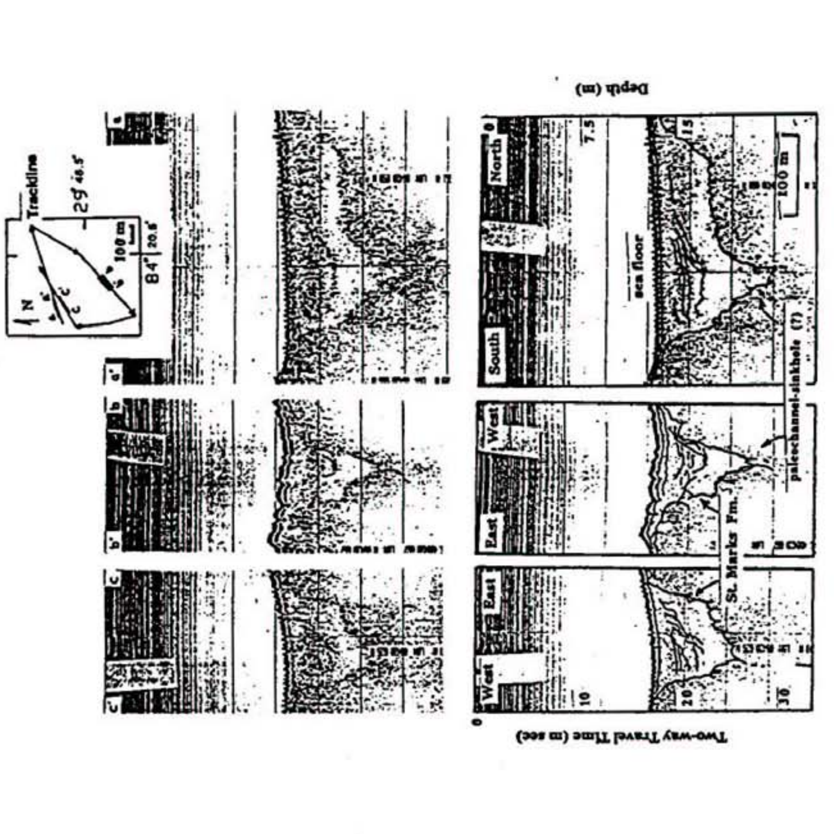

Figure 3. Sub-bottom seismic profiles south of Alligator Point (see Figure 1). The figure shows three crossings of the same isolated karst trough or paleochannel, separated by approximately 50 m and 300 m, respectively. The track lines of these crossings are shown in the map on top of the figure. Note the direction indicators on this figure (see Figure 1 for location). The three images indicate that the feature has been influenced by karstification. Evidence of subsidence can be observed in the disturbed sediment that has filled the feature.

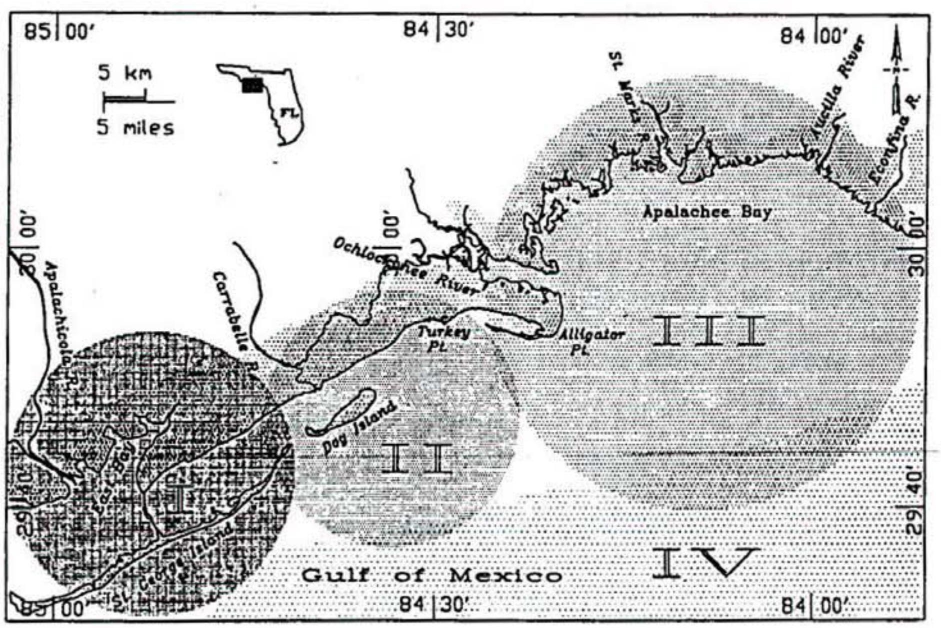

Figure 4. Extent of the four major geomorphologic divisions of the offshore extension of the Woodville Karst Plain. I. Western intensive karst region. II. Central transitional region. III. Eastern karst region. IV. Outcrop region. See text for explanation.

ST. MARKS RIVER BASIN:
WATER RESOURCE VULNERABILITY

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ABSTRACT

Three maps were developed using Geographic Information Systems (GIS), to evaluate water resource vulnerability in the St. Marks River Basin.

Surface water vulnerability - This map was created by combining four different factors: distance weighted vicinity to major wetlands and water bodies, soil runoff characteristics, soil composition, and slope. The most vulnerable areas of the St. Marks River Basin are: the areas above the Cody Scarp, where most water flow is in streams and wetlands on the land surface, and in the coastal regions immediately adjacent to Apalachee Bay. Individual sinkholes and ponds are areas of vulnerability, as are the courses of the St. Marks and Wakulla Rivers. The area with the lowest vulnerability to surface water problems is a large area in the center of the basin. This marks the area of karst development in the Woodville Karst Plain where there is no surface water flow. Rainfall directly infiltrates into the groundwater.

Ground water vulnerability - This map was created by combining two factors: soil runoff characteristics and underlying geology. Areas with differing degrees of vulnerability coincide fairly well with the geomorphic provinces of the region. The area where ground water is most vulnerable is the Woodville Karst Plain, followed by the Gulf Coastal Lowlands. The least vulnerable area is above the Cody Scarp, in the Tallahassee Hills.

Combined surface water and ground water vulnerability - This map was created by combining the surface water and groundwater vulnerability maps. The areas with the highest vulnerability are at the coast, along the surface water drainage systems, and at the lakes and sinkholes scattered throughout the basin. The Woodville Karst Plain is highly vulnerable to groundwater contamination. A large area of the Tallahassee Hills, including the Lake Lafayette Drainage Basin, is the next most vulnerable. The Gulf Coastal Lowlands, roughly the western one third of the basin, is the least vulnerable area.

The maps are standardized on a scale from 0 to 10 to indicate relative water resource vulnerability. Darker colors indicate areas with a higher vulnerability. It should not be construed that areas with higher vulnerability should never be developed. Special design criteria must be developed for these areas to insure that impacts are minimized. Similarly, areas with lower vulnerability should not be construed to be suitable for all types of development. The maps suggest that with prudent use, impacts to ground water and surface water should be minimal.

In the St. Marks River Basin, only the movement of water is constant. Where and how the water moves and what it carries with it changes with the form and nature of the land, soils, and rock. When surface water and ground water vulnerabilities are placed on a map, the wise and unwise use of water resources can be identified.

DETERMINATION OF GROUNDWATER FLOW PATTERNS FROM CAVE EXPLORATION IN THE WOODVILLE KARST PLAIN, FLORIDA

Christopher Werner, Woodville Karst Plain Project

ABSTRACT

The Woodville Karst Plain (WKP), located in the panhandle of Northern Florida, is characterized by a layer of unconsolidated sediments 3-20 m thick, predominantly sands, with shell and clay, overlying an extensive sequence of carbonate deposits, 150-600 m thick. The surface of this area is distinguished by the presence of numerous sinkholes, karst windows, sinking streams, and large springs. There are over 42 km of surveyed underwater cave passages present in several large systems within the WKP. These include Indian Spring, Sally Ward Spring, Wakulla Springs, Shepherd Spring and the Leon Sinks Cave System. Several physical controls are observed to operate, with varying degree, in cave passage development, including lithology, stratigraphy, regional and local groundwater flow patterns, and water table elevation directly influenced by sea-level fluctuations. These parameters are considered in the context of cave-system development presently charted in the WKP. Regional groundwater flow extends from southern Georgia through the WKP and south to the Gulf of Mexico. The orientations of cave passages within the WKP suggest a nearly parallel alignment with regional flow. Current drainage patterns primarily transport groundwater south through these conduits toward the Gulf. However, notable exceptions to this trend occur within Wakulla Spring cave and Indian Spring cave. Geomorphic features, cave passage orientation, current branchwork drainage patterns and flow directions suggest paleoflow directions during conduit formation in the above mentioned caves were most likely in contrast to present day observations.

INTRODUCTION

The exploration and survey of underwater cave systems south of Tallahassee by the Woodville Karst Plain Project (WKPP) has significantly improved the ability of hydrologists to understand the complexity of groundwater flow in a multiple-porosity medium such as the carbonates of the WKP. The improvement in understanding has been hampered in the past by the lack of qualified scientists to visit the remote and hostile environment of deep underwater caves. There is no substitute for detailed observations in improving the quality and quantity of information needed to advance scientific understanding within this multifaceted system of fluid flow.

While the recent observations are an important glimpse into the groundwater flow regime, it should be noted that they represent a significantly limited data set. The small size of the data set and its relation to the regional groundwater flow pattern may be restricted, but this does not mean that it is insignificant. Reasonable assumptions may be made, such that a greater overall understanding of the evolution of this complex groundwater drainage basin may emerge. This paper is an endeavor to add accurate and thorough scientific observations to the current body of knowledge. By using reasonable assumptions in conjunction with detailed observations, it is expected that significant conclusions may be drawn which aid in the understanding of this unique resource.

REGIONAL GEOLOGY AND HYDROLOGY

The WKP developed in Leon, Wakulla, and Jefferson Counties, Florida, is characterized by a thin veneer of unconsolidated and undifferentiated Pleistocene quartz sand and shell beds, overlying a thick sequence of relatively horizontal carbonates (Hendry and Sproul, 1966). The WKP is a gently sloping topographic region of low sand dunes and exposed carbonates rising northward from the Gulf of Mexico to approximately 20 m in elevation within Leon County, terminating at the Cody Scarp. The loosely consolidated Pleistocene sands, being very porous and permeable, allow rapid infiltration of precipitation. Important to our study, the St. Marks and Suwannee limestones, underlying the unconsolidated sands, comprise hydrostratigraphic units of the Upper Floridan aquifer system (FAS). These limestones, being very porous, permeable and soluble, have undergone considerable dissolution from groundwater movement (Hendry and Sproul, 1966). Consequently, the topography is karstic in nature, with numerous sinkholes, karst windows, sinking streams, and large springs (Rupert & Spencer, 1988).

The St. Marks is a predominately fine to medium-fine grained, partially recrystallized, silty to sandy limestone that has undergone degrees of secondary dolomitization (Hendry and Sproul, 1966). It also contains extensive shallow conduits in portions of the Leon Sinks cave system, Chips Hole cave and Indian Springs cave. It pinches out against the

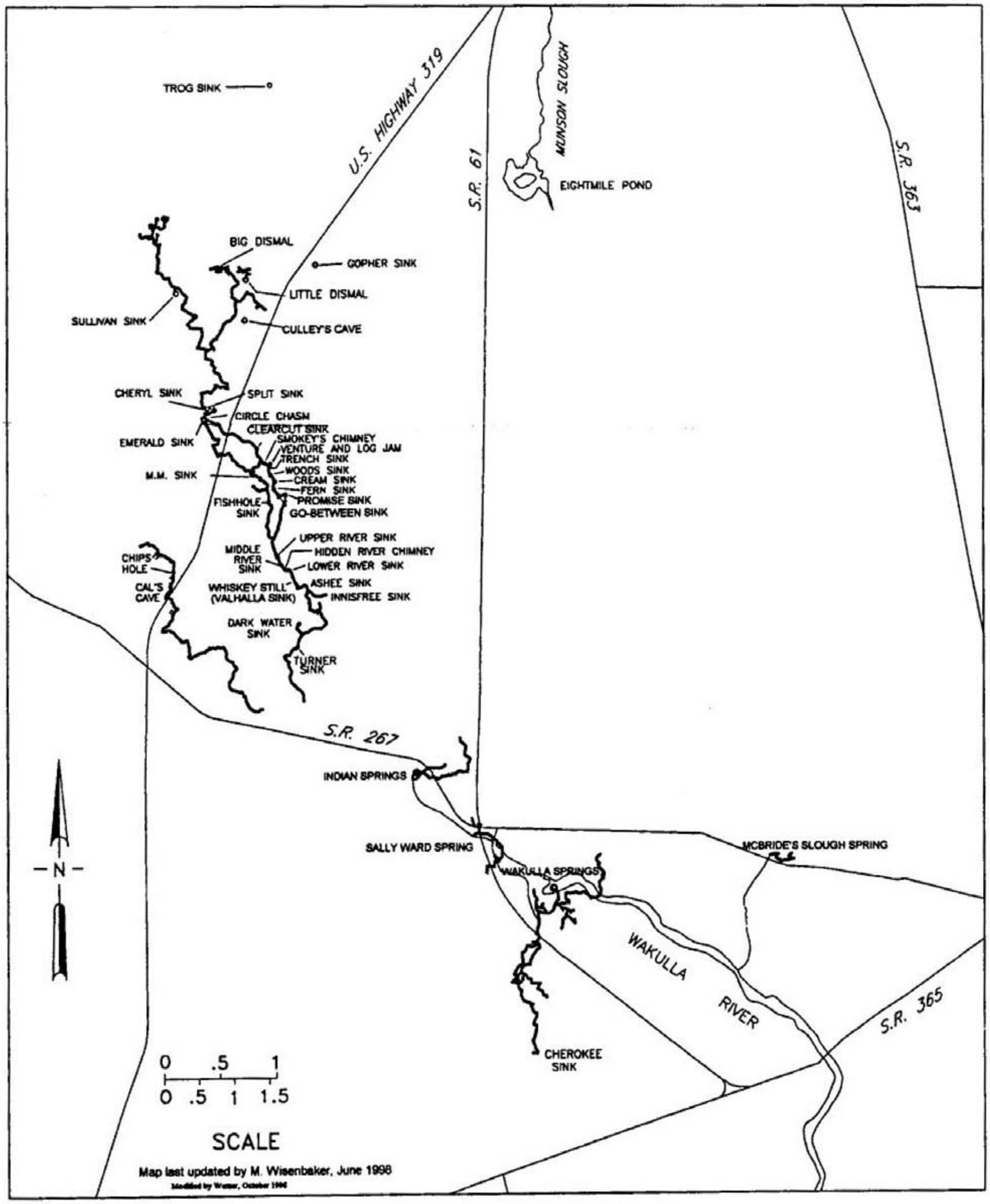

Figure 1. Plan view map of the western Woodville Karst Plain illustrating the Leon Sinks cave system (comprising northernmost Sullivan sink and Big Dismal sink to southernmost Turner sink), Chips Hole cave, Indian Springs cave, Sally Ward Spring cave, McBride's Slough Spring cave and Wakulla Springs cave system.

Suwannee limestone in southwestern Jefferson County and reaches a maximum thickness of approximately 60-m in western Wakulla County.

The Suwannee limestone, Oligocene in age, reaches a maximum thickness of 160 m at approximately 30-150 m below land surface within Leon and Wakulla Counties (Davis, 1996). The thickest portion of the Suwannee is found south at the Gulf of Mexico and the thinnest is located near the Georgia border (Hendry and Sproul, 1966). It consists of two types of permeable rock: (1) a crystalline tan, highly fossiliferous limestone and (2) a white to cream, finely crystalline limestone containing foraminifer with micritic limestone pellets (Davis, 1996). The Suwannee limestone is the principal lithology transporting much of the groundwater of the Upper FAS within the WKP. The majority of dissolution conduits within the WKP are primarily developed in the Suwannee limestone.

The regional recharge area for WKP extends north of the Georgia border for over 80 km and covers portions of over five Georgia Counties (Davis, 1996). The regional groundwater flow pattern, taken from piezometric contour maps, shows overall south trending flow lines (Davis, 1996; Fig. 32, Scott *et al.*, 1991). There is an interesting feature of the piezometric contour maps which show a saddle or potentiometric low area extending well into the WKP. This indicates a convergent flow line pattern toward the south-central region of the karst plain. In this area, there are several first-order magnitude springs including Wakulla Springs, St. Marks Springs and Spring Creek Springs. The regional convergence of flow is thought to originate from the fact that the WKP confining unit is absent. Thus, flow through Leon County, being confined by the Miccosukee and Hawthorn Formations, converges in the WKP, where the lack of confining units allows groundwater transport to result in artesian flow at the surface.

We will turn our attention to the south-central region within the WKP. Within this region, where the majority of springs discharge and the majority of caves have been explored, there are several interesting features. The first is the numerous sinkholes. These depressions are readily observed on 7½ minute quadrangles, as well as easily identifiable in the field. As an example, the Leon Sinks cave system connects over 25 sinkholes through multiple underground conduits (Fig. 1).

The second is the dimensions of the conduits. Many of the large conduits, herein referred to as primary conduits, have interior dimensions that typically exceed heights of 15 m and widths of 20 m. Most are easily recognized as having a phreatic origin, where a slight few appear to have been modified by vadose entrenchment. These primary conduits typically extend several kilometers in length and transport great volumes of groundwater. There are several smaller dimension passages, which in most cases serve as tributaries to the larger primary conduits. The exception is where the primary conduit ceiling has collapsed blocking the conduit. In these cases, of which there are many, flow has been captured or redirected along a smaller tributary.

The third and most interesting feature is the apparent convergence of groundwater flow lines in the vicinity of Spring Creek. Here as many as ten springs continually discharge groundwater into the Apalachee Bay of the Gulf. Spring Creek appears to be the convergence of a branchwork (dendritic) groundwater drainage pattern (Palmer, 1991). It may include waters from as close as newly discovered caves a few kilometers north of Spring Creek to those of the Leon Sinks cave system, Chip's Hole cave, and Wakulla Springs cave.

CAVE PASSAGE ORIENTATION

Surveys and plan-view maps of the conduits, obtained from the WKPP divers (Irvine, 1998), were utilized to infer orientation of many of the primary conduits. The maps clearly exhibit a roughly north-south trendline (Fig. 1). In fact, a majority of the primary conduits show slight deviations from the regional hydraulic gradient. With this in mind, it is reasonable to infer that the evolution of this drainage basin has resulted from a nearly continuos southward-directed regional hydraulic gradient. In so much as this hydraulic gradient has not been entirely steady, it is reasonable to suggest that it has remained, for the most part, in its present state for some time. It is obvious, from glacial and interglacial records of the Quaternary, that sea level has not been constant this entire time, but has fluctuated significantly. Given these fluctuations and the proximity of the WKP to the present sea level in the Gulf, it is reasonable to suggest that the overall drainage pattern directions have not been significantly altered during this brief geologic time scale.

To better visualize the cave passage trendlines, rose diagrams were created for some of the major cave systems (Fig 2). The compass directions from the surveys were calculated to have an error no greater than $\pm 4.6°$. Given the large error inherent in these underwater surveys, the orientation plots provided clearly illustrate the significant trendlines found in most of the cave systems of the WKP.

Sinkholes constitute the most prevalent geomorphic feature of the WKP. Sinkholes form from the collapse of large cavernous voids within the carbonates underlying the land surface. The cavernous voids are the result of dissolution of the carbonate rock by chemically aggressive waters. Sinkholes form as the ceilings of these large voids become unstable and collapse. The distribution of sinkholes is not without patterns or trends.

To better understand the spatial distribution of sinkholes, it is important to realize that sinkholes are indicative of collapsed caves and/or caverns. These void spaces are not formed in isolation from other void spaces, but are typically formed in response to the concentrated flow of aggressive waters. Concentrated flow routes are generally interconnected forming the precursor toward primary conduit formation. As aggressive waters are concentrated, extensive dissolution of limestone occurs initiating connections between the void spaces. The subsequent increase in void space and/or porosity allows the influx of larger volumes of aggressive waters, reinforcing the interconnected flow route. As time progresses, this system may evolve to become a primary flow route transporting groundwater. During this evolution, primary conduits are formed and enlarged by the imposed hydraulic gradient and the positive feedback loop.

As the size of the primary conduits is systematically enlarged, many parts of the ceiling become unstable and collapse forming a sinkhole. To envision this, we will refer to the earlier example of the Leon Sinks cave system (Fig. 1). Here, there have been over 25 collapsed cave ceilings producing sinkholes, which are all direct entrances for divers into the cave system. The sinkholes formed in response to enlargement of the primary conduits comprising the cave system. These sinkholes are aligned, in most cases, directly above primary conduits. This sinkhole alignment provides invaluable evidence for locating primary conduits.

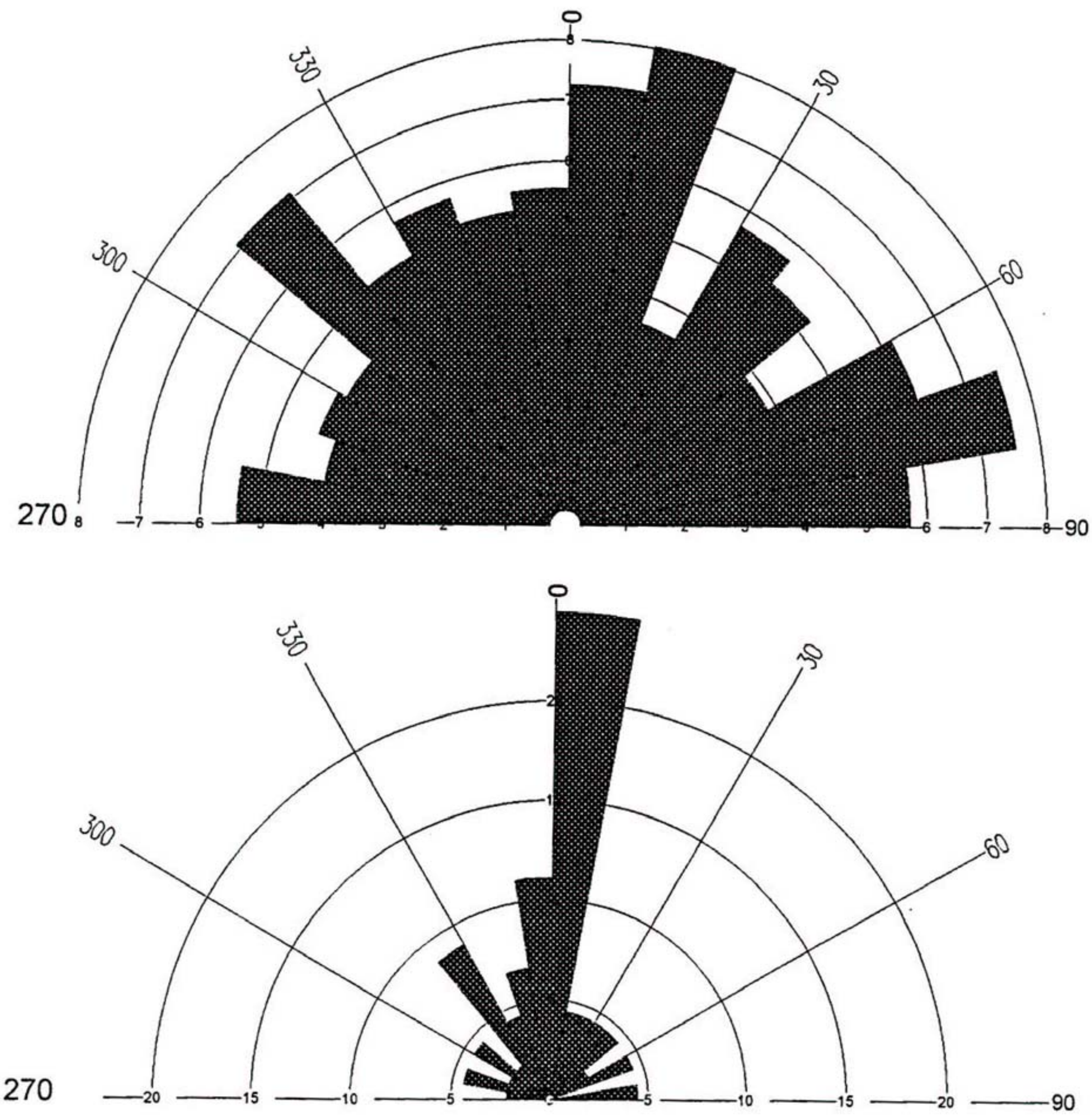

Figure 2. Cave passage orientations from Leon Sinks cave system (top) and Shepherd Spring cave (bottom).

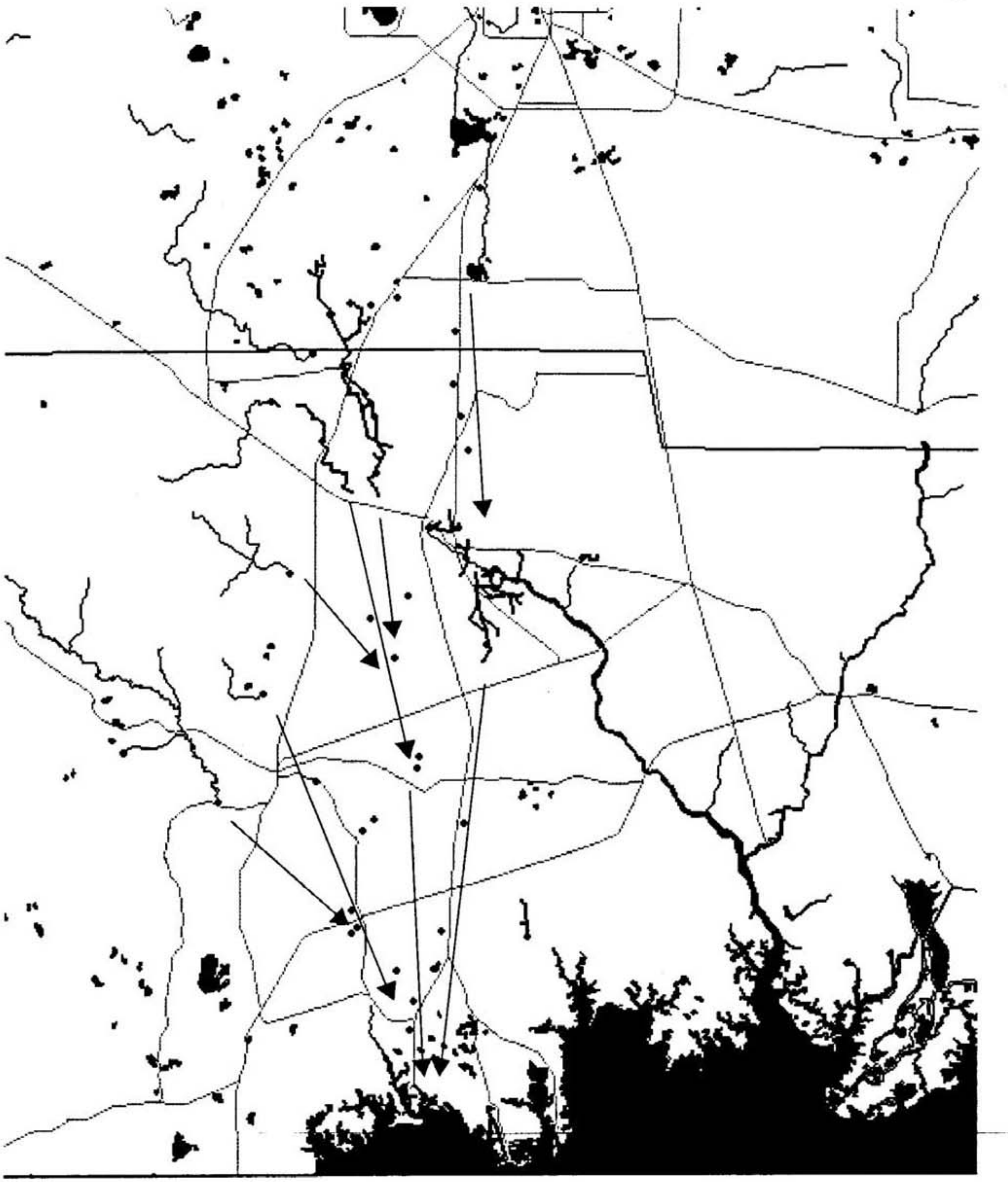

Figure 3. Map of southwestern WKP at 1/300,000. Grey dots are sinkholes, thin black lines surface streams and rivers, dark grey lines are primary cave passages and lines with arrows are inferred branchwork (dendritic) drainage lines.
Refer to Fig. 1 for specific cave and sinkhole names.

Topographic maps, aerial photographs and USGS orthoquadrangles were employed to locate additional sinkholes south of the Leon Sinks and Wakulla cave systems. These sinks, as well as others not detectable on published maps, were located and surveyed in the field and plotted (Fig. 3). The constructed map indicated several possible primary conduit locations. One of the more interesting features of the sinkhole location map (Fig. 3) was the nearly north-south trendlines of the majority of the sinkholes. This is consistent with the sinkhole alignment of the Leon Sinks cave system. In addition, the sinkhole trendlines are also consistent with the regional hydraulic gradient within the WKP.

CAVE PASSAGE FLOW PATTERNS

The majority of subsuface conduit flow moves from north to south, which is in agreement with the regional flow pattern. However, there are some exceptions to this trend. The two most notable exceptions occur in Wakulla Springs cave and Indian Springs cave.

In Wakulla Springs cave, the primary conduit discharging water to the spring mouth, A-tunnel, flows north for upwards of approximately 1.5 km. The interface between northward and southward flowing water varies considerably within the cave. It appears to be dependent on head conditions. During periods of low precipitation and low head conditions, the interface between the divergent flowing water occurs near the junction of A-tunnel and D-tunnel, a distance of 0.65 km from the spring mouth. Conversely, following periods of extensive precipitation and high head conditions, the interface between northward and southward flowing water occurs at a penetration distance of 2.3 km inside the cave at the junction of O-tunnel and A-tunnel. Here at the interface, the northward flowing water travels up A-tunnel 2.3 km to the spring mouth. Both of these conditions transport water in the opposite direction to the regional and local flow regimes.

In Indian Springs cave, a similar situation occurs. Approximately 0.2 km inside the spring mouth, in a northward trending passage, there is a junction between the upstream and downstream tunnel. Here the downstream tunnel continues north for 0.55 km where it terminates in a debris cone from a collapse. Slightly before the debris cone there is a small siphoning southwestward trending passage. The upstream tunnel trends westward for 0.85 km and then turns and trends northward for another 0.8 km.

During high head conditions, a majority of water flows from the upstream tunnel and turns south exiting the cave at the spring mouth. A small proportion of water turns north into the downstream tunnel and flows into the downstream siphon. During extended periods of low head, the majority of water flowing from the upstream tunnel turns north and flows toward the downstream siphon. Usually in these conditions, there is no discharge of water from the upstream tunnel into the spring mouth. In cases of extremely low head conditions, water flowing from the upstream tunnel is entirely diverted to the northward directed downstream tunnel and flows to the downstream siphon. In addition, water from the spring basin is siphoned back into the cave and flows north 0.75 km to the downstream siphon. Thus, depending on head conditions, the water in the front section of the cave, from the spring mouth to the junction of the upstream and downstream tunnels, can flow either north or south.

PALEOFLOW PATTERNS

In order to gain further insight into the conduit system drainage patterns, it is necessary to envision the present drainage system during its Pleistocene evolution. In addition to existing passage enlargement and increased connections (permeability) of large secondary-porosity voids, sea level height was fluctuating significantly. There are indications that sea level was at the Cody Scarp 100,000 years BP and approximately 100 m lower 18,000 years BP (Rupert & Spencer, 1988; Chappell & Shackleton, 1986). These extreme variations may have greatly affected fresh and salt water mixing zones, as well as alter drainage basin size and extent. In as much as the conduit and geomorphic features are indicative of N-S paleoflow, it is important to realize that there were several mechanisms working to varying degrees and during particular times, in order to have produced the present drainage system.

Following careful study of the geomorphic features and the current extent of explored passages a key observation becomes relevant. There are four large sinks north of Wakulla Springs located parallel to FL highway 61. These sinks are in linear alignment with the Leon Sinks cave system and Wakulla Springs Cave system. It appears, after land and in-water dive surveys, that the surface area and volume of Cherokee sink, Wakulla Springs basin, and the large sink directly north of Wakulla on Rt. 61 are all of approximately the same magnitude. Noting how these sinks trend linearly south, there is sufficient evidence to make a hypothesis as to their origin and evolution.

First, it is proposed that Wakulla Springs A-tunnel passage formed from southward directed flow along the hydraulic gradient. This indicates that paleoflow was at one time directed south from the spring mouth toward Cherokee sink. This is reinforced by the passage dimensions of A-tunnel and O-tunnel, which have nearly the same overall box-canyon/ phreatic tube shape and size.

Second, it is proposed that there was a large conduit, the size of A-tunnel, connecting the large sink on Rt. 61 north of Wakulla and Wakulla Springs A-tunnel (Fig. 1). This passage appears to have been a primary conduit of the paleodrainage basin and originated somewhere near the termination of Munson slough or Eight Mile Pond (Fig. 3). This is in alignment with the four large sinks which parallel Rt. 61.

Last, it is proposed that there was a large collapse of this primary paleoconduit at the present Wakulla Spring location. This collapse caused a complete blockage of the southward directed flow. The collapse feature evolved into the large spring now present.

OVERFLOW VALVE

It is necessary to place Wakulla Springs cave system in the context of the regional drainage basin patterns to understand its flow evolution to its present state. The WKPP has believed for some time that Wakulla Springs cave, the Leon Sinks cave system, as well as many of the other caves south of these, were at one time connected or are still physically connected at present (Irvine, 1998). This assumption has been a major driving force in the continued exploration of this area. When the southwestern extent of the WKP is displayed in the context of the cave systems, the regional hydraulic gradient, and sinkhole alignment, it becomes clear that a drainage basin trend emerges.

This trend, coupled with the presence of the sinking surface streams, indicates a very large branchwork (dendritic) drainage pattern (Palmer, 1991). Each cave system, after proposed drainage lines connecting the systems along sinkhole trendlines are drawn (Fig. 3), appears to be part of the larger branchwork drainage system. The terminal mouth of this system also appears to be Spring Creek Springs, at the edge of the Gulf.

With this in mind, following large precipitation events and/or a large head gradient within the basin, flow backs up at Spring Creek and other springs near the coast. This causes an overall decrease in the ability of the conduit system to effectively transport water to the Gulf. Increased flow at several springs, such as Shepherd Spring and Wakulla Springs, becomes the direct result of this inefficiency. A very large head gradient appears to be responsible for the extreme fluctuations in discharge seen at Wakulla Springs.

This intricate and complex feedback loop is typical of karst groundwater / surface water flow regimes (White, 1988). There are several examples of these conditions in the literature, of which Mammoth Cave, Kentucky is the most notable (White & White, 1989). The observations of Indian Springs made above are also consistent with the proposed model above.

CONCLUSIONS

It is evident that the alignment of regional groundwater flow lines with primary conduits and sinkholes are not a coincidence. They are intimately related surface and subsurface features. Much of the subsurface flow through the cave passages are tied to surface water flow. This indicates that the entire drainage basin, both surface and subsurface, must be considered in any further study. It also becomes clear that the evolution of the drainage basin has been intricate and complex through its history. The seemingly anomalous cave passage flow patterns may be explained by simple groundwater / surface water interactions during varying hydraulic head conditions. These observations, models and conclusions should provide a foundation for continued exploration and research into this unique drainage basin.

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URANIUM AND STRONTIUM ISOTOPE CHARACTER OF WATERS IN THE WAKULLA KARST PLAIN

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ABSTRACT

Both uranium and strontium are conservative elements in oxic natural waters, and both exhibit readily measurable isotopic variations that can be used to characterize water sources. The activity ratio of ^{234}U to ^{238}U, normally high in surficial run-off and swamp water, is unusually low in Wakulla Springs and related karstic ground waters. This can be shown to be the result of changes in Upper Floridan aquifer water as it moves southward and becomes oxic and aggressive at the margins of confining beds near the Cody Scarp in Leon County. The mass ratio of ^{87}Sr to ^{86}Sr has increased through geologic time at a rate that can be used to characterize limestone formations and their included ground waters. These same ground waters exhibit significant increases in this ratio if exposed to shaley strata and soils high in potassium. As a result of these two isotopic fingerprint approaches, we estimate that most of the aquifer effluence and surficial drainage in Wakulla Karst Plain springs and sinks is derived directly from the southward flow of the Floridan Aquifer.

INTRODUCTION

U and Sr isotopes in natural waters

Knowledge of the source and pathway of groundwater flow is essential in the protection of our water resources. To this end, any characteristic of the groundwater which retains a "memory" of the location of its recharge into the ground or of the formations through which it has traveled is useful in gaining understanding of the underground flow system. Generally, substances dissolved in the water provide the most useful clues. Concentrations or relative concentrations of major or minor elements or ions are often helpful; isotopic ratios of certain elements can be equally or even more useful. In this investigation, we have utilized the isotopes of the two elements, uranium (U) and strontium (Sr) to gain insight into the groundwater system of the Wakulla Karst Plain.

Uranium is a heavy metal that can be found as a trace constituent in all natural waters. In oxygen rich ("oxic") water U is soluble whereas in oxygen poor ("reducing") water it is very sparingly soluble. In oxic waters the concentration of U may vary over many orders of magnitude. In our study area U is generally found in the range from 0.05 to 10 micrograms per liter (μg/l) but even at these relatively low concentrations it can be measured easily and accurately because of the radioactivity of all of its isotopes. U-238 is a nuclide that has been present on Earth for the entire history of our planet. Because it is a slightly unstable nuclide it takes about 4.5 billion years for half of an amount of it to decay into another nuclide (^{234}Th). However, ^{234}Th is also unstable (radioactive), so it, in turn, is transformed into yet a different nuclide. Thus, a cascade is formed with each member having a different rate of radioactive decay (half-life). The cascade ends at the element lead. Figure 1 shows part of the decay series headed by ^{238}U.

In a closed system, one in which no atoms can enter or leave, the physical laws governing radioactivity dictate that the radioactivity ("activity") of each member of the decay series must be the same; in such cases the ratio of activities of any two members of the series is equal to exactly 1.0. However, in many systems in which minerals are in contact with water it is found that the radioactivities of various members of the decay series are not equal; that is, they are in radioactive disequilibrium. The disequilibrium is especially pronounced in the waters of the Earth. Because each element has a different chemistry than any other element, it is easy to understand how different elements might separate because of their different solubilities. However, the two isotopes of U in the series, ^{238}U and ^{234}U, are almost always found to be in disequilibrium in natural waters, despite the fact that they are separated in the decay series only by two very short lived and highly insoluble nuclides.

In most natural waters ^{234}U is found to have greater radioactivity than ^{238}U. However, a zone in Florida, extending from the Tallahassee area to the vicinity of Tampa and including the Wakulla Karst Plain, contains waters which are quite different in that many of them contain dissolved U in which the activity ratio ^{234}U/^{238}U is less than 1.0 (Osmond, et al., 1968; Kaufman, 1968; Rydell, 1969; Macesich, 1993; Whitecross, 1995). The usual situation (activity of ^{234}U/^{238}U > 1.0) is thought to occur because the ^{234}U has been physically recoiled out of the outer boundary ("rind") of the mineral as a result of radioactive decay (Figure 2) or by selective leaching of ^{234}U from damaged sites in the mineral which resulted from the radiogenic origin of the ^{234}U. These two processes can occur under both oxic and reducing conditions.

If the surrounding waters are gaining ^{234}U by either or both of these processes, then the mineral itself must be deficient in ^{234}U (Figure 2). In the situation wherein low U concentration reducing ground waters bathing the minerals are replaced quickly (geologically speaking) by oxic and somewhat acid waters a profound change may occur. The aggressive oxic waters have the capability of adding U by the dissolution of the minerals containing U. In the case of carbonate minerals the dissolution can be significant. The portion of the mineral dissolved releases all of the U that was associated with it. Because it is the "rind" of the minerals that is most likely to be dissolved, the U released is not only in higher concentration than formerly but also is relatively deficient in ^{234}U (activity of $^{234}U/^{238}U < 1.0$). Under ideal conditions the activity of $^{234}U/^{238}U$ ("AR") can approach 0.5 in aquifer waters. Waters with relatively high U concentrations and ARs less than 1.0 are often found downflow from sinkholes or scarps, places where reducing waters are displaced by or mixed with aggressive oxic waters. Thus, the presence of a water having such characteristics provides a clue as to its source (Osmond and Cowart, 1976, 1992).

In a locale having waters with a variation in U concentration of at least several orders of magnitude (a common occurrence) and a significant variation in the AR (also common), water sources and their histories can often be deduced. Systematic variation of these parameters is well displayed on a graph plotting AR versus the reciprocal of the U concentration (Osmond, et al., 1974; Osmond and Cowart, 1976, 1992)). This display, shown in Figure 3, is termed by us a "mixing diagram" and it can be used to help calculate the relative contribution of up to three separate sources of U to a resultant water (such as a spring).

Strontium is an alkaline earth element that behaves rather similarly to Ca. Therefore, the abundant marine calcium carbonate rocks always contain a minor amount of Sr. Strontium has no naturally occurring radioactive isotopes and has four stable isotopes. However, one of these, ^{87}Sr, is formed by the radioactive decay of ^{87}Rb which means that its relative abundance has changed through geologic time. The ratio of ^{87}Sr to the stable, non-radiogenic ^{86}Sr is used as a measure of this change. For the past forty million years or so the $^{87}Sr/^{86}Sr$ ratio has generally changed monotonically, as may be seen in Figure 4. This means that determination of the Sr isotope ratio in a Neogene marine carbonate rock is a measure of its age. But it also means that ground water which solubilizes some of the incorporated Sr from the rock through which it is flowing will eventually have a Sr ratio similar to that of the rock. As such water flows to other places, it will retain, at least for a period of time, an "isotopic memory" of the rocks along its earlier travel path.

Regional Hydrology

The area of this investigation can be identified as the possible catchment and source region for Wakulla Springs water (Hendry and Sproul, 1966; Miller, 1986; Rupert and Spencer, 1988; Davis, 1996). This includes southern Leon County and northern Wakulla County (Figure 5). Geologically it includes the region just north of the Cody Scarp where the Floridan aquifer is capped by clays and clayey sands and is generally confined, although dotted with sinkholes, and the region south of the scarp where the marine carbonate host rock of the aquifer is exposed or thinly veneered with sand (Figure 6).

ISOTOPIC CHARACTER OF WAKULLA KARSTIC WATERS

Waters issuing from Wakulla springs, Spring Creek, and other first magnitude springs in the area are notable for having uranium ARs less than 1.0 (Osmond, et al., 1968; Kaufman, 1968; Rydell, 1969; Macesich, 1993; Whitecross, 1995). Values from 0.5 to 0.9 are usual, as are U concentrations greater than 0.5 μg/l. On the basis of at least 15 analyses done over more than 30 years, the values for Wakulla Springs are 0.85 with a U concentration of 0.65 μg/l, with virtually no variation over that time. Surficial swamp waters in the same area are characterized by AR values ranging from 1.0 to 1.3 and U concentrations usually less than 0.2 μg/l. As a consequence, it is relatively easy to determine water mass mixing volumes in the karst region when the two source types, spring and surface waters, are involved. As an example, water from the St. Marks river is somewhat higher in AR than is that of the Wakulla River because of a surface-derived U component.

ISOTOPIC CHARACTER OF FLORIDAN AQUIFER WATERS

The Tallahassee municipal water supply is derived from the Upper Floridan Aquifer. Samples of this water analyzed for their U isotopic composition before and during this investigation (Korosy, 1984; Whitecross, 1995; Miller, 1998; Osmond et al., 1998) exhibit, with few exceptions, ARs of 0.76 to 1.15 and U concentrations of 0.3 to 0.8 μg/l. (Table 1 and Figure 7). These values, although not extreme, are more variable than would be expected of a major confined aquifer. A logical explanation for such variability would be admixture of surface water infiltrating through the relatively thin and sinkhole-punctured confining layer overlying the Floridan Aquifer (Katz, et al., 1997). However, simple mixing does not explain the observation that some down-flow waters have higher concentration and lower ARs than up-flow waters. We interpret this to mean that the infiltrating waters are acting not only as diluents of the aquifer but also acting to leach and/or dissolve the aquifer rocks containing U (and Sr). If the mobilized U from the rocks has an AR close to 0.5 (see Figure 2) then it is possible to calculate the residual excess of ^{234}U (Figure 7) as it becomes diluted from north to south in the area (Figures 8).

ISOTOPIC CHARACTER OF SURFACE WATERS

Like surface drainage world-wide, the streams and lakes of Leon County have relatively low U concentrations coupled with AR's greater than about 1.0 (Table 2 and Figure 9). The few samples which carry more than one ppb of U are suspected of being contaminated (Osmond, et al., 1998). Karstic springs have low AR values, consistent with travel through the deep aquifer.

SOURCES OF WAKULLA SPRINGS WATERS

Uranium Isotopes

Using available U isotope data and plotting all reasonable source waters for the Wakulla Springs discharge, we see that the Springs values (Osmond, et al., 1998) lie entirely outside the surface water regime but within the aquifer regime (Figure 9). We conclude that the primary source of Wakulla Springs is southward flowing Floridan Aquifer water. If and when the Wakulla Springs conduits have been accurately and repeatedly sampled, we should be able to make quantitative estimates of the contributions of the two sources types. We anticipate that Wakulla Springs discharge will be shown to be composed of at least 90% deep aquifer water.

Strontium Isotopes

The Sr isotope ratios from waters in the area of investigation fall into three distinct groups (Table 3 and Figure 10). One group, consisting of analyzed samples taken from wells known to produce water from the Floridan Aquifer, has the lowest ratios, ratios that are consistent with those associated with the marine carbonates which make up the Floridan Aquifer. Another group, the one having the highest Sr ratios, consists of samples which come from surficial clayey areas and are unlikely to have mixed with Floridan Aquifer water nor with significant amounts of urban runoff. The ratios for this group are much greater than those of the marine carbonates. The third group consists mainly of samples that have a large urban runoff component. An exception appears to be the two samples of Lost Creek, a stream that originates within the Apalachicola National Forest and flows just south of Crawfordville before being captured by underground drainage. In this case, the ratio may result from a mixing of surface runoff from the clayey sands of the headwaters and upwelling Floridan Aquifer waters lying just below the veneer of surficial sediments.

The Sr isotope ratio for water from Wakulla Springs falls within the values obtained from Floridan Aquifer waters. Thus, it seems that the source of waters feeding the spring are unlikely to be solely from nearby local recharge; rather, it comes from waters which have spent considerable time in contact with the marine carbonates that comprise the matrix of the Floridan Aquifer.

ACKNOWLEDGEMENTS

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S.N.	LOC	COLL	A.R.	CON	1/C
4862	W-1	6/96	0.50	13.761	0.07
4970	2	3/97	0.91	0.50	2.02
4482	4	3/97	1.03	0.58	1.72
4973	5	3/97	1.01	0.53	1.89
4975	6	3/97	0.76	0.52	1.92
4976	7	3/97	1.01	0.40	2.49
4480	8	6/96	0.83	0.51	1.96
4972	9	3/97	1.01	0.48	2.08
4497	11	6/96	1.15	0.57	1.75
4967	12	3/97	0.88	0.47	2.13
4813	13	4/96	0.92	0.75	1.33
4484	14	1/94	0.98	0.37	2.70
4471	15	1/94	0.97	0.56	1.79
4467	17	7/97	1.14	0.31	3.23
4487	18	9/97	0.99	0.31	3.23
4473	19	9/97	1.01	0.47	2.13
4478	20	9/96	0.91	0.43	2.33
4903	21	9/96	0.93	0.42	2.38
4477	22	1/94	1.06	0.35	2.86
4465	23	1/97	0.93	0.59	1.69
5042	26	7/97	0.72	0.58	1.74
4966	27	3/97	0.88	0.49	2.04
4485	29	1/94	0.95	0.37	2.70
5043	30	9/97	0.99	0.47	2.13

Table 1. Representative U Isotopic data for selected City of Tallahassee Wells

GEOGRAPHIC GROUP	LOCAL GROUP	MEDIAN VALUES U CON (ppb)	MEDIAN VALUES U AR	NUMBER OF SAMPLES
L Jackson drainage area	high springs	0.02	1.21	4
	drainage ditches	0.17	1.15	5
	Lake Jackson	0.03	1.49	3
L Munson drainage area	high springs	0.03	1.24	4
	West lakes	1.34	1.05	4
	West ditches (hi U)	1.50	1.00	3
	West ditches (lo U)	0.20	1.00	5
	Munson Slough	0.60	1.40	3
	Lake Munson (& Crk)	0.20	1.30	5
L LaFayette drainage area	Upper Lake drainage	0.10	1.00	6
	Lower Lake drainage	0.06	1.90	4
	Lake LaFayette	0.05	1.30	10
	Mosquito Canal	0.03	1.40	3.
St. Marks R	above Natural Bridge	0.25	0.95	5
Karst Plain	sinking streams	0.05	1.20	13
			TOTAL	77

Table 2. Summary of U Isotopic Data in Surface Waters

SAMP NUMB	DATE COLL	87Sr/86Sr RATIO	LOCALITY
		SURFACE WATERS AND HIGH SPRINGS	
4943	09/12/97	0.710462 +/-0.000055	Spring - Meyer's Park
4907	06/14/97	0.709030 +/-0.000010	NW Corner Tallahassee Mall
4915	09/06/97	0.709407 +/-0.000011	Tallahassee Mall Drainage
4916	06/15/97	0.709172 +/-0.000009	Park Ave near Gov Sq
4908	06/13/97	0.708991 +/-0.000030	Gov Sq drainage
4879	09/08/97	0.709193 +/-0.000010	Piney Z Lake
4878	12/18/96	0.708765 +/-0.000010	U L Lafayette @ Falls Chase
5018	06/19/97	0.709314 +/-0.000039	U L Lafayette @ Falls Chase
5014	06/19/97	0.710376 +/-0.000010	Lower L Lafayettee
4919	06/15/97	0.710495 +/-0.000036	Outlet L L Lafayettee (Chaires)
4896	09/10/97	0.710548 +/-0.000009	St Marks R @ US27
4927	09/19/97	0.709335 +/-0.000040	Munson Slough @ Capital Circle
5000	04/30/97	0.709071 +/-0.000011	Munson Slough @ Orange Ave
4894	12/30/96	0.709033 +/-0.000008	Lost Creek (Crawfordville)
4922	06/15/97	0.709133 +/-0.000009	" "
		FLORIDAN AQUIFER WATER	
4846A	07/31/97	0.708151 +/-0.000008	6923 Hanging Vine Way
4846B	07/31/97	0.708140 +/-0.000007	" (N of L. Lafayette)
4970	06/18/97	0.708283 +/-0.000008	City Well #2
4975	09/19/97	0.708338 +/-0.000011	City Well #17 (CapCir/Apalachee)
4967	09/17/97	0.708201 +/-0.000052	City Well #12 - Country Club Dr
		WAKULLA SPRINGS	
5053	09/20/97	0.708279 +/-0.000017	Main pool
5052	09/20/97	0.708235 +/-0.000011	Tunnel "D"

Table 3. Strontium Isotopic Data

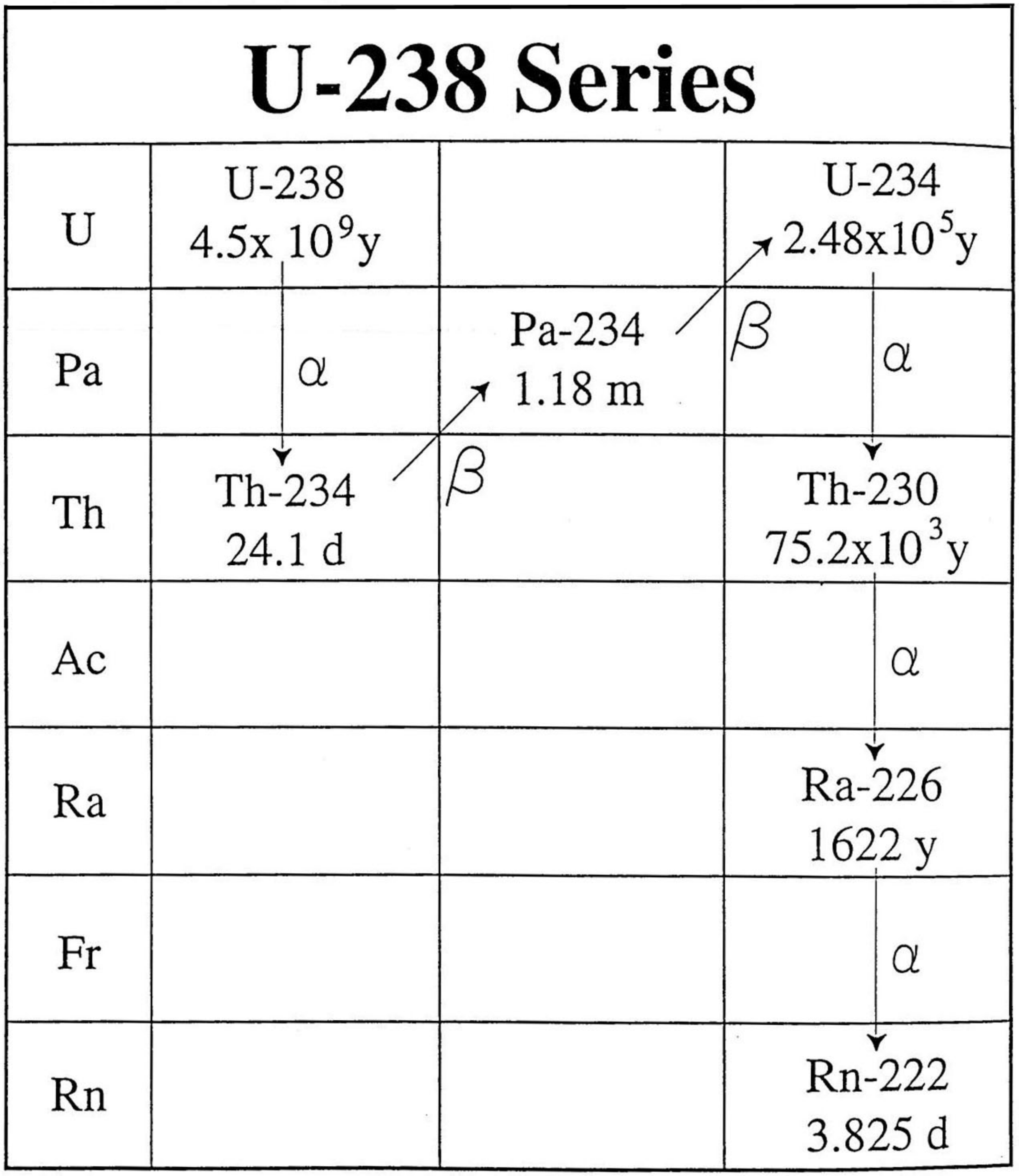

Figure 1. **Early part of U-series decay scheme.** The principal nuclides of interest are ^{238}U and ^{234}U. The reason for the variation in relative activity of the two U isotopes, and their usefulness in identifying ground water sources, is one subject of this paper.

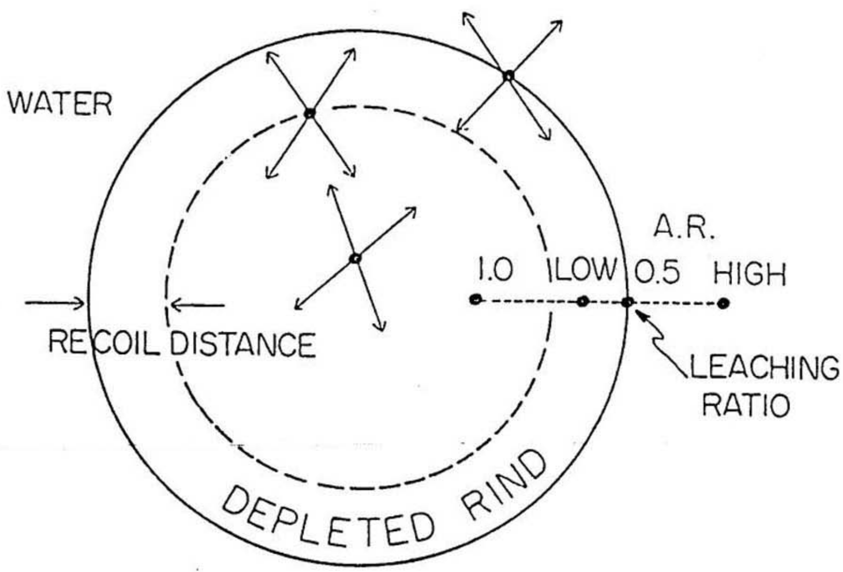

Figure 2. **High and low A.R. schematics.** Recoil displacement as a result of alpha decay of ^{238}U to produce ^{234}U can be invoked to explain both high and low AR in ground water: (1) recoil directly into aquifer waters produces high A.R. in water and low A.R. in solid; (2) subsequent leaching of the solid by water mobilizes low A.R. U.

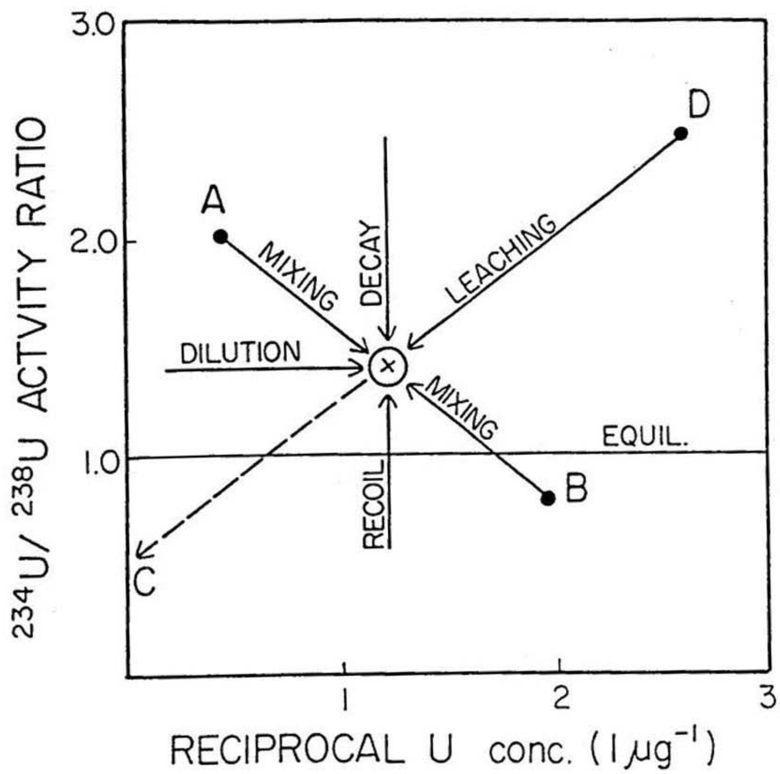

Figure 3. **U isotopic mixing diagram.** The U activity ratio and concentration data can be used to infer water mass evolution and mixing. By plotting the A.R. values against reciprocal of U concentration, such evolutionary trends and mixing proportions show up as straight lines.

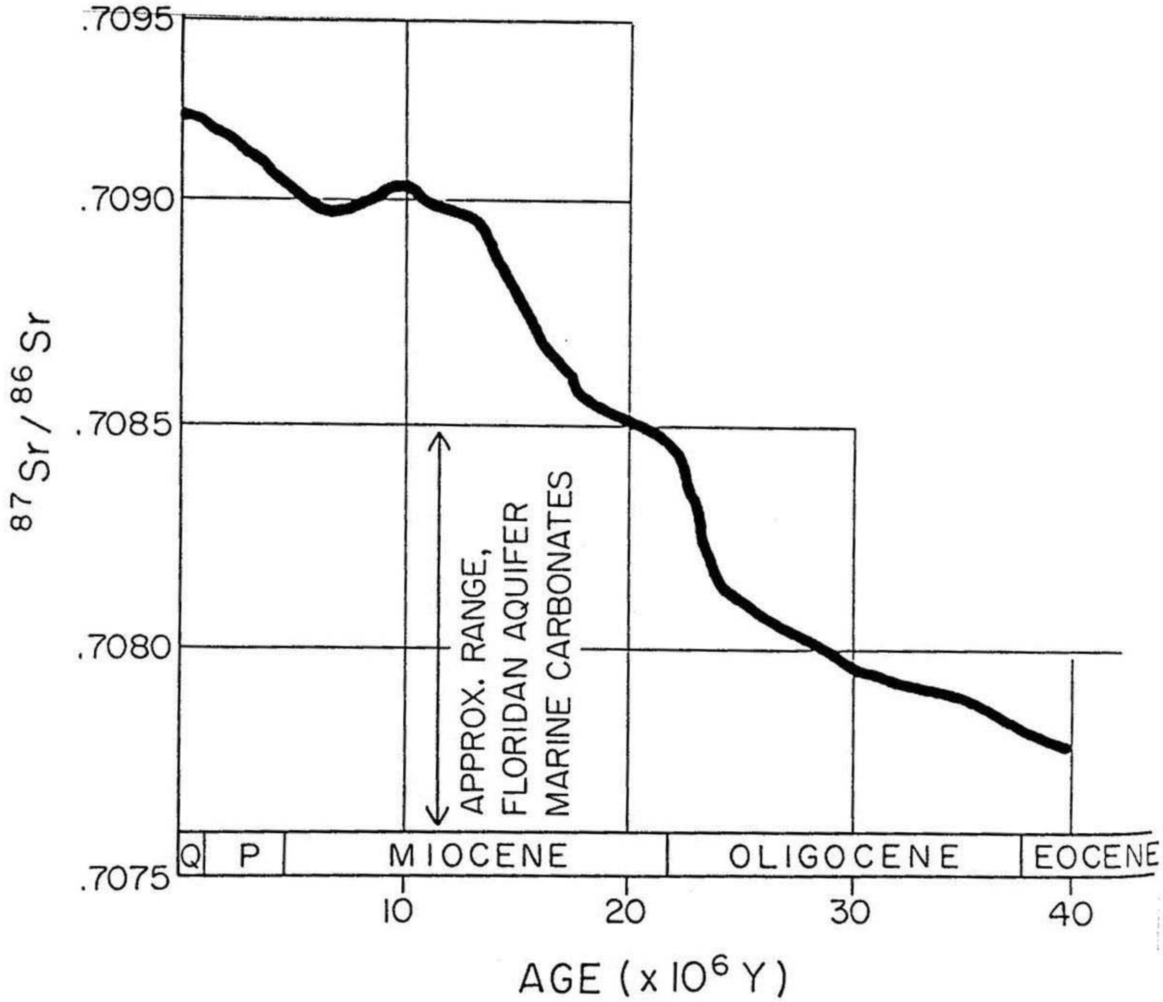

Figure 4. **Sr isotopes evolution.** The ratio of $^{87}Sr/^{86}Sr$ in ground water can be used to infer the ages of aquifer host limestone strata, because ocean water and associated chemical sediments have experienced a gradual evolutionary increase in $^{87}Sr/^{86}Sr$ ratio with time (modified from Burke et al., 1982).

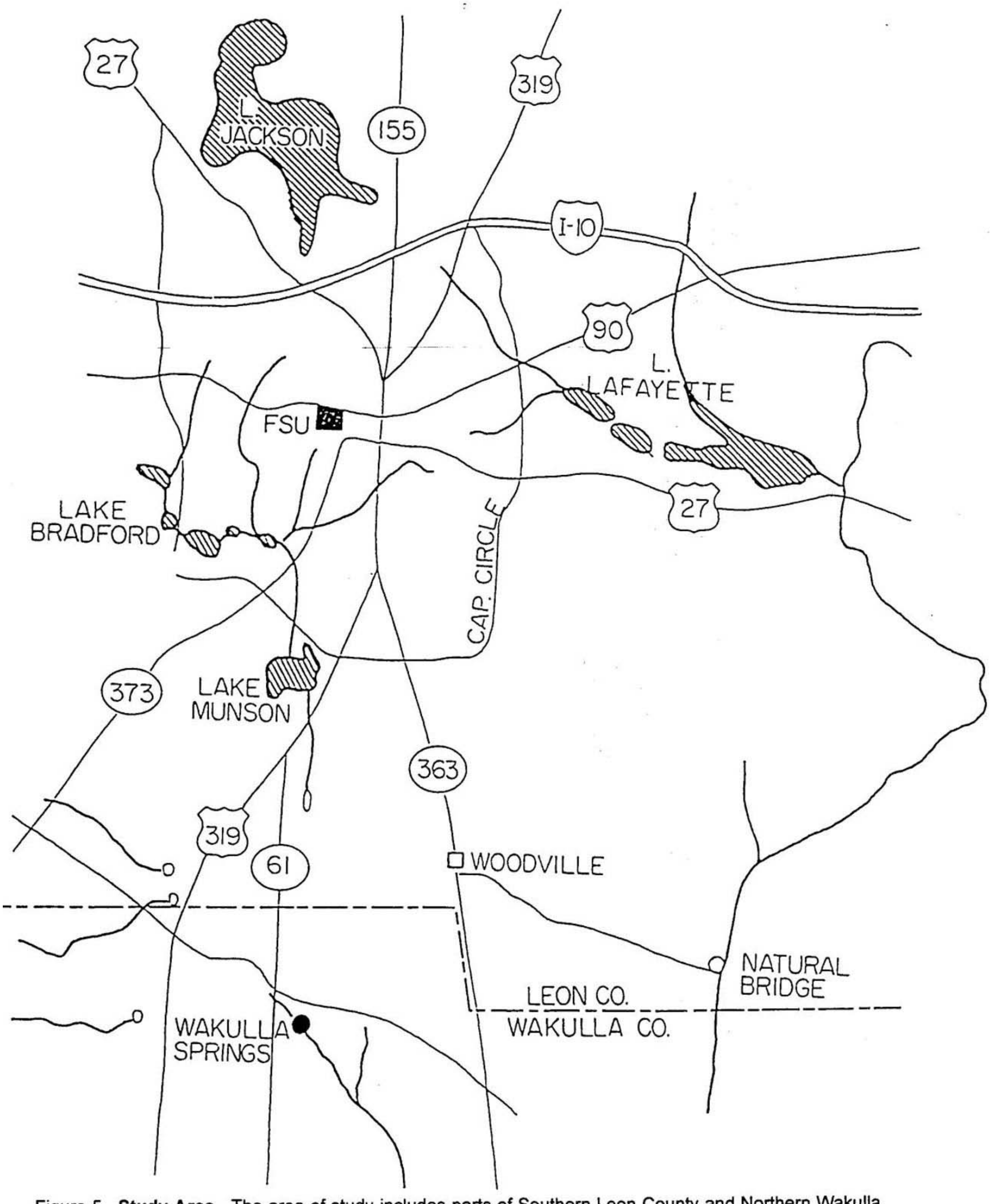

Figure 5. **Study Area.** The area of study includes parts of Southern Leon County and Northern Wakulla County and includes the area from which Wakulla Karst Plain waters are derived.

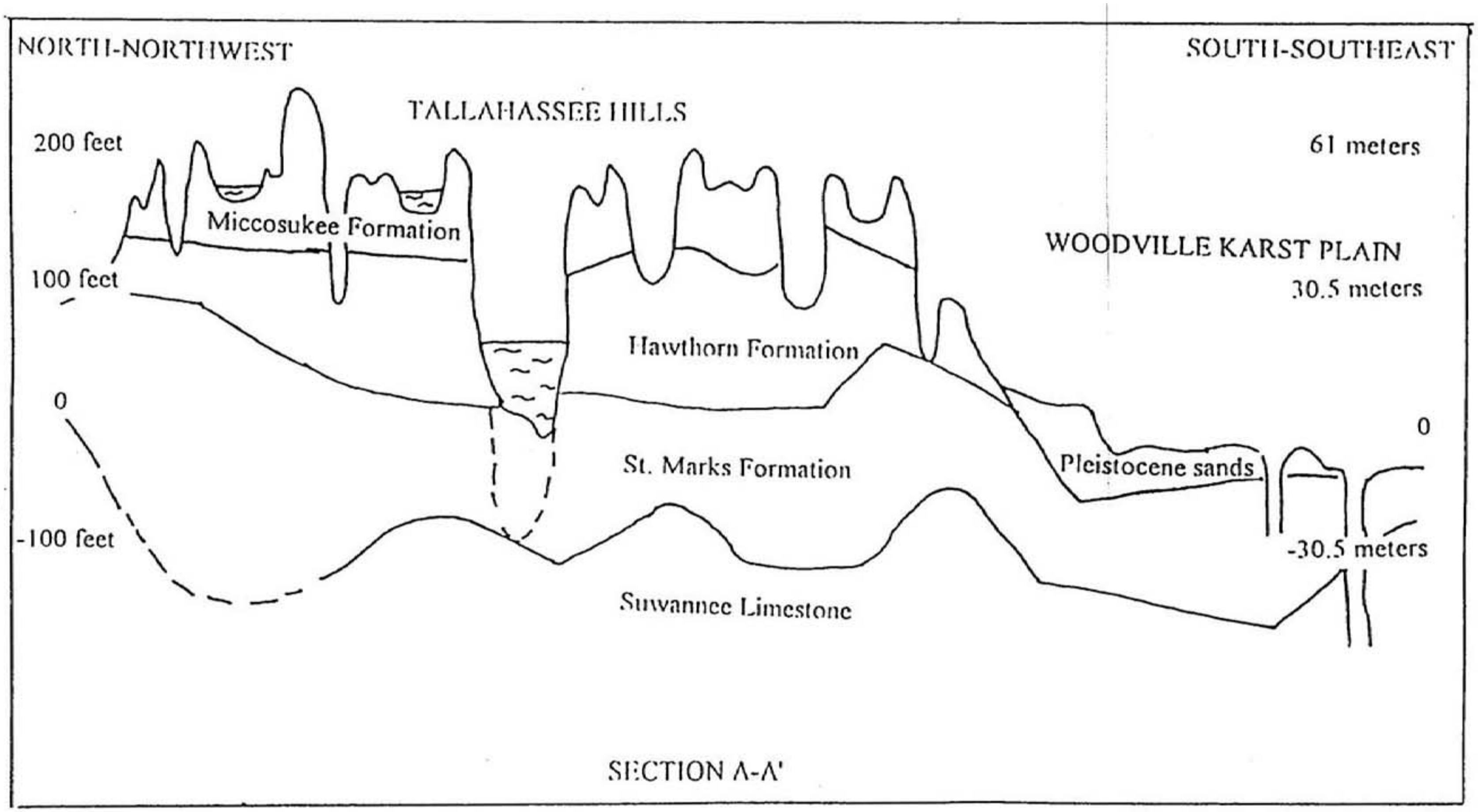

Figure 6. **Hydrostratigraphic profile of the study area.** The St. Marks and Suwannee Limestones constitute the Upper Floridan Aquifer, while the Hawthorn and Miccosukee Formations are aquicludes.

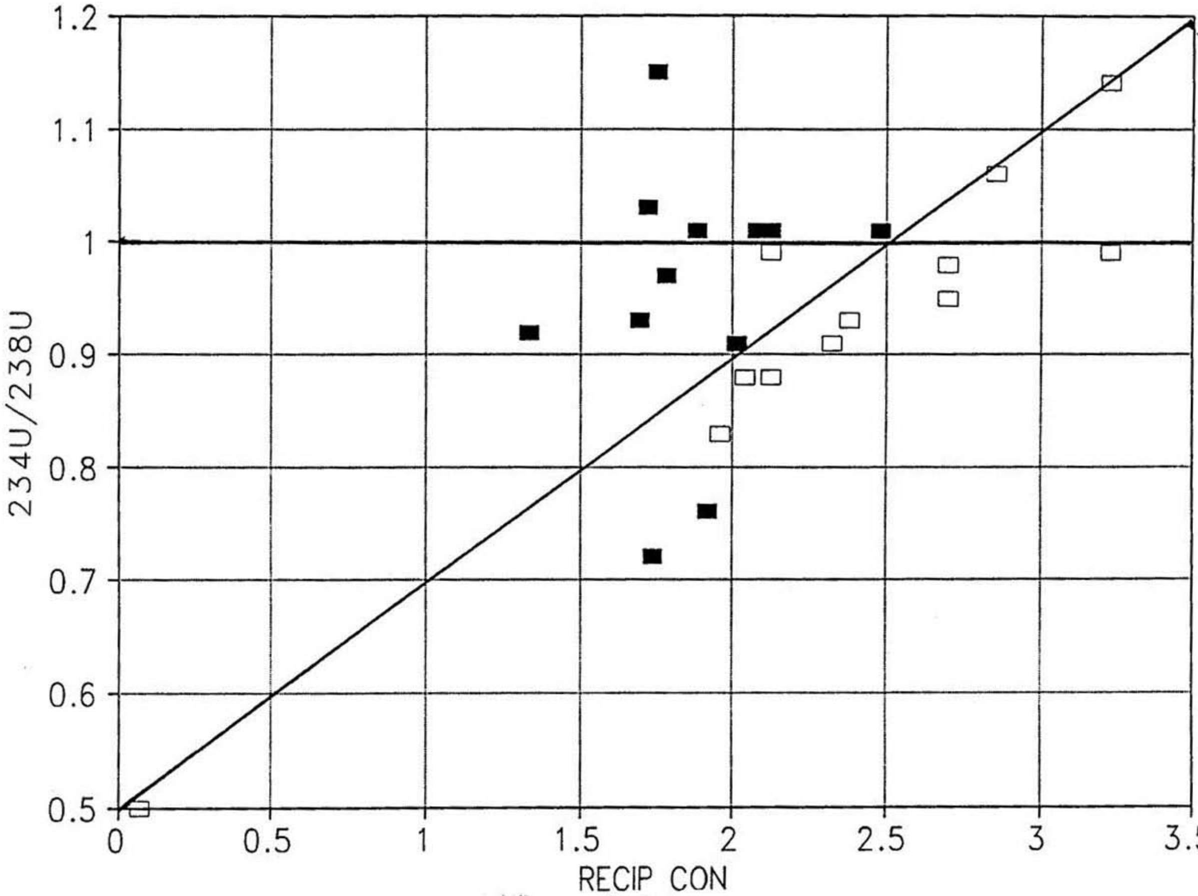

Figure 7. **Mixing diagram of City of Tallahassee water wells.** These wells sample Upper Floridan Aquifer water. Variation of U concentration and A.R. across the region could appear to be random. However, each sample can be regarded as a mixture of leachate U with A.R. near 0.5 (y-axis intercept) and relatively dilute high A.R. aquifer water (joined by a mixing line). The slope of this line has units of "Excess ^{234}U". The line shown has slope of 0.20 ppb (U-equivalent) excess ^{234}U. Sample points shaded are from the northwest sectors of the city and have generally higher excess values; the unshaded are from the southeast and have generally lower values.

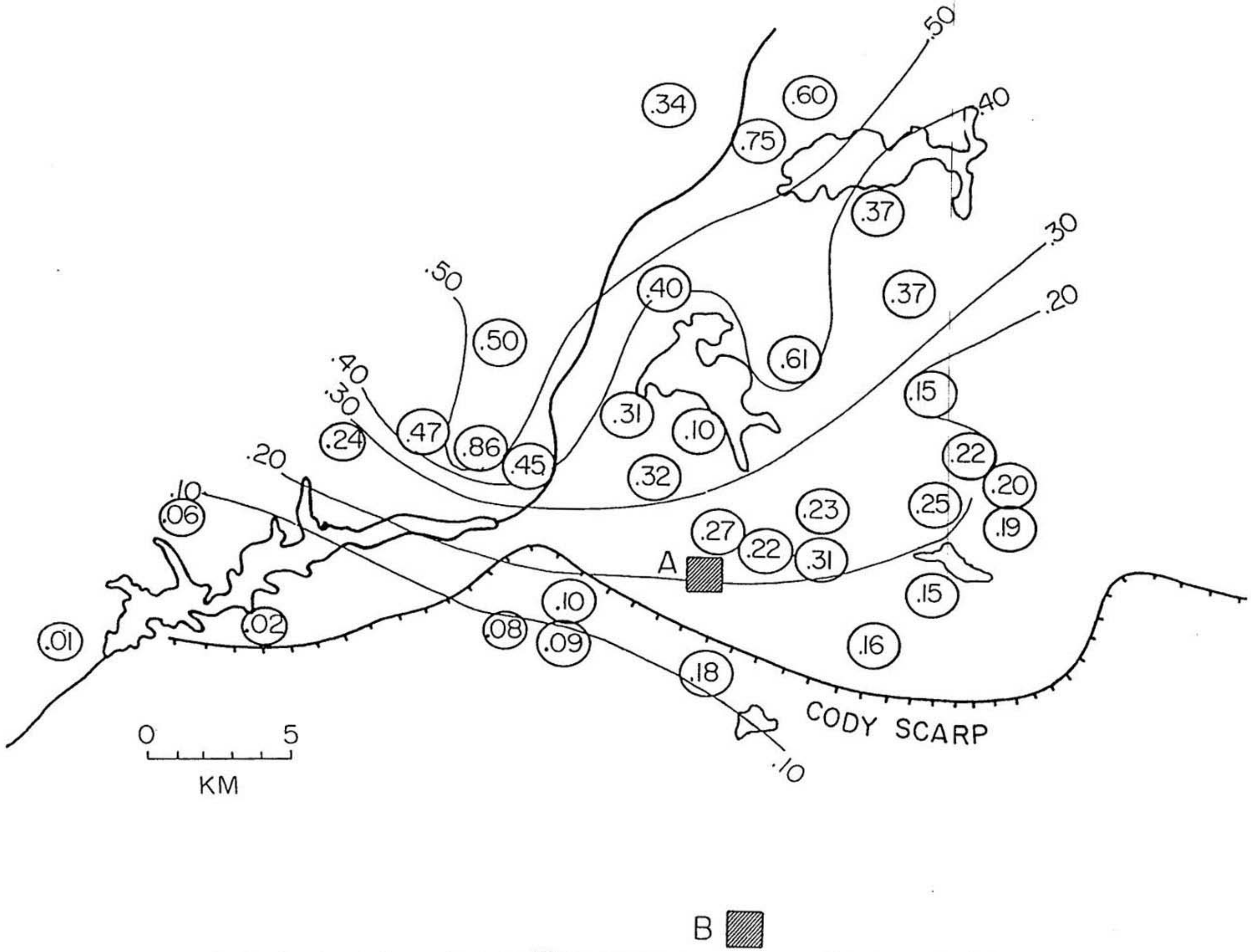

Figure 8. **Regional variations of excess ^{234}U in the study area.** Data points from wells in Leon and Gadsden counties are plotted. For orientation, the FSU campus (A) and Wakulla Springs (B) are shown. Infiltration from the surface causes the aquifer water to be diluted with respect to its conservative excess ^{234}U. As a result the regional variation shows aquifer flow direction, generally from north to south.

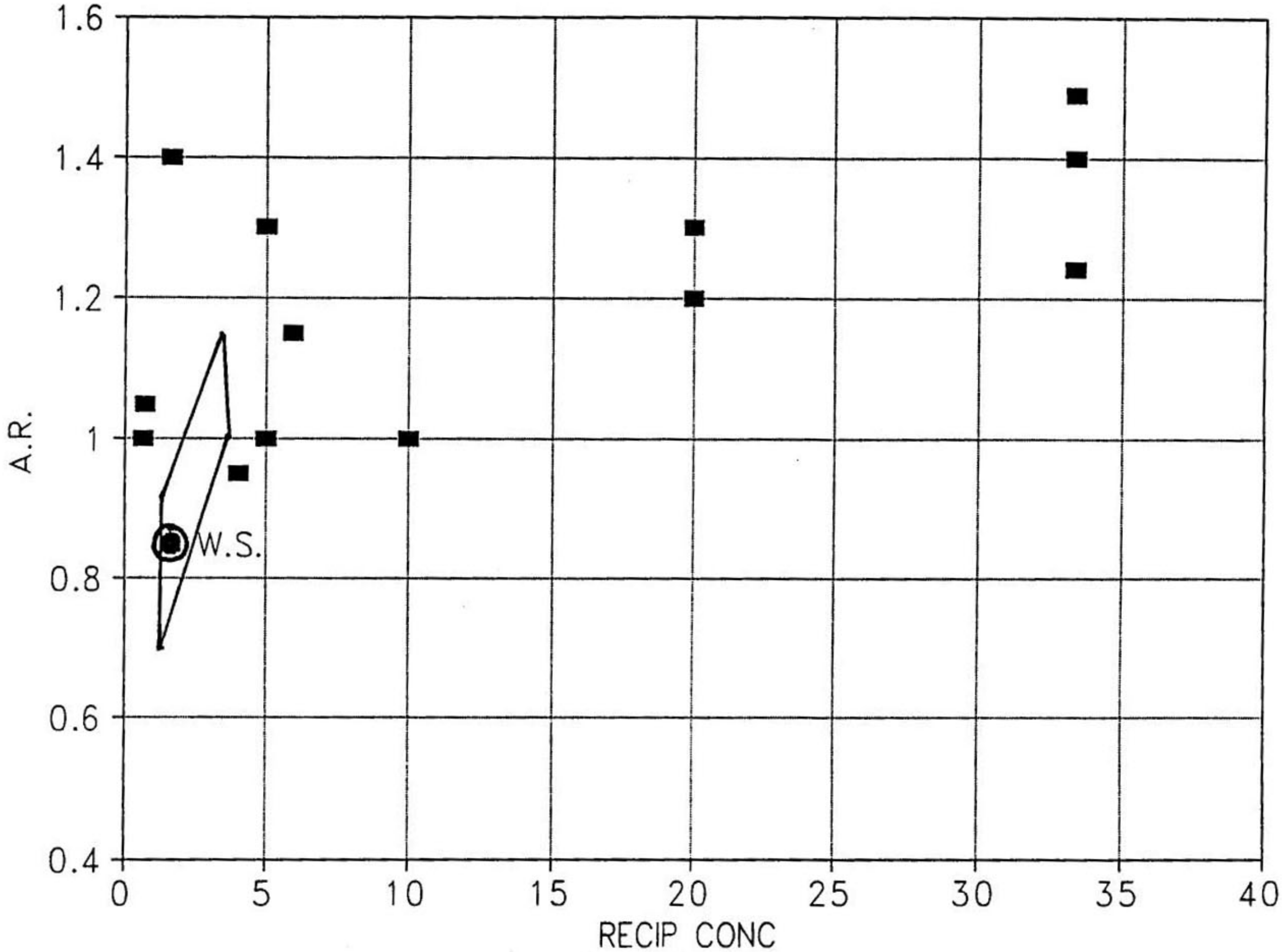

Figure 9. **Mixing plot of U in waters from Wakulla Springs, Floridan Aquifer, and regional streams and lakes.** The shaded squares are surface streams and lakes, characterized by low concentration (to the right) and high A.R. values, 0.95 and above. The polygon shows the plotted area of Floridan Aquifer water as represented by Tallahassee wells (Figure 7). The water from Wakulla Springs plots within the aquifer region and well below the surface water region.

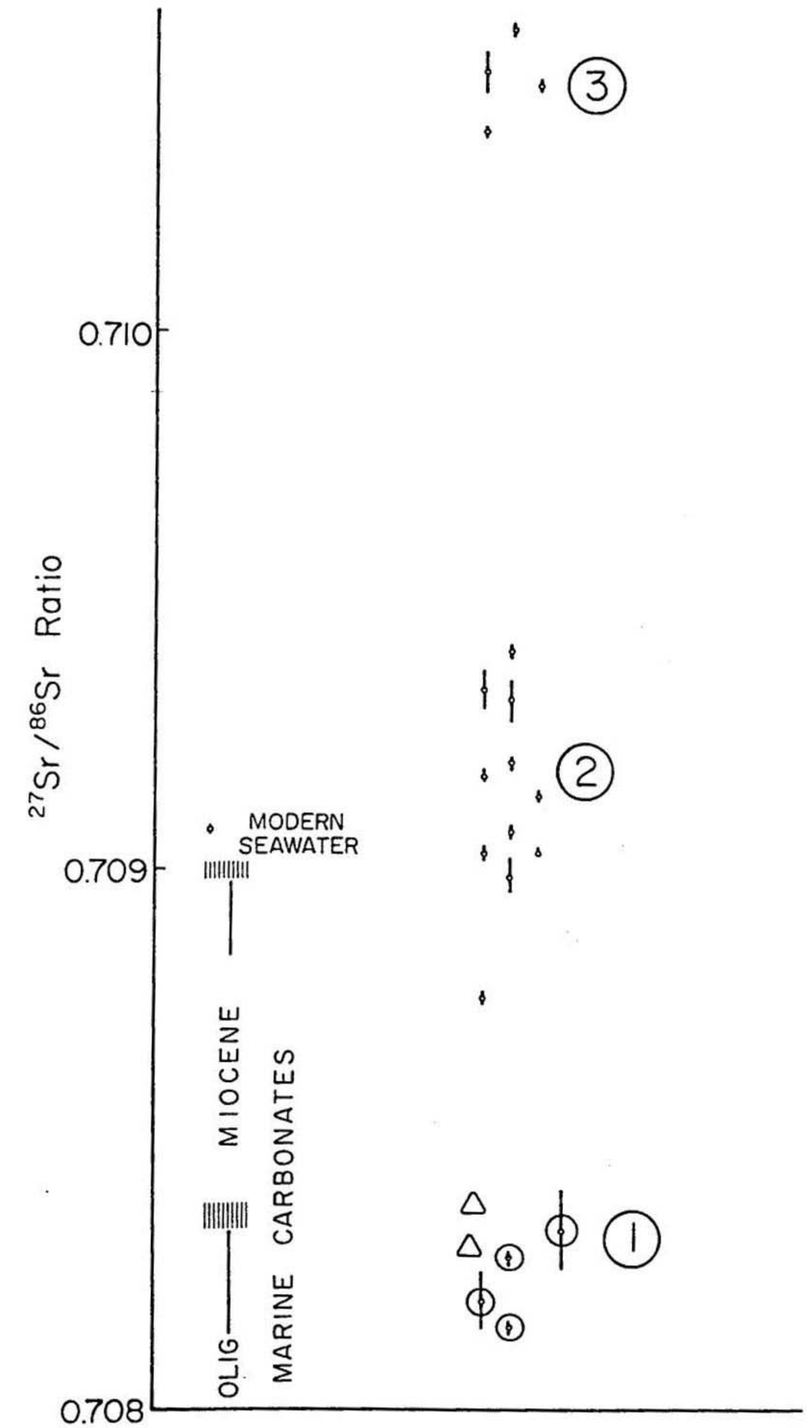

Figure 10. **Strontium isotopic ratios of surficial, aquifer, and karstic waters in the study area.** Group 1: samples from Floridan Aquifer; Group 2: samples having significant urban drainage component, including input from clayey confining layer; Group 3: samples in contact only with clays of confining layer. Triangles represent water analyzed from Wakulla Springs.

HYDROCHEMICAL INTERACTIONS BETWEEN GROUND WATER AND SURFACE WATER IN THE WOODVILLE KARST PLAIN, NORTHERN FLORIDA

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ABSTRACT

Hydrochemical interactions between surface water and ground water in the Woodville karst plain in Leon and Wakulla Counties have resulted in water-quality impacts on both resources. Karst features such as sinkholes, springs, disappearing streams, and solution conduits, provide direct pathways for surface water to enter the Upper Floridan aquifer (UFA), the source of potable water in these two counties. In parts of Leon County, ground-water samples analyzed for stable isotopes ($d^{18}O$, dH, and $d^{13}C$) along with results from geochemical mass-balance modeling indicate that isotopically-enriched surface water from sinkhole lakes enters the UFA and mixes with shallow ground water in proportions ranging from 0.07 to nearly 0.90. Ground water in deeper parts of the UFA also had an enriched isotopic signature, indicating mixture proportions of as much as 0.25 surface water. Based on tritium age-dating, the shallow and deep ground water was recharged during the past 30 years, indicating a very dynamic system through the full thickness of the aquifer. Blackwater streams, such as Fisher Creek and Lost Creek, flow directly into the UFA through sinkholes and transport large amounts of organic carbon (such as tannins and lignins) into the aquifer. When these naturally-occurring organic compounds react with chlorine during disinfection of the water supply, harmful products such as trihalomethanes are produced. The unconfined Upper Floridan aquifer in the karst plain also is vulnerable to contamination by nitrate from nonpoint and point sources, such as septic tanks (at least 4,000 in the eastern half of Wakulla County), fertilizers, publicly-owned treatment works, and stormwater runoff. In recent years, nitrate-N concentrations have increased to approximately 1 mg/L in Wakulla Springs. Because Wakulla Springs is a first magnitude spring and drains ground water from a large regional area, there is concern about a widespread increase in nitrate levels in ground water and the potential for increased algal growth in this State-designated priority water body.

THE BIG PICTURE: AQUIFER VULNERABILITY MAPPING EFFORTS IN THE WOODVILLE KARST PLAIN OF NORTHERN FLORIDA

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ABSTRACT

For the last twelve years, state and local government agencies involved in ground-water monitoring and protection efforts have developed aquifer vulnerability maps as a generalized tool to depict relative susceptibility of aquifer systems to contamination. Several vulnerability mapping efforts have focused on or included the Woodville Karst Plain subdivision of the Gulf Coastal Lowlands. Pilot vulnerability mapping projects have centered on this region and the adjacent Northern Highlands, due to the wide range in potential vulnerability of the Floridan aquifer system within these adjacent geomorphic areas.

DRASTIC, a widely-used aquifer vulnerability mapping system developed jointly by the U.S. Environmental Protection Agency and the National Water Well Association, has been mapped in the Woodville Karst Plain by Northwest Florida and Suwannee River Water Management Districts, the Florida Geological Survey, and the Ambient Monitoring Section of the Department of Environmental Protection (DEP). DRASTIC is complete for the Floridan and surficial aquifer systems in this area, and the coverages are currently available in the DEP GIS map library. These maps were originally developed as a tool to aid in the selection of DEP ground-water monitoring efforts designed to quantify the impact of various land use types on ground-water quality. Subsequently, these coverages have also served as regional planning tools useful to local and state governments charged with consideration of aquifer impacts resulting from land use changes.

KARSTIC, developed by Leon County, incorporates karst features into a vulnerability mapping product similar to DRASTIC. KARSTIC has only been mapped for Leon County. Florida Aquifer Vulverability Assessment (FAVA) and Aquifer Vulnerability Assessment Model (AVAM) are two proposed vulnerability assessment methodologies which are designed to better portray potential aquifer vulnerability in Florida. Pilot mapping projects using both methods are in progress in portions of the Woodville Karst Plain. A unified Florida-specific mapping methodology, incorporating karst features, will result from this effort.

TRACING GROUNDWATER FLOW INTO THE NORTHEASTERN GULF OF MEXICO COASTAL ZONE

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ABSTRACT

Submarine springs and seeps deliver an unknown quantity of groundwater to the coastal ocean, lakes, and rivers. This process has been demonstrated to be ecologically significant as a nutrient input or contaminant source in some local areas. Is the process important on a wider scale? Some information suggests that inputs of various chemicals via submarine discharge of groundwater may be regionally significant. The problem is how to quantify this diffusive flow.

Our research team has been developing an assessment method based on measurements of: (1) naturally-occurring tracers, such as radon and methane, found at very high concentrations in groundwater relative to surface waters; and (2) artificial tracers such as SF_6 *and* ^{131}I *that can be traced from specific points after injection. Thus far, only the natural tracer approach has been applied in the coastal Gulf of Mexico. We have also made direct measurements of groundwater seepage using seepage meters in the same areas where we are collecting the tracer information. Both the tracer data and the direct measurements indicate that groundwater flow into this area is significant.*

PHYSICAL FRAMEWORK FOR UNDERSTANDING FLORIDAN AQUIFER GROUNDWATER FLOW AND NUTRIENT TRANSPORT WITHIN THE WOODVILLE KARST PLAIN

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ABSTRACT

The Northwest Florida Water Management District and the U.S. Geological Survey are currently engaged in a four-year investigation of the fate and transport of nutrients within the Floridan Aquifer in Leon and Wakulla counties. Understanding the transport of nutrients through a karst flow system requires knowledge of the physical context in which nutrient transport is occurring. This paper presents a discussion of major aspects of the ground water flow system beneath the Woodville Karst Plain. The major inflows and outflows and their relative magnitudes are described. One of the goals of the project is to create a simple predictive model that can be used to estimate nutrient concentrations in the outflow, given various nutrient input functions. Creation of such a model requires linking the volumetric inflows to the outflows. Various conceptualizations of ways to create this linkage are discussed.

THE SPRING CREEK SUBMARINE SPRINGS GROUP, WAKULLA COUNTY, FLORIDA

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ABSTRACT

Submarine springs are offshore discharges of ground water, usually associated with a coastal karst area. Submarine karst springs and sinkholes on the Florida Platform constitute integral parts of Florida's hydrogeological regime. They are some of the ultimate down-gradient discharge points for fresh water from Florida's aquifers. Knowledge of their location, hydrology, and stratigraphy will add to an understanding of the overall structure and extent of Florida's aquifer systems. Conceivably, they may represent supplementary sources for fresh water supplies. In addition, they are micro-environments for fish nurseries; and some are known to contain archaeological artifacts. They are key elements in the linked Earth systems among Florida's environments and ecosystems: the uplands, the coasts, and the continental shelf marine realms.

The Florida Geological Survey is gathering information on these karst features as part of ongoing Florida coastal research programs. This report documents the results of the first investigation, to locate and determine the physical characteristics of the Spring Creek Submarine Springs Group, Wakulla County, Florida.

INTRODUCTION

Submarine springs occur on continental shelves around the world. Figure 1 shows the location of the better known submarine springs and sinkholes that occur around Florida's coastline, or on the Florida Platform. The Florida Geological Survey has several ongoing coastal research programs along the coastlines of Florida. An important part of these programs is gathering information on these submarine springs, sinkholes, and other karst features. This report documents the results of the first investigation of submarine springs, on the Spring Creek Springs Group, Wakulla County, Florida.

The purpose of the present investigation is to gather background information on the largest group of submarine springs in the Big Bend area of the northeastern Gulf of Mexico, the Spring Creek Springs Group. The immediate goal is to locate and determine the physical characterisics of the springs. The long-term goals for future research will be to determine the **linkages** between the land and the ocean, and to determine the role of submarine springs in those linkages. More specifically, what are the linkages among the ecosystems and environments of the uplands, the coast, the coastal marshes, the marine realm, *and* the springs and sinkholes that occur in all of them?

Location of Study Area - the Woodville Karst Plain

The study area is on the southern coast of Wakulla County, in the Big Bend area of the Florida panhandle (Figure 1). The study area is in the Woodville Karst Plain, which includes the entire eastern half of Wakulla County, extending eastward into Jefferson County, and northward to the Cody Scarp at Tallahassee in Leon County (Hendry and Sproul, 1966) (Figure 2). This part of the northeastern Gulf of Mexico is a low energy coast, characterized by muddy or fine grained sediments, small tidal ranges of one to three feet, extensive marshes, and low gradient tidal streams.

WATER RESOURCES

The region's climate is semi-tropical and an occasional hurricane delivers enough rain to cause extensive flooding. Convective storms and thunderstorms occur year-round, many of which drop large quantities of rain in a short time. For the 30-year period of record from 1951 to 1980, average annual rainfall was between 56 and 60 inches. Also, during this time the maximum amount of rainfall for the entire state during any 12-month period, 107 inches, was recorded at St. Marks, just seven miles east of Spring Creek (Fernald and Patton, 1984). Because of this large amount of annual rainfall, the local water table is usually close to land surface. Even in periods of low rainfall, though, the water table only drops a few feet.

The Floridan aquifer system underlies all of Wakulla County (Miller, 1986). In the study area the Floridan aquifer system extends from land surface to about 2,400 feet below sea level (Scott *et al*., 1991). The carbonate St. Marks Formation and the Suwannee Limestone constitute the upper part of the Floridan aquifer system in the study area, and they supply all of the potable ground water used. In the Woodville Karst Plain there are no low-permeability units between land surface and the carbonate aquifer units, so the Floridan aquifer is unconfined (*i.e*., it is at atmospheric pressure) and its potentiometric surface is essentially the elevation of the water table.

Ground-Water Recharge and Discharge

The ultimate source of all recharge to the aquifers in the study area is from precipitation (Davis, 1996). The eastern part of Wakulla County (the Woodville Karst Plain) is classified as a high recharge area to the Floridan aquifer system, with rapid infiltration of rainfall through the thin layer of clean sand that overlies the limestone aquifer, as well as direct recharge through karst solution features, such as sinkholes that breach the overburden (Scott, *et al*., 1991). In addition, large quantities of ground water moves down gradient from adjacent areas, supplying water to Wakulla Springs and the Spring Creek Springs Group.

Discharge from the aquifers is from pumpage, upward leakage and evaporation from lakes that intercept the water table, point-source terrestrial and submarine springs, and diffuse submarine discharge that takes place offshore along the coast. It is probable that undetermined quantities of ground water alternately recharge-discharge through interbasin flow, especially when their locally adjacent potentiometric surfaces fluctuate irregularly due to uneven distribution of rainfall, or during droughts.

SPRING CREEK SPRINGS GROUP

Previous Investigations

Spring Creek is a low-gradient tidal stream in the northwest part of Apalachee Bay (Figure 3). It is aptly named, for there may be as many as 14 large submarine springs in its lower reaches. Rosenau *et al*. (1977) showed the locations of eight springs, and assigned numbers 1 through 8 to them (Figure 3). Figure 4 is an aerial photograph of the study area.

In 1972, 1973, and 1974, the U.S. Geological Survey collected water quality samples and estimated flow rates for the spring group. The results of their investigations were reported by Rosenau *et al*. (1977). On May 30, 1974 the USGS measured aggregate stream flows of about 2,000 cubic feet per second (cfs) (3,096 million gallons per day (mgd)), attributable to the eight springs, and apparently to many other submarine springs thought to exist in the area (Rosenau *et al*., 1977). For comparative purposes, the maximum recorded flow of Wakulla Springs was 1,910 cfs (2,957 mgd) on April 11, 1973 (Rosenau *et al*., 1977).

Woodville Karst Plain Project

The Woodville Karst Plain Project is a continuing program to map the underground conduit systems that link the sinkholes and springs throughout the plain. The project was formally initiated in 1986, although sporadic, uncoordinated, scuba cave diving activities go back to the 1950s. Investigations under the present project are conducted by experienced, certified cave divers, because all of the conduits are flooded year-round. The main thrust has been to find and map, or otherwise prove, direct connections between the up-gradient components of the karst drainage system, starting with Big Dismal Sink in Leon County, and the main down-gradient discharge point, which is thought to be Wakulla Springs.

Physical Descriptions of the Spring Creek Springs Group

Several of these submarine springs were investigated by the Florida Geological Survey in August and September 1995, November 1997, and September 1998, to gather background data on them. Three new springs, not described by Rosenau *et al*. (1977), were located (numbers 9, 10, 11 on Figure 3). Springs 1, 2, 3, and 8 were located by their surface boils, but springs 4, 5, 6, and 7 of Rosenau *et al*. (1977) were not located; their flows may have been too small to create surface boils at the time of these investigations.

Spring Creek and its tributaries meander through low-lying coastal marshes. Stream beds are silt, mud, and mollusk debris. However, at low tide, when the water is clear, fragmented limestone boulders can be seen in places around the rims of the springs' basins, apparently exposed where the springs' discharges scour away the thin sediments.

A Sitek Model HE-203 sonic depth indicator, with a strip-chart recorder, was modified to obtain continuous cross-section profiles of the springs. *(Any use of trade names is for descriptive purposes only and does not imply endorsement by the FGS).* To obtain depth recordings, several boat-runs were made over each spring, from varying directions, in order to get the best quality print-out. Some shallow spot-depths were taken using a lead line. The springs' basins and pools appeared to be relatively symmetrical, varying from broad, shallow bowl-shaped pools to steep-walled, conical shapes, as shown on Figures 5 through 9.

Spring 1 (Spring Creek Rise): It was not possible to obtain a depth profile across Spring 1 due to the enormous amount of discharge, which created so much boiling, surface turbulence that the boat could not be held steady over the spring. The active boil is about 40 to 50 feet in diameter and, in places, can rise nearly a foot above the level of the stream's surface. Rosenau *et al*. (1977) reported its depth as being 100 feet.

During high, onshore tidal surges caused by hurricanes, reversal of flow into Spring 1 has been observed, taking brackish estuarine water and flotsam into the aquifer (pers. comm., Mr. Spears, 1995). The reversal of flow caused by the relatively small amount of increased head over Spring 1's orifice due to hurricane tidal surge indicates that its potentiometric surface is so low that its flow is in tenuous balance with the marine environment. By inference, then, it appears that a change of only a few inches of head on the upland side of the aquifer system can make the difference between discharge from, or recharge to, the local aquifer system supplying the springs. The same thing could happen if the springs are exploited and pumped to such an extent that salt-water intrusion is induced.

Spring 2: This spring's basin is about 75-feet across. A small canal extends to the northeast, and a narrow channel on its southeastern side connects to Spring 3. This spring has the largest and deepest basin of any measured during this investigation. Approaching the pool from any direction the floor falls away precipitously, dropping to 90-feet deep or more. Based on the sizes of the surface boil and the pool, this spring may rival Spring 1 in magnitude of flow.

Spring 3: This spring's pool is circular, about 50 feet in diameter, and its pool floor drops precipitously to about 40-feet deep. Crumbling concrete and cement-block walls outline its southeastern side. These walls enclose what appears to be a very shallow, rectangular, wading pool, possibly the remnants of an old spa or hotel, which no longer exists.

Spring 8: This spring's basin is about 80 feet in diameter, resembling a shallow bowl in cross section, whose bottom slopes gradually to about 30-feet deep, then drops steeply to 45-feet deep. Although not as deep as Spring 2, it appears to have a large flow, since its surface boil was about as large and as turbulent as that of Spring 2.

Spring 9: This spring was located by a surface boil that was about 30 feet in diameter in the channel of Spring Creek, several hundred feet to the southwest of Spring 1. Its basin appears to have a symmetrical cone shape, with a depth of about 30 feet. The size and turbulence of its surface boil indicates a large flow. It was the only spring observed to be discharging muddy water.

Spring 10: The basin of this spring is circular, about 75 feet in diameter, with a narrow canal entering its northern side. The pool has a gently sloping bottom that drops steeply to 45-feet deep. As with Spring 8, the large, turbulent boil indicated considerable flow.

Spring 11: This spring was located by a surface boil that was about 30 feet in diameter in the channel of Spring Creek, several hundred feet to the southwest of Spring 10. Its pool resembles that of Spring 9, although not as deep. The size and activity of its boil indicates significant flow.

Pulsating Flow

All the springs were observed to exhibit pulsating flow, a phenomenon characterized by alternating surges of boiling surface turbulence, followed by relatively quiescent flow. Each phase could take as long as a minute or more to complete. Some of the more active boiling phases had noisy, splashing turbulence, that was created by what appeared to be large bubbles of water that suddenly erupted upward above the stream surface.

A possible explanation for this phenomenon may lie in the spring group's underground karst drainage system. It seems reasonable to assume that the springs are fed by a complex, even tortuous, interconnected network of large-diameter tunnels, similar to those supplying Wakulla Springs (Stone, 1989; Rupert, 1988; Rosenau *et al*., 1977), which lies only 10 miles north on the Woodville Karst Plain. Scuba divers have established that some of Wakulla Springs' largest conduits' flows change direction, and that their local source of water also changes (George Irvine, Director, Woodville Karst Plain Project, pers. comm., March, 1998).

These phenomena are controlled by the state of Wakulla Springs' local potentiometric surface. Large rains over Wakulla Springs' recharge basin can change its potentiometric surface so that ground water is routed differently within the underground drainage system supplying the springs. A change of only a foot or two in the potentiometric surface in various parts of the recharge basin can change both the direction of flow and the source of ground water supplying individual conduits. This balance of recharge-discharge routing within the underground drainage system is so sensitive to changes in head that it also appears to be influenced by tidal effects on the springs (George Irvine, pers. comm., 1998). The water surface of Wakulla Springs' main pool is less than five feet above sea level, and the Wakulla River is tidally influenced at least as far upstream as the bridge at US 319, about two-miles below the springs, and possibly even further upstream to the spring-head, itself.

Given that the Spring Creek Springs Group probably has a similar maze-like "plumbing" system, it is easy to visualize how enormous quantities of water, moving rapidly and turbulently through the conduits, could create blockages and pressure surges that would propagate through the system. In this scenario, a tunnel feeding a particular spring that had a pressure surge would momentarily get more of the system's water, resulting in an increase in its discharge. That surge would relieve pressure in that part of the system and the spring's discharge would decrease; then another tunnel would experience an increase in pressure, causing a pulse of water to its orifice; and so on.

SUMMARY

The geological element that controls or greatly influences most of Florida's coastal environments and ecosystems is the karstified limestone that underlies the state. These karstified limestones form a common, unifying linkage among the uplands, the coastal and estuarine environments, and the continental shelf marine realms; they link the terrestrial environments to the marine environments. Submarine springs discharging large quantities of terrestrial ground water can have profound affects on the estuarine, marsh, or littoral environments they discharge into. For example, significant effects on salinity will determine the marine biota that can live in the local area affected by the springs' discharges.

Empirical evidence indicates that the spring group's flow regime is in precarious balance with the local water table's potentiometric surface. When water in the creek rises approximately two or more feet above low tide some of the springs, at least, appear to stop flowing or they exhibit reversal of flow. Such a situation argues against the use of the springs as a source for large-scale withdrawals of fresh water, as has been suggested recently. Heavy pumpage of the springs' source water from the local water table would probably induce rapid infiltration of brackish creek water into the aquifer.

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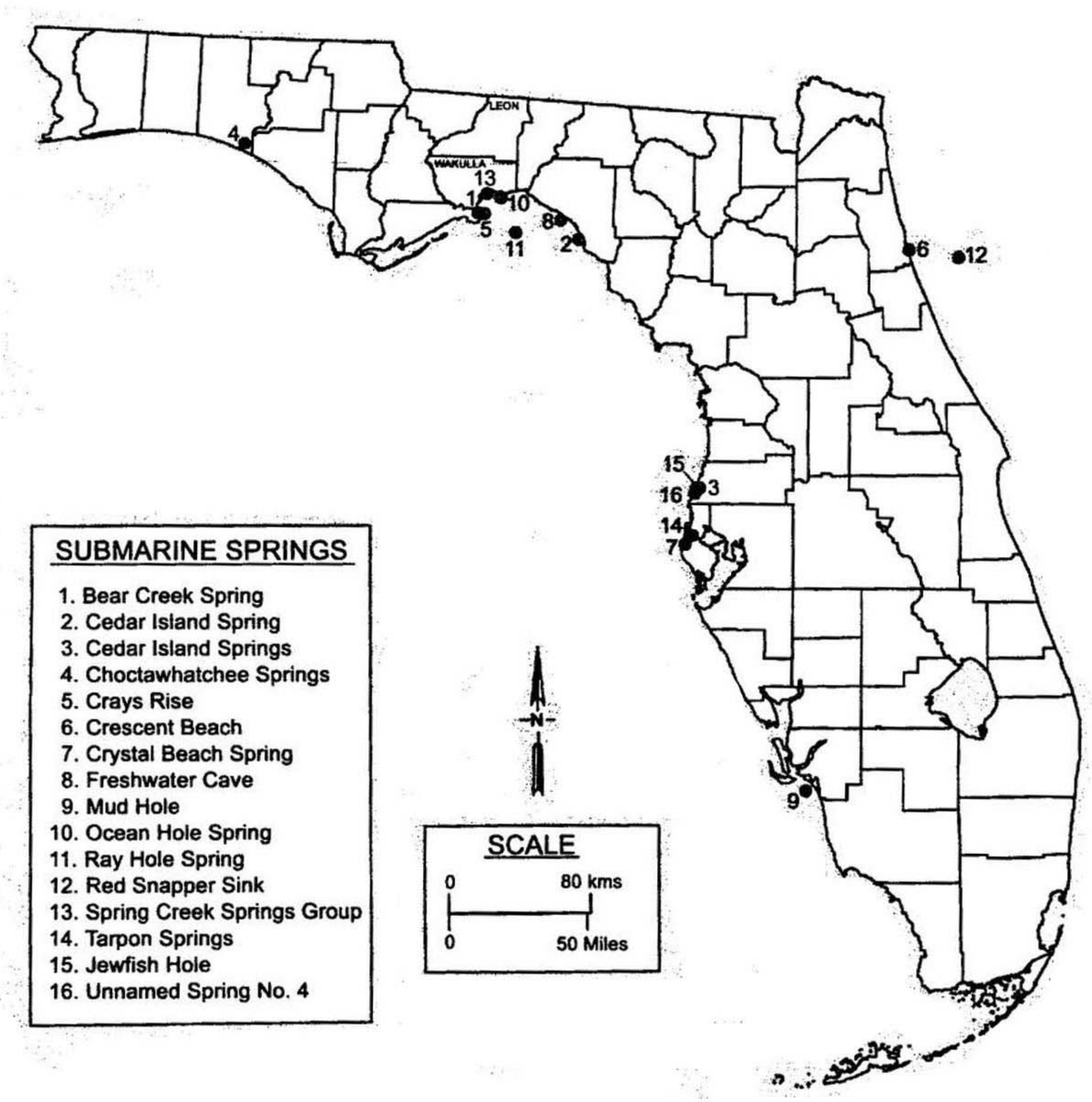


Figure 1. Map of Florida showing locations of 16 submarine springs described by Rosenau et al. (1977). Study area is at No. 13, Spring Creek Springs.

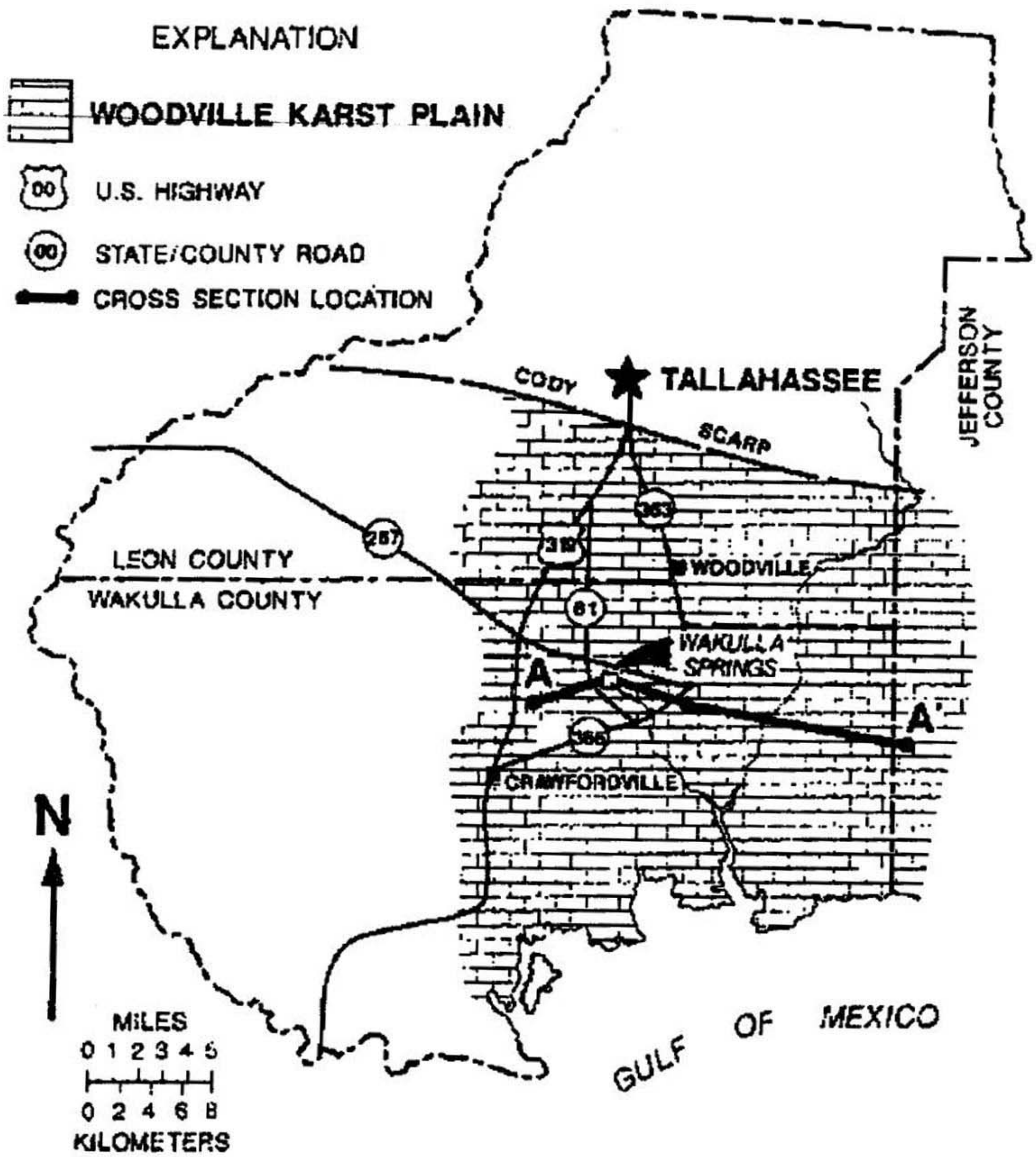


Figure 2. Map of Leon and Wakulla Counties showing extent of the Woodville Karst Plain (after Rupert, 1988)

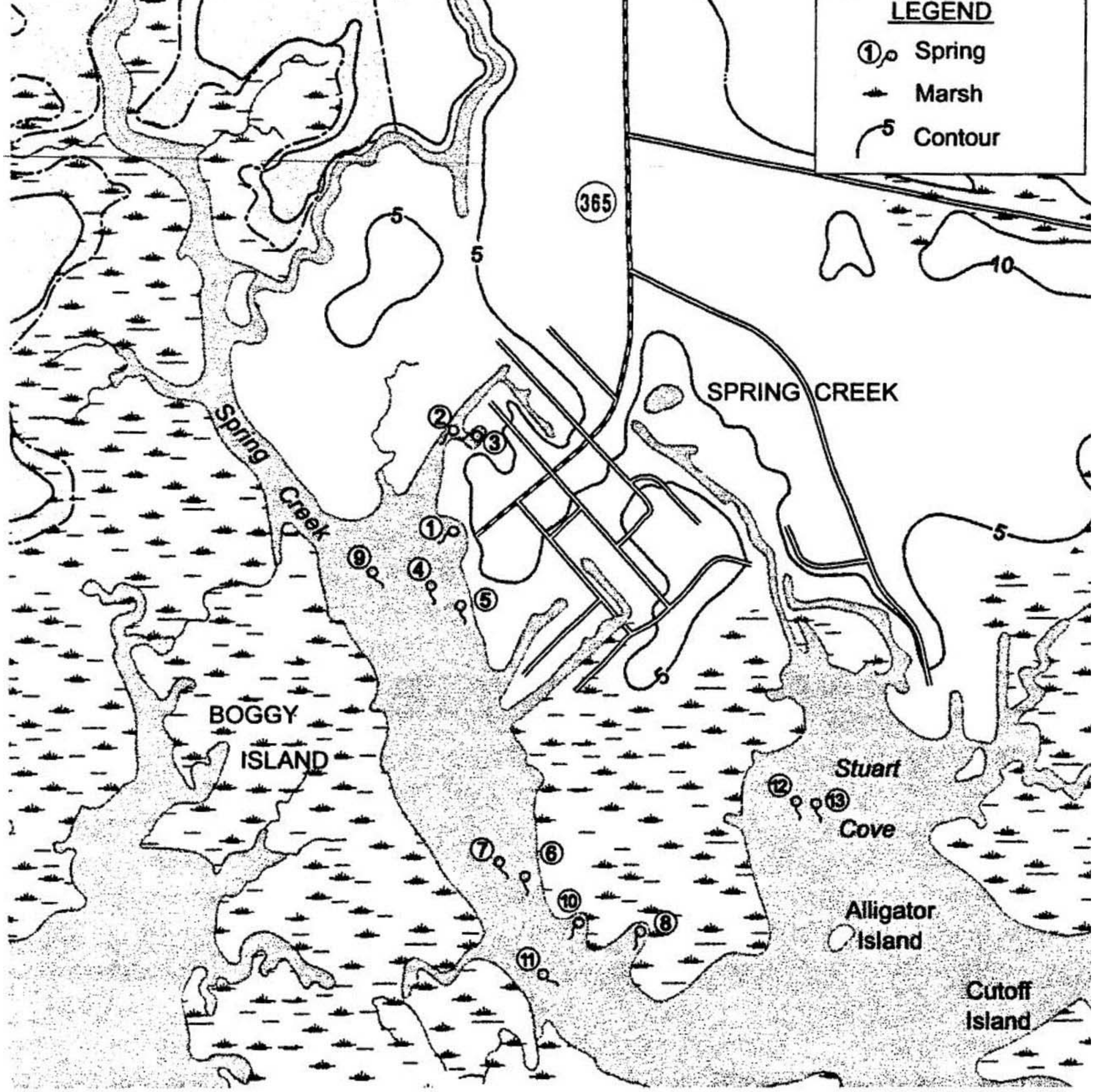


Figure 3. Map of locations of the numbered springs of the Spring Creek Springs Group.

Figure 4. Northeasterly oblique aerial view of the Spring Creek area from an altitude of 1,000 feet, October 1998 (FGS photograph).

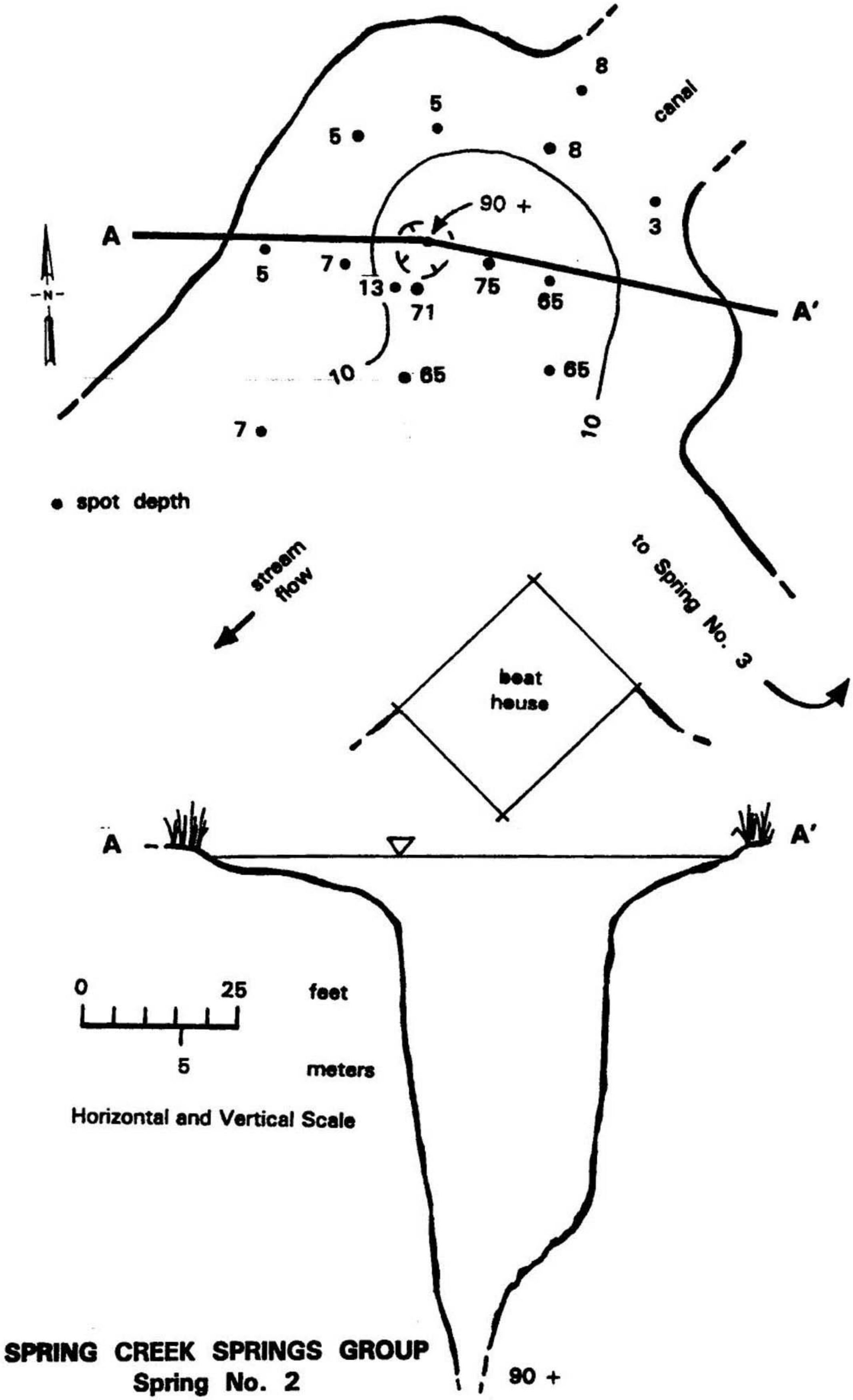


Figure 5. Plan and cross section of Spring 2.

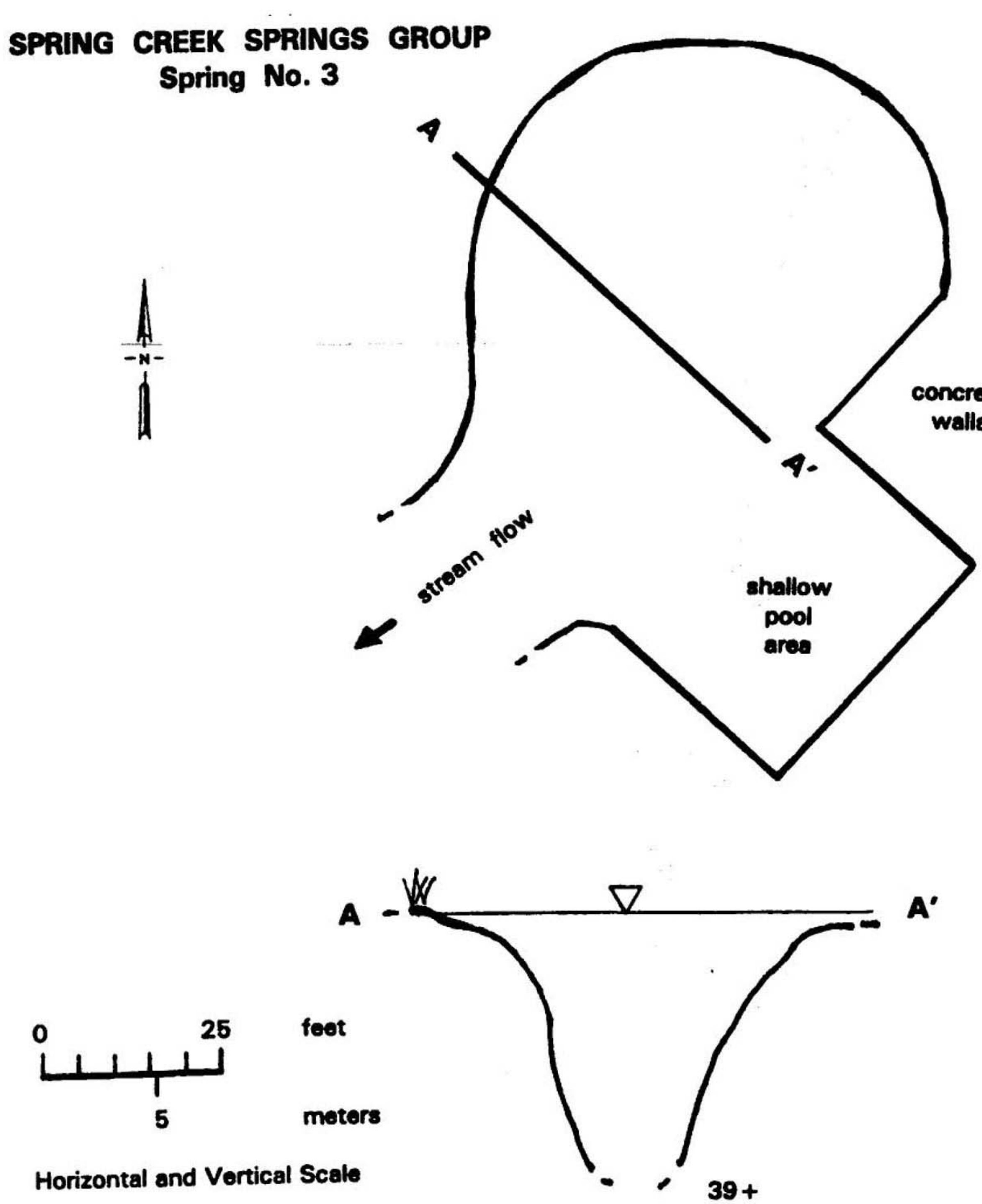


Figure 6. Plan and cross section of Spring 3.

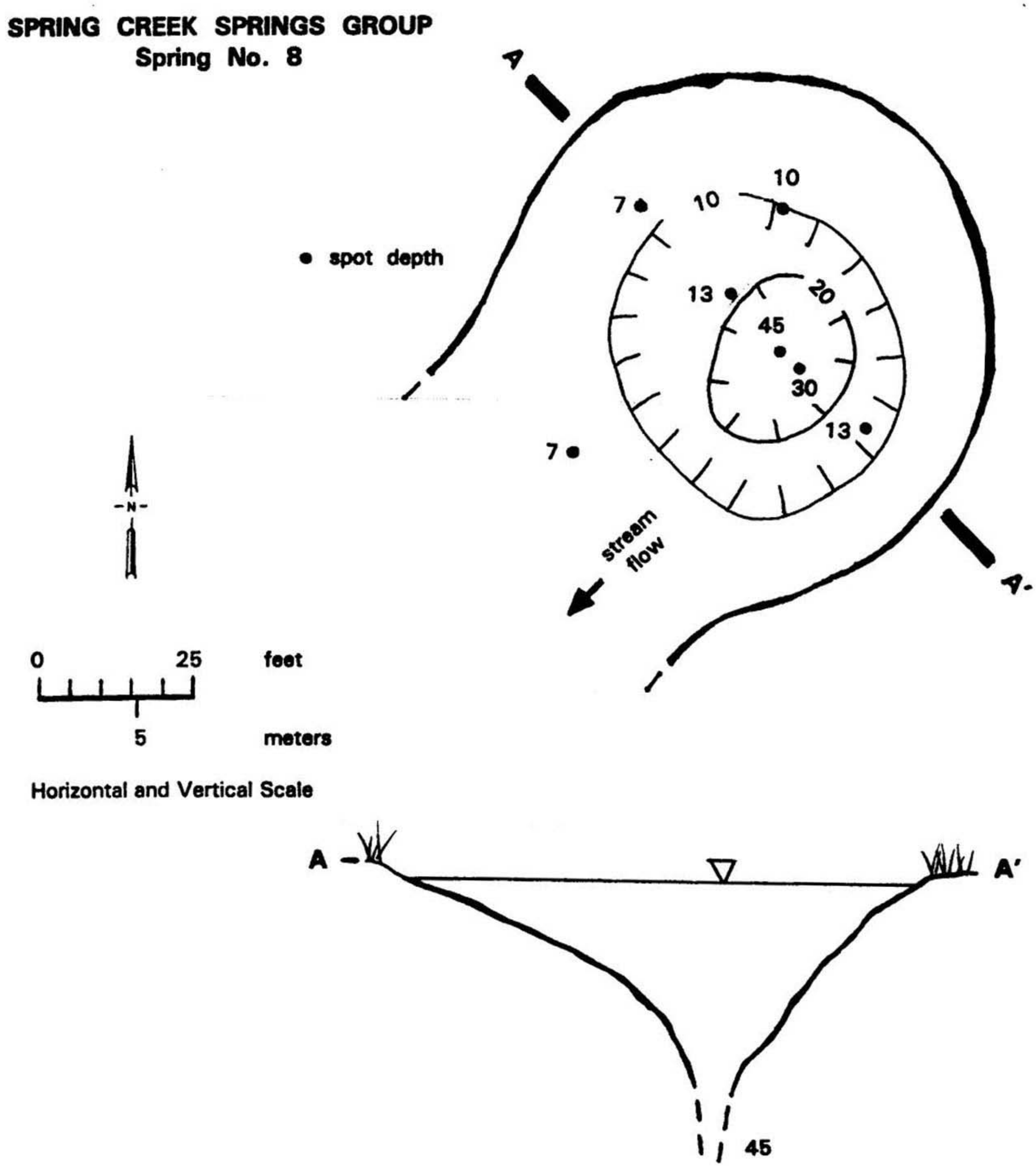
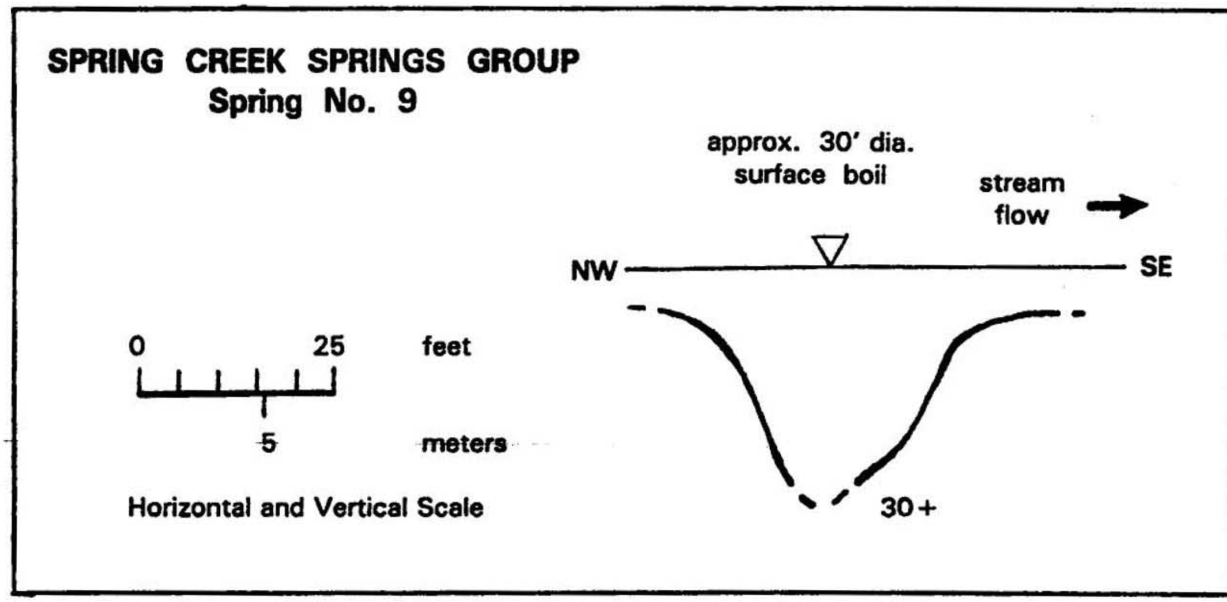


Figure 7. Plan and cross section of Spring 8.



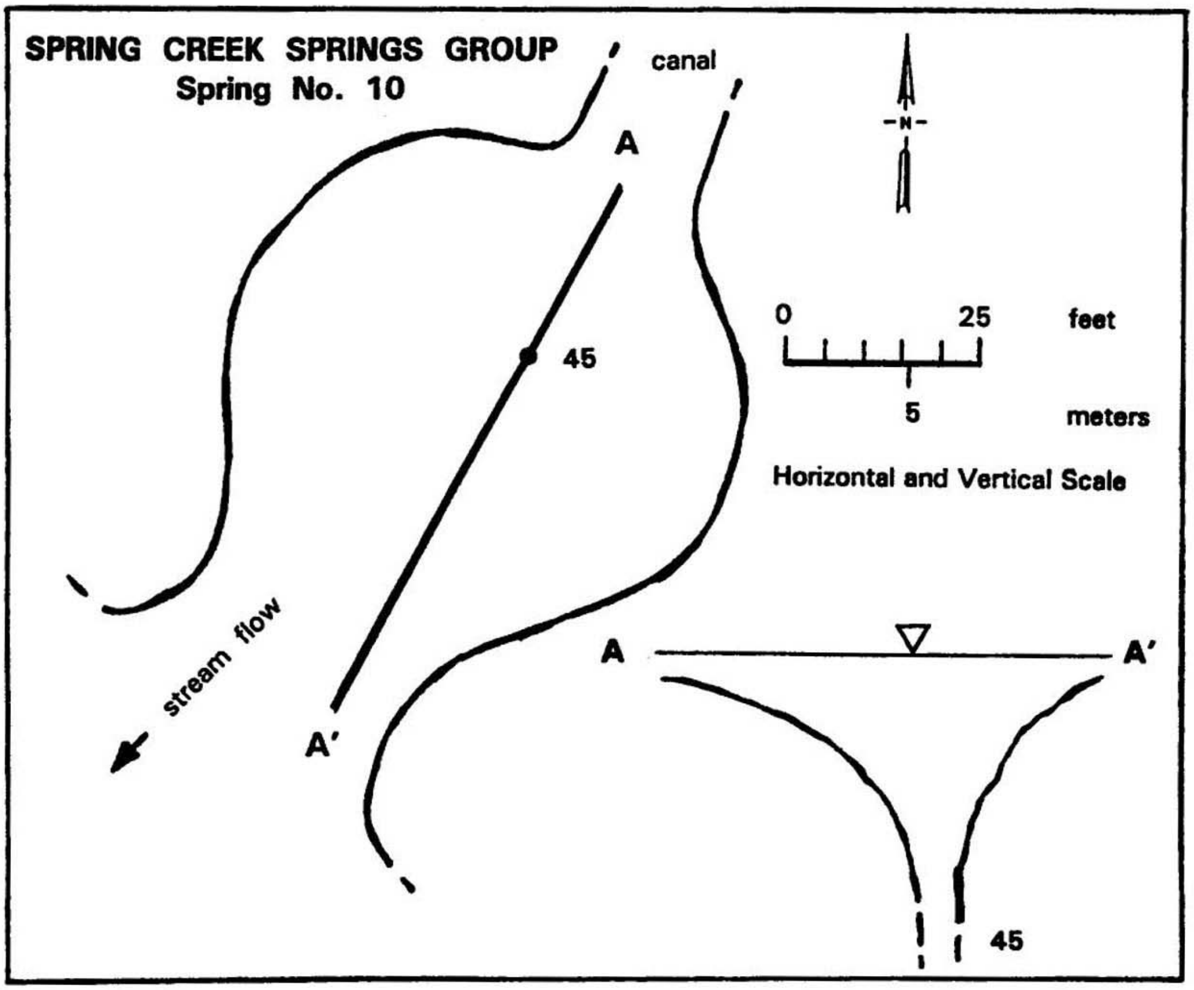


Figure 8. Cross section of Spring 9 (in main channel of Spring Creek), and plan and cross section of Spring 10.

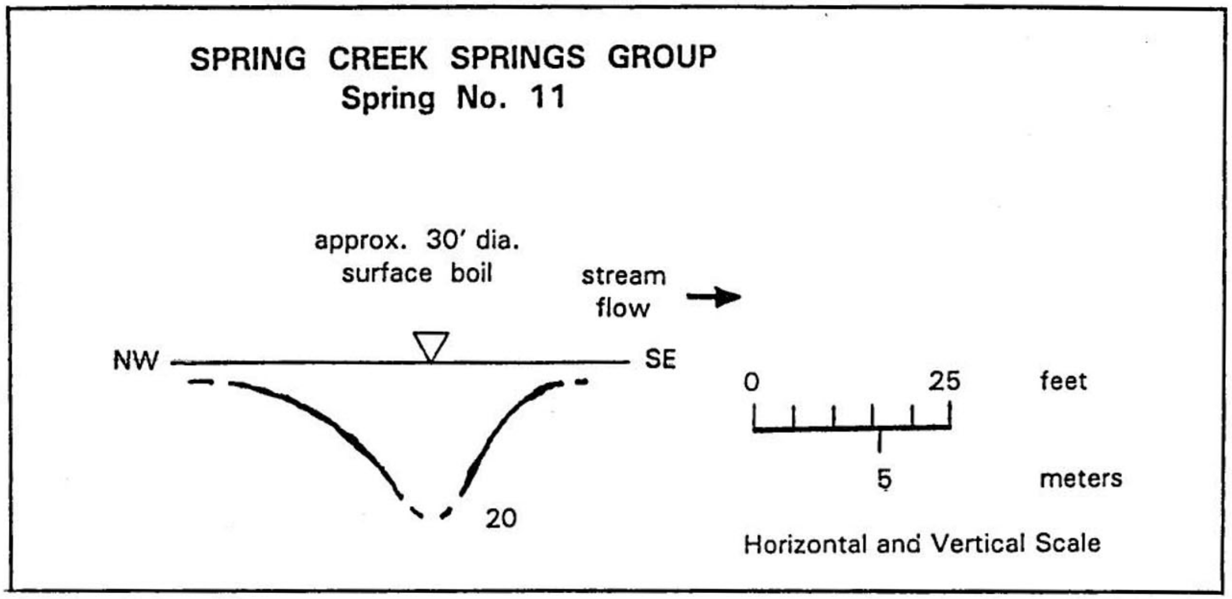


Figure 9. Cross section of Spring 11, in main channel of Spring Creek.

RESTORATION OF THE FLORIDAN AQUIFER TO POTABLE CONDITIONS, ST. MARKS PENINSULA, ST. MARKS, FLORIDA

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ABSTRACT

In the late 1950's the City of Tallahassee began withdrawing ground water as a source of make-up cooling water for a small electric generating station located in the St. Marks peninsula, Wakulla County, Florida. The peninsula is formed by the meeting of the St. Marks River (east) and the Wakulla River (west). Both of these rivers serve as a discharge line for the Floridan aquifer as noted by the numerous seeps and springs observed along their banks.

The earliest wells, located near the St. Marks River, initially supplied abundant quantities of good quality water for cooling purposes. After a few seasons of pumping it was observed that the water quality had deteriorated in the wells located nearest the St. Marks River. Additionally, wells were drilled away from the river and northward towards the mainland. Located approximately 800 feet apart this practive continued until nine (9) wells had been drilled of which seven (7) had been abandoned due to deterioration in water quality.

In 1995 a study was initiated to determine how the city should proceed to secure a good quantity of good quality water on the peninsula, however it was necessary to implement a resource management plan to spread the pumping stress over a larger area. This was accomplished primarily by alternating the pumping on a weekly basis between two sets of wells to minimize upcoming of poorer quality water from lower depths in the aquifer.

Three formerly abandoned wells were redeveloped, geophysically logged and pump tested. From these tests a decision was made to plug back a portion of the open borehole. As a result, no new wells were needed to attain the quantities or groundwater required under current operating conditions.

The St. Marks Peninsula is located in the Florida Panhandle approximately 20 miles south of Tallahassee (Figure 1). The peninsula is a triangular-shaped area formed by the convergence of the Wakulla River on the west and St. Marks River on the east. The Gulf of Mexico is located about two miles south of the convergence of the rivers. The peninsula is a low-lying sandy area underlain by the St. Marks Limestone at a depth of generally less than 10 feet. The St. Marks Limestone crops out along the river banks and can be seen in both river beds.

Discharge of ground water from the Floridan Aquifer (St. Marks Limestone) occurs throughout the area from numerous springs and seeps in the river beds. Although millions of gallons of fresh water per day discharge from this area through the river systems, the ground water quality deteriorates rapidly with depth. The sources of the *poor quality* water are deeper waters of poorer quality and water from the toe of the saline wedge underlying the peninsula.

In the late 1950s, the City of Tallahassee began withdrawing ground water as a source of make-up cooling water for a small electric generating station located in the St. Marks Peninsula.

The earliest wells, located near the St. Marks River, initially supplied abundant quantities of good quality water for cooling purposes. After a few seasons of pumping, it was observed that the water quality had deteriorated in the wells located nearest the St. Marks River. Additionally, wells had been drilled away from the river and northward towards the mainland. This practice continued until nine (9) wells, located approximately 800 feet apart had been drilled. Seven (7) of these wells have been abandoned due to deterioration in water quality (Figure 2).

The wells typically had 50 to 100 feet of casing, with an additional 50 to 100 feet of open hole section in the limestone. Many of the wells were completed open hole at 150 to 200 feet, near the interface of *poor quality* water. The fresh-brackish interface is deepest near the center of the peninsula and *shallowest* near the rivers.

The life of the well, (the time at which an individual well's water quality would deteriorate) would depend upon proximity to the river, total depth, and rate at which the wells were pumped. Pumping rates generally ranged from 200 to 500 gallons per minute (gpm). However, the wells generally pumped continuously 24 hours a day to supply make-up water for the power plant's boilers.

The life of the wells ranged from one year to nearly ten years. Wells 1, 2, and 3 were drilled from the edge of the St. Marks River, westward towards the center of the peninsula, where a power line extended northward along the water edge of the peninsula.

Distances between the wells were generally 500 to 800 feet.

In 1995, a study was commissioned by the City of Tallahassee to locate a long-term source of ground water for the electric generating facility. During the gathering of data for the abandonment of the existing wells, it was determined that the lower section of the abandoned wells was fresh (i.e., the wells had been restored to predevelopment conditions). It was then theorized that wells had been over-pumped, and the poorer quality water at depth had been drawn to the wells.

Since the water quality in the wells appeared to have returned to prepumping conditions, variable rate pumping tests were conducted to assess the safe yield of the wells in the peninsula. It was reported that pumping the wells continuously in the 300 to 500 gpm range was exceeding the safe yield for the area. Pumping test data were modeled and evaluated for long-term safe yield pumping rates. Specific capacities measured in eight (8) wells on the peninsula ranged from 9 to 78 gpm/feet of drawdown, with most of the wells in the 15 to 27 gpm/feet of drawdown range. Transmissivities generally ranged from 33,000 to 59,000 gallons per day/feet.

Step drawdown tests were conducted for this study on abandoned Wells 6 and 7. Prior to running the pumping tests, borehole geophysical logs were run on Wells 3, 4, 5, 6, and 7 to determine construction specifications and water quality in each well.

Water quality parameters (chlorides and specific conductance) were monitored for changes during each of the pumping steps. Only a slight degradation of water quality was detected in Well 7. Based on the borehole geophysical logs and pumping tests, it was decided to plug the lower portion of the open hole from 213 to 150 feet to help assure the poorer quality water from the lower depths would not be drawn to the producing zone of the well.

Although water quality results are not well documented, it appears the background water quality for most of the peninsula is in the range of <5 to 10 for chloride, 300 to 350 μmhos for specific conductance. Water quality was measured in Well 9 in 1994, with chlorides at 101 mg/L and specific conductance at 782 μmhos.

Safe yield was determined to be in the range of 300 to 400 gpm at a continuous pumping rate. However, other factors affected these figures, particularly distance and rate of pumping of other wells in the area and precipitation conditions which recharge the Floridan in this area.

Based on the pumping tests, it was recommended that:

- Four wells would function as supply wells for the power plant (Wells 6, 7, 8, and 9), with only even or odd wells pumping at the same time in order to maximize the distance between pumping centers.
- Wells would be equipped with four identical submergible pumps which would be capable of pumping only 150 to 175 gpm at the wellhead under pressure conditions (two miles of pipeline plus 80 feet of elevated storage).
- Wells would be controlled by radio telemetry to *turn off* once the elevated tank read full conditions.
- Pumping would be rotated between the even and odd pairs on a daily (minimum) to weekly (maximum) time interval.

All recommendations were adapted and implemented in late 1994. The latest water quality data available (late 1998) indicate that the quality is very similar to background water quality for the area, without any sign of deterioration.

A substantial cost savings was realized by not drilling new wells and laying additional pipeline. A considerable cost savings from the limited use of chemicals to demineralize the water was also realized, not to mention the improvement of the water quality in the Floridan aquifer through the peninsula for other users of the aquifer.

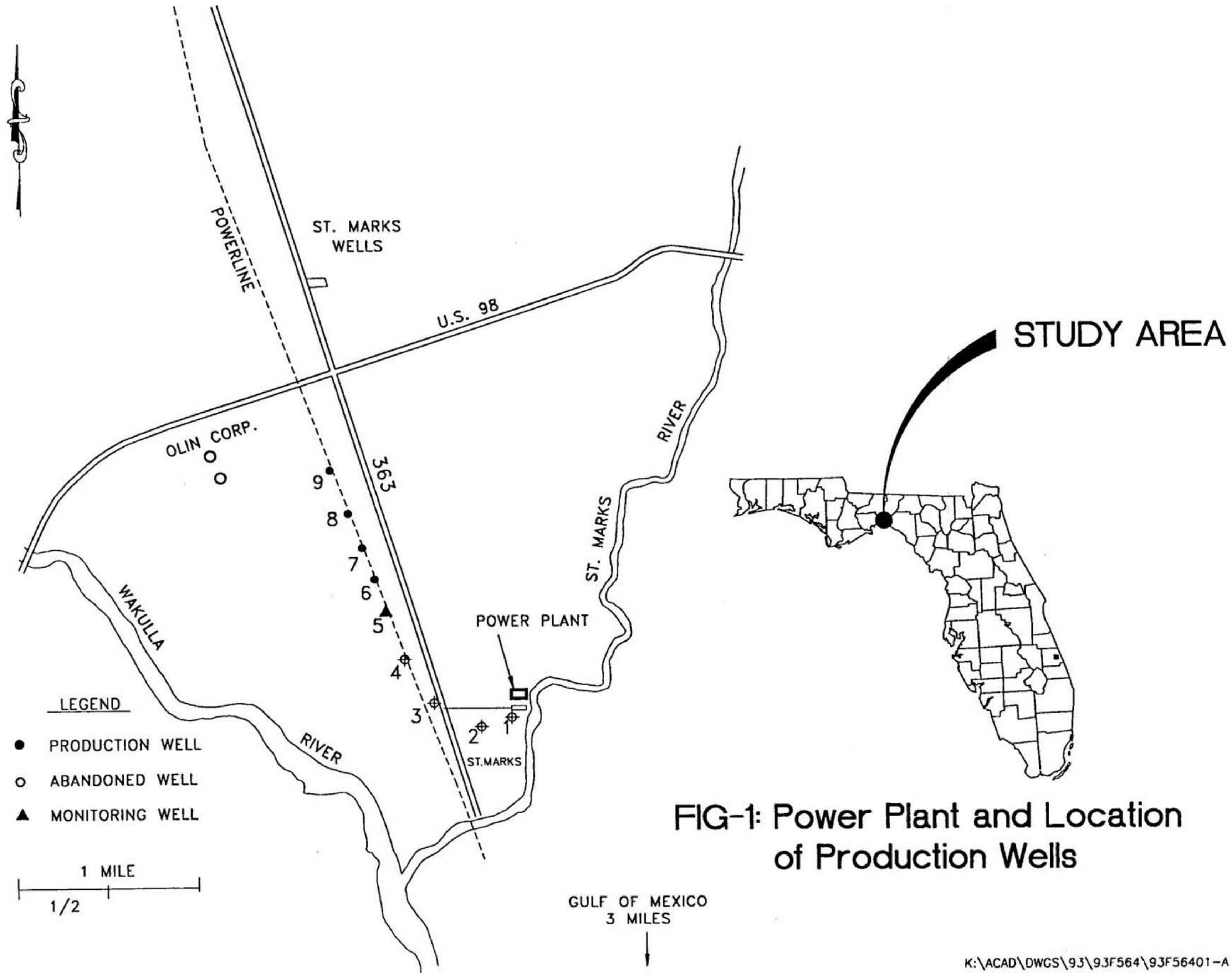

FIG-1: Power Plant and Location of Production Wells

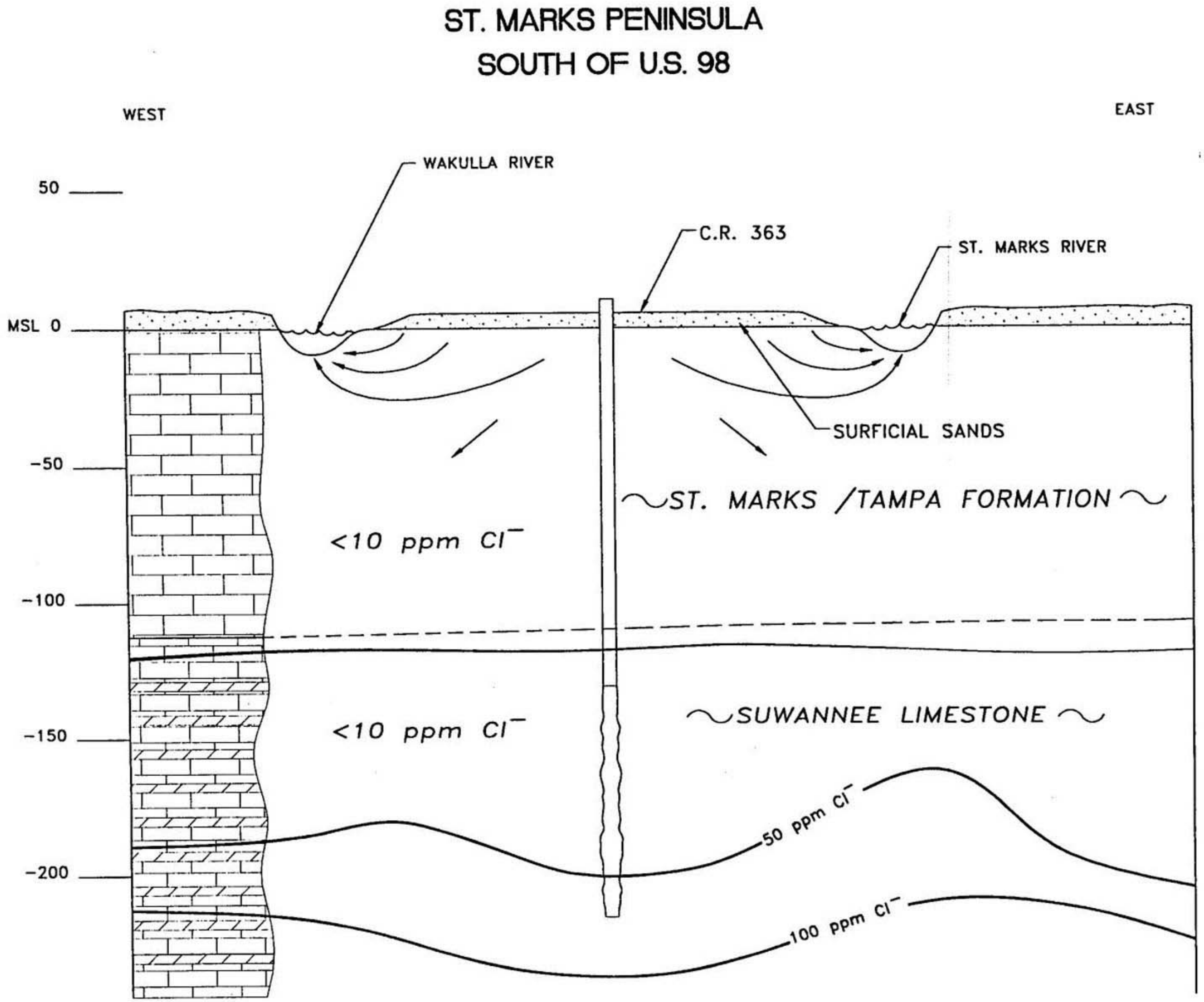

FIG-2: HYDROGEOLOGIC CROSS-SECTION THROUGH ST. MARKS PENINSULA

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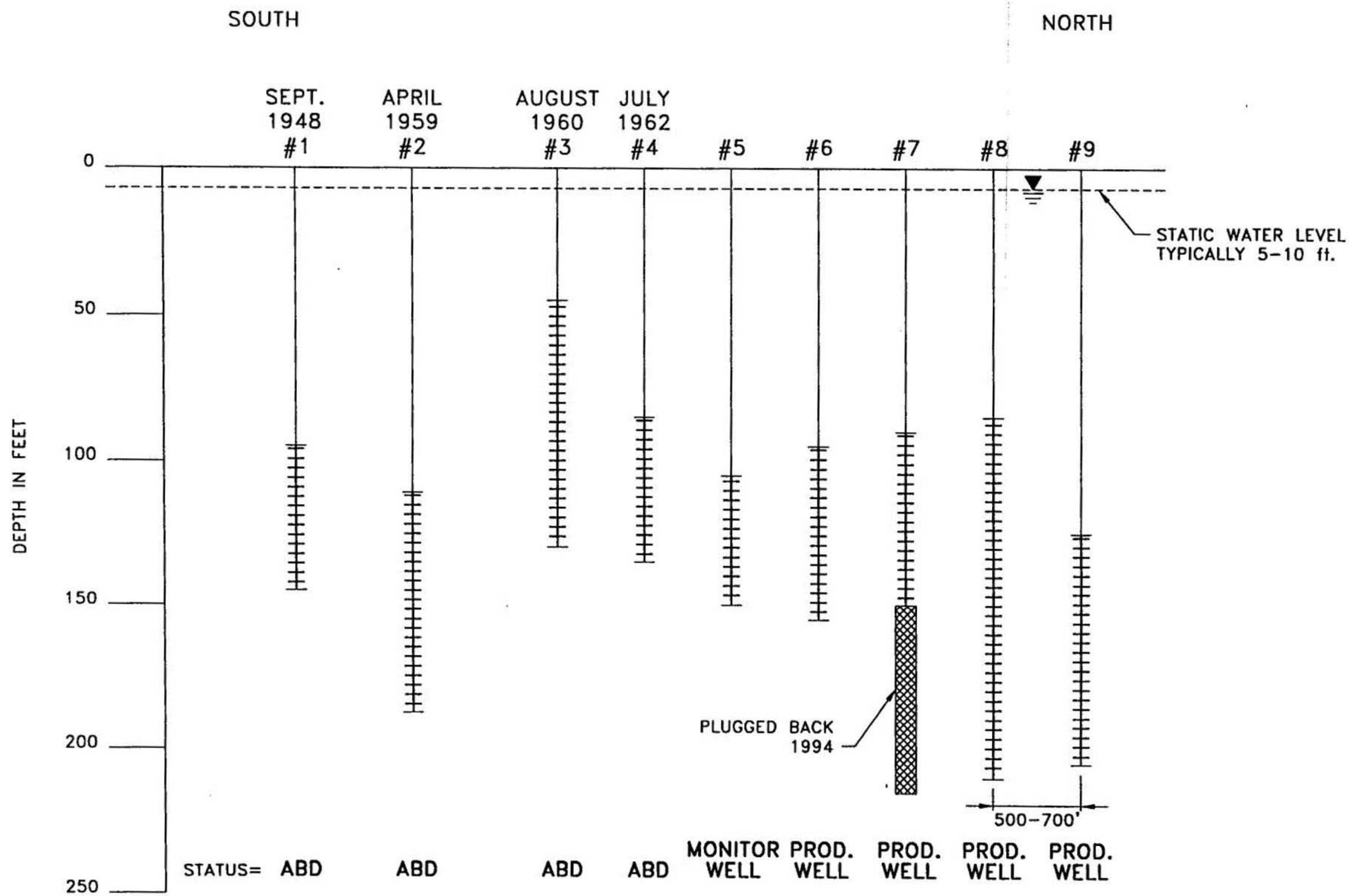

FIG-3: PROFILE OF PRODUCTION WELL CONSTRUCTION SPECIFICATIONS

K:\CDRIVE\DWG\JOB\93F564\WELLS

ST. MARKS RIVER WATERSHED SURFACE WATER IMPROVEMENT AND MANAGEMENT (SWIM) PROGRAM

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ABSTRACT

The St. Marks River watershed covers approximately 1,170 square miles extending from Thomas County in the red clay hills region of southern Georgia to the Gulf of Mexico. The watershed includes the St. Marks River, its major tributary the Wakulla River, Apalachee Bay, and lakes Miccosukee, Lafayette, and Munson. In May 1997 the NWFWMD completed the first SWIM Plan for the St. Marks River Watershed in accordance with the SWIM Act, which was enacted by the Florida Legislature in 1987 and amended in 1989.

The St. Marks River Watershed SWIM Plan was developed in cooperation with the St. Marks River Technical Advisory Committee (TAC), made up of representatives from various jurisdictions in the watershed, resource management agencies, and other technical experts. The plan addresses priority issues identified by the TAC (water quality, land use, pollution, environmental factors, and public awareness) through four programs: Watershed Management, Biological Concerns, Water Quality, and Public Awareness. Each of the programs has a set of goals, issues, and objectives to guide its implemention as well as a number of projects that have been identified to address specific issues.

The following St. Marks River SWIM Plan Projects are either currently underway or scheduled to commence during Fiscal Year 1999-2000:

1. *Planning and Coordination - This project includes coordination of the TAC; coordination with the DEP Ecosystem Management Team, other agencies, and local governments; general program oversight; project tracking and administration; monitoring or relevant planning and development activities within the watershed; efforts to supplement SWIM funding through grants.*
2. *Land Use/Land Cover Mapping for the Entire Watershed - This project entails analysis of detailed land use and land cover information for the watershed. Tasks will include obtaining existing land use and cover data from DEP and developing map layers and watershed specific acreage tables using Geographic Information System (GIS). A watershed future land use map will be developed using local government comprehensive plan future land use maps. A general environmental land use assessment will be developed, considering historic change and potential future development, as they relate to water resources and various government jurisdictions.*
3. *Baseline Biological and Water Quality Assessment and Monitoring - This project will provide comprehensive water quality, sediment, and biological assessments of sites in the St. Marks River Basin. Monitoring will be concentrated in the lower basin, with a few upper basin sites at locations suspected to have a significant, direct influence on water quality in the lower basin. In order to estimate pollutant loadings, flows will be measured at selected tributaries, and in the main channel.*
4. *Inventory of On-Site Sewage Disposal Systems (OSDS) - This project will determine the number and location of on-site sewage disposal systems (OSDS) within the Woodville Karst Plain portion of the St. Marks River Watershed. GIS coverages representing the spatial distribution of septic tanks in the study area and estimates of nitrate load from OSDS will be used in the following SWIM project.*
5. *Examination and Prediction of Nitrate Flux through the Surface Water-Ground Water System in the Wakulla Karst Plain - This project will identify the dominant hydrochemical processes that control the movement and fate of nitrate in shallow and deep parts of the ground water flow system in the Woodville Karst Plain. At present, a network of wells is being established to provide for ground water sampling and water level data collection.*
6. *Public Education and Awareness - Public education and awareness initiatives will focus on informing area residents and tourists of all ages about the significance of local habitats, natural resources and unique geological characteristics such as the area's karst features. These efforts will address issues such as: the proper use and maintenance of on-site disposal systems; the necessity of surface and groundwater protection; the impact of point and nonpoint source pollution; the importance of fostering land and water stewardship; ecosystem management and various environmental concerns related to the St. Marks and Wakulla Rivers and Apalachee Bay.*

FLORIDA'S SWIM PROGRAM

Florida's Surface Water Improvement and Management (SWIM) Act was enacted by the State Legislature in 1987 and amended in 1989. The Act recognized that water quality in many of the state's surface waterbodies is degraded or is in danger of degradation, and directed the state's five water management districts to develop and implement plans to improve water quality and related aspects of threatened surface waters.

Prior to plan development, each district was required to determine which waterbodies were eligible for the SWIM program and then prioritize those waterbodies based upon the need for restoration and preservation. Prioritizing SWIM waterbodies is an iterative task, with review and updating of priority lists required every three years. The current Northwest Florida Water Management District (NWFWMD) SWIM priority list consists of fourteen waterbodies, four of which—Lake Munson, Lake Lafayette, Lake Miccosukee, and St. Marks River—are located within the St. Marks River basin.

The SWIM Act directs the District to develop SWIM plans, in priority order, to include activities, schedules, and budgets for preservation and/or restoration. The Department of Environmental Protection (DEP), Florida Game and Fresh Water Fish Commission (FGFWFC), Department of Agriculture and Consumer Services (DACS), Department of Community Affairs (DCA), and local governments are cooperators in this process. Once developed, the plans are to be reviewed and, if needed, revised a minimum of once every three years.

Currently the SWIM program is funded primarily by legislative appropriation to the Ecosystem Management and Restoration Trust Fund, which is administered by the DEP Office of Water Policy. The NWFWMD is guaranteed at least ten percent of the Fund in any given year, with 50 percent available for statewide discretionary distribution. Funding for the SWIM program has been inconsistent and generally decreasing since its initiation. Annual statewide budgets have ranged from fifteen million dollars in FY 87-88 through FY 89-90 to zero in FY 95-96 and FY 97-98. This situation limits the overall effectiveness of the SWIM program by hindering long-term planning and delaying or precluding project implementation. Project planning and implementation are time-consuming, and monitoring of trends and progress are inherently long-term activities.

NWFWMD SWIM program expenditures include more than SWIM Trust Fund dollars. A twenty percent local match (often divided among local governments and the NWFWMD) is required to secure funds from the SWIM Trust Fund. Additional funding is derived from a variety of sources, including various state and federal granting agencies.

ST. MARKS RIVER WATERSHED SWIM PLAN

The St. Marks River Watershed SWIM Plan was completed in May 1997 (NWFWMD, 1997). The plan's coverage is restricted to those waters in the lower basin that have direct flow connections to the St. Marks or Wakulla rivers. (Three closed or semi-closed basins in the upper watershed—Lake Munson, Lake Lafayette, and Lake Miccosukee—are scheduled for future separate SWIM plans.) The St. Marks River plan is organized into a hierarchy of programs, goals, issues, objectives, and projects. Programs are general categories that have been used to divide the plan into distinct subject areas based upon priority issues identified for the watershed by the Technical Advisory Committee (TAC). The St. Marks River TAC is made up of representatives of the various jurisdictions in the watershed, resource management agencies, and other technical experts. The TAC should play an integral role in the development and implementation of the SWIM plan by providing a forum for agency and technical review and input. An active TAC also helps maintain other agency and jurisdiction commitments to watershed management. The St. Marks River Watershed TAC is a joint committee serving the DEP Ecosystem Management Program as well as the SWIM program.

The plan addresses the priority issues (water quality, land use, pollution, environmental factors, and public awareness) through the following four programs: Watershed Management Program, Biological Concerns Program, Water Quality Program, and Public Awareness Program. Each of the programs has a set of goals, issues, and objectives to guide its implementation as well as projects. The program goals are broad based, identify ultimate program objectives, and provide the underlying framework for the plan. Under each program a number of projects have been identified to address specific issues.

The four St. Marks River Watershed SWIM Plan programs with their goals, issues, objectives, and projects are described below:

Watershed Management Program

Goal: Provide comprehensive, coordinated management of the watershed in order to preserve and protect the watershed environment.

Issues: Information regarding location of sinkholes, small streams, and various resource features.

Information regarding existing and future land uses for the entire basin and the impact of land uses upon water resources.

Multiple government entities responsible for managing components of the system.

Need to apply existing research and define data gaps for further research to guide management strategies and decisions.

Objectives: Implement and update as necessary a comprehensive plan for the watershed and develop the research necessary to guide the management program.

Projects: **M1–**Administration, Planning and Coordination

M2–Analysis of Permitted Activities

M3–Land Use/Land Cover Mapping for the Entire Watershed

M4–Institutional/Regulatory Assessment

M5–Economic Valuation

Biological Concerns Program

Goal: Conserve and protect the biological resources of the St. Marks and Wakulla rivers and Apalachee Bay ecosystem.

Issues: Estuarine/saltwater resources and environmental conditions of Apalachee Bay.

Biological and water quality information.

Adverse impacts of exotic aquatic plants.

Adverse impacts resulting from proposed oil drilling operations in the Gulf of Mexico.

Identification of specific biological resources and habitat within the basin.

Adverse impacts resulting from water withdrawals.

Objectives: Increase information available about the natural resources of the St. Marks and Wakulla rivers and Apalachee Bay.

Obtain and utilize the information necessary to assess and project changes in the St. Marks and Wakulla rivers and Apalachee Bay system.

Projects: **B1–**Baseline Biological and Water Quality Assessment and Monitoring

B2–Seagrass Mapping, Monitoring, and Restoration

B3–Riverine/Estuarine Ecological Assessment

Water Quality Program

Goal: Maintain or improve current water quality conditions within the St. Marks River watershed.

Issues: Characterize ambient fresh and saltwater quality and water quality trends.

Relationship between surface and ground water in the watershed.

Nonpoint pollution sources.

Cumulative impacts of point and nonpoint sources of pollution.

Potential threat to water quality due to the impacts of various land use activities.

The potential impacts to water quality and habitat from recreation.

Potential adverse impacts of on-site disposal systems (OSDS) on groundwater quality, and the possible resulting impacts on surface waters.

Objectives: Identify and quantify both point and nonpoint sources of pollution in the watershed and develop management strategies that will protect and preserve water quality.

Document water and sediment quality and relate ambient conditions and changes in water quality to specific activities, such as land use, shoreline alteration and nutrient inputs in order to improve the management of the system.

Determine ground and surface water interactions/relationships and identify possible sources of water quality problems.

Projects: **W1–**Point and Nonpoint Source Assessment

W2–Sediment Assessment of the St. Marks River at the City of St. Marks

W3–Development of Total Maximum Daily Loads (TMDLs) and Pollution Load Reduction Goals (PLRGs)

W4–Inventory of On-Site Sewage Disposal Systems (OSDS)

W5–Examination of On-site Sewage Disposal Systems (OSDS) Construction and Maintenance Standards to Determine Effectiveness in Karst Areas

W6–River Users Sanitary Facility Survey

W7–Examination and Prediction of Nitrate Flux Through the Surface Water-Ground Water System in the Wakulla Karst Plain

W8–Evaluation of Surface and Groundwater Pollution Potential Within the St. Marks River watershed

Public Awareness Program

Goal: Promote sustainability of the resources of the St. Marks River watershed by providing for public education opportunities to increase public awareness of the problems and issues associated with the system.

Issues: Lack of public awareness of natural resources within the watershed and human impact upon those resources.

Objective: Improve public awareness about the St. Marks and Wakulla rivers and Apalachee Bay ecosystem through an aggressive public education campaign that informs citizens about basin habitats and natural resources, on-site disposal systems (OSDS), responsible recreational behavior, and responsible land and water stewardship.

Projects: **P1–**Public Education and Awareness

STATUS OF ST. MARKS RIVER WATERSHED SWIM PROJECTS

In addition to project **M1*,*** Administration, Planning and Coordination, which is continuously active throughout the life of the SWIM plan, the following projects have been initiated as of November 1998.

M3–Land Use/Land Cover Mapping.

This project entails analysis of detailed land use and land cover information for the watershed. Tasks include obtaining existing land use and cover data from DEP and developing map layers and watershed specific acreage tables using Geographic Information System (GIS). A watershed future land use map will be produced using local government comprehensive plan future land use maps. A general environmental land use assessment will be developed, considering historic change and potential future development, as they relate to water resources and various government jurisdictions. To date a scope of work has been developed for this project and initial data collection efforts have begun.

B1–Baseline Biological and Water Quality Assessment.

This project is currently in the experimental design/quality assurance plan stage. The project will be similar in concept to a joint DEP/NWFWMD study conducted in the Deer Point Lake watershed in 1990-91 (DEP Biology Section, 1992). Repeated measurements of a broad range of biological and water quality parameters will be performed in order to quantify natural variation in baseline conditions. Approximately fifteen sampling sites will be distributed from the upper reaches of the St. Marks and Wakulla Rivers through Apalachee Bay. Many of these sites will correspond to those selected for a DEP pilot study conducted in 1996 (Singleton et al. 1997). Water quality grab samples (nutrients, dissolved oxygen, pH, conductivity, suspended solids) will be collected monthly, while biological sampling (benthic macroinvertebrates, algae, bacteria) will be done bimonthly for two years. Algal growth assays will be conducted either quarterly or every four months, and 24-hour dissolved oxygen measurements will be done at a subset of sampling stations bimonthly. Sediments will be sampled for nutrients, metals, and petroleum hydrocarbons at the beginning and the end of the study. Sampling is expected to begin in early spring, 1999.

W4–Inventory of On-site Sewage Disposal Systems.

This project involves determining which areas in Leon & Wakulla counties rely on septic tanks, identifying the type of structure occupying each parcel with a septic tank, applying HRS OSDS flow rates according to structure type, and calculating flow rates. GIS coverages will be developed to represent the spatial distribution of septic tanks in the study area. Estimates of nitrate load from OSDS will be used in the following SWIM projects: *Examination of On-Site Disposal Systems Construction and Maintenance Standards to Determine Effectiveness in Karst Area* and *Examination and Prediction of Nitrate Flux Through the Surface and Ground Water System in the Woodville Karst Plain*. Preliminary data gathering efforts have begun and current information sources include: Tallahassee-Leon County, Wakulla County, Talquin Electric, and HRS.

W7–Examination and Prediction of Nitrate Flux

Through the Surface Water-Groundwater System in the Wakulla Karst Plain. This project will identify the dominant hydrochemical processes that control the movement and fate of nitrate in shallow and deep parts of the ground water flow system in the Woodville Karst Plain. At present, a network of wells is being established to provide for ground water sampling and water level data collection. A Quality Assurance Plan for the work has been submitted to FDEP and is awaiting approval. Additionally, the *Inventory of On-site Sewage Disposal Systems Project* is in progress and an order of magnitude ground water budget for the study area has been calculated.

P1–Public Education and Awareness.

Public education and awareness initiatives focus on informing area residents and tourists of all ages about the significance of local habitats, natural resources and unique geological characteristics such as the area's karst features. To accomplish this, the comprehensive educational program will include: a portable educational display about the District and local environmental issues, interagency coordination and general public awareness activities such as special exhibits, media relations, community events and other endeavors. St. Marks River watershed educational display has been featured at the Humantee Festival, Springtime Tallahassee, and the Wakulla Springs Earth Science Fair. Various program issues and needs of existing area public education programs

(Wakulla Springs State Park, Gulf Specimen Marine Lab, FSU Marine Lab, St. Marks Wildlife Refuge) have been identified as well as ways the District can facilitate the education programs currently operating within the watershed.

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STORMWATER CONCERNS AND MANAGEMENT ON THE WOODVILLE KARST PLAIN

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ABSTRACT

Nonpoint sources of pollution are the largest contributor of pollutant loading to be surface and ground water systems of the Woodville Karst Plain. In patricular, urban stormwater runoff from the City of Tallahassee that drains into Lake Munson, along with contributions of runoff that drain into Lake Lafayette are the major sources of pollutant loading to these waters. This talk will present a brief introduction to the stormwater problem but will focus mainly on what actions are being taken, or need to be taken, to minimize stormwater pollution. Current structural improvements planned by the City of Tallahassee and Leon County, along with other suggested improvements will be reviewed.

WATER QUALITY STATUS IN LEON COUNTY, FLORIDA: WHAT'S HAPPENING UPSTREAM...

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ABSTRACT

Leon County and its primary urban complex, the City of Tallahassee, sit atop the clayhill and sandhill covering a vast and dynamic karstic substrata, including, among other things, the southern tip of the Floridan aquifer. Area groundwater discharges include Wakulla Springs and numerous other springs and associated riverine systems of this generally wet natural environment. The past 15 years (or so) of local environmental history has included a recognition of this and other related surface water and ground water quality and quantity phenomena, resulting in considerable research, planning, management and regulation. However, the effectiveness of these efforts remain unclear. While a comprehensive and objective evaluation of effectiveness is well beyond the scope of this talk, if we had to guess, based on what we know now, where are we?

Four reasons come to mind for discussing Leon County's lakes at a Woodville Karst Plain Symposium:

1. the obvious reason is that they are all uphill and that whether by surface connection or ground water connection, or both, there are direct hydrologic connections;
2. what Leon County has learned about the sensitive ecology of these waterbodies is at least generally applicable to the future ecology of the WKP's surface water and ground water habitats;
3. the programmatic and policy history of pain and struggle may be prophetic as the WKP, the coastal marsh belt and the maritime of Apalachee Bay feel the impacts of urbanization; and,
4. perhaps the most frightening reason is that our city and county politicians are developing what is euphemistically referred to as a "south side strategy". Consider a subtle but significant precedent set by the giant Southwood development, portions of this project actually fall south of the Cody Scarp!

From a long-term ecological perspective, Leon County's clayhill, closed-basin lakes give a historic account of the adverse threshold effects of the anthropogenic impacts. In the period following European settlement, a continuous process of land change began, from agriculture, to silviculture and most recently, urban-culture have incrementally altered and re-altered the landscape. Land use intensification facilitated economic development on the one hand, while, in the aggregate, adversely affecting local and regional biogeochemical processes, on the other. As a result, a consistent and increasingly urgent scientific literature has focused on the elimination and decline of many area natural features. Unfortunately, this scientific awareness has yet to effect the full range of necessary remedial actions.

Consider for example, that in the early 1970's, the Florida Division of State Planning published its concerns that increasing urbanization and associated stormwater pollution entering through the Megginnis Arm watershed would eventually lead to degraded lake quality. Since then there have been numerous additional episodes, so many in fact, that from time to time, it has been difficult to tell the random noise from the clear warnings. Unfortunately, Lake Jackson and other Leon County lakes continue to show signs of urban stormwater pollution and associated natural aquatic habitat deterioration.

Lack of follow-through and polarized rhetoric have both confused the picture and served to damper the enactment of effective policy. The problems of the Kissimmee-Okeechobee-Everglades system, well documented by the mid-1970s, led not to corrective measures but to squabbling over who was most to blame and who now has to pay to fix the problem. This discussion has been going on for 25 years. Central Florida's Lake Apopka went hypereutrophic in the 1960s and is still the focus of much fruitless debate. The pollution-induced problems of Apalachicola Bay, with its productive oyster beds and spartina marshes also began to show up in the early 1970s, and so on and so on. Environmental literature around the world is full of similar case studies. Tallahassee-Leon County is not unique in its under-functioning when it comes to being stewards of the natural world.

In fact, this may be part of the problem – that it is the natural world suffering. When people, our money or our property suffer adverse environmental impacts, amazing things happen with incredible speed! A fact of the contemporary world – especially the western, industrialized world – is that most of us are several steps removed from nature, often oblivious to its presence unless the weather is bad, the infrastructure goes out, or worse, both. How many of us actually miss drinking lake water while we swim? How many of us even miss swimming in lakes?

A confusing aspect for the public has been the frequent arguing among experts. However, what sounds like uncertainty and disagreement – over Lake Jackson's fate, for example – is really semantics – an argument over the adjectives used to describe its condition. Words and phrases like "dying lakes", "sick fish", "toxic algae", and so forth become the focus. There is no real disagreement among experts that stormwater run-off is polluting our lakes.

Another confusing issue is the role of regulation. If we have so many tough environmental regulations, why does surface water quality continue to decline and the list of adverse ecological changes continue to grow larger? The answer lies in what we have <u>not</u> done, which I will discuss in a moment.

Lake impacts began with the early settlers; the biggest hit was probably pre-1960s when, as a part of public policy, most of the creeks, marshes, sloughs and swamps leading to area lakes were ditched, drained, diverted and culverted. Subsequently, the ecology of the entire system was affected. Streams meandering through vegetated floodways and sloughs are nature's way of cleaning water before it enters the receiving waterbody. When streams are eliminated, the problem-causing sediments, nutrients and other pollutants go right into the lake. The final assault was the placement of non-regulated roads and strip commercial developments upstream of the water bodies. In the Lake Munson Basin, for example, much of the polluted stormwater comes from the pre-ordinance development throughout downtown Tallahassee, the Gaines Street corridor, FSU and FAMU areas, among others. The same is true for Upper Lake Lafayette, where most of eastern Tallahassee drains highly polluted runoff into the ground water.

Lake's Jackson, Lafayette, Munson, Hall and now, Iamonia have, to varying degrees, early signs of adverse ecological changes from stormwater pollution. Not little dead canaries, as the metaphor suggests, but subtle changes in lake ecologies – more frequent and longer lasting algae blooms, turbid water, liquid mud replacing sandy bottoms, invading exotics replacing native plants, nutrient over-enrichment, fish kills and a variety of chemical changes including higher ammonia levels and declining dissolved oxygen and so forth.

However, despite the slow call to arms, some steps have been taken. One victory as noted, are the tough standards that new development are required to meet. However, what we have <u>not done</u> is gone back to retrofit all the already impacted watersheds, bringing them up to current standards of treatment. This water quality retrofit requirement, by the way, is one of many failed promises made to the community in the Tallahassee-Leon County Comprehensive Plan.

This, however, is old news. The state-required Evaluation and Appraisal Report (EAR), lists all the unaddressed objectives, policies and program initiatives of the comprehensive plan. The critical point here is that until we retrofit for water quality treatment, the lakes will continue to decline and as the ecological effects of decline increase from threshold to threshold, the costs of lake restoration will increase exponentially until such undertakings become unaffordable.

Water quality retrofit is not to be confused with flood control; these are two different objectives, although with careful planning and design the same measures can work for both objectives. Pursuing duel design objectives is particularly important given that city flooding inevitably pollutes the downhill county lakes. Unfortunately, up through the present, the city and county have been unable to coordinate resolution of this issue – in spite of agreeing in the comprehensive plan that their regulatory and stormwater management programs should be consolidated, or at the very least, coordinated. (Another failed item mentioned in the EAR Report). In the meantime, the city is moving ahead to improve stormwater conveyances and flood control within its jurisdiction but stonewalling in meeting its environmental responsibility to join the county downhill in lake management. The county on the other hand, still does not have a handle on the extent of the lake problem, how to address it and most importantly, how to pay for it. In this regard, the county has botched several previous efforts to secure appropriate funding. Let us hope that this interjurisdictional squabbling is not a sign of things to come between uphill neighbors of Leon County and Tallahassee and those downhill including Wakulla and Franklin Counties.

This is not to say that no progress has been made in the Leon County lakes issues. There are many examples of good, albeit uncoordinated, water quality management. Some positive examples include the Gum Swamp and Lake Henrietta restorations (Leon County); the Piney-Z restoration (City of Tallahassee); greenway acquisitions whereever floodplains, riparian forests, creeks, ravines and lake shores have been involved; the advances in GIS and watershed planning; stormwater utilities; and the dredging of polluted sediments from the Megginnis Arm of Lake Jackson (Northwest Florida Water Management District), and so forth. However, the problem remains one of lack of a coordinated, informed and aggressive water quality program that takes our science seriously, recognizing the increasing urgency of the matter.

In achieving this, several steps must be taken. <u>First</u>, combine the regulatory and stormwater management programs of the city and county into one holistic group responsible for all elements of the system. <u>Second</u>, develop a water quality retrofit plan for all the currently problematic watersheds (there are probably 25 to 30 of them at this point). Include an inventory and performance evaluation of all the existing treatment facilities, both individual sites and regional ponds, and based on a 3% factor (i.e. a 2,000 acre watershed needs 60 acre-feet of treatment), plan, design, construct, maintain and evaluate all new facilities. Third, buy, beg or trade for all possible wetland, riparian and flood prone areas remaining in critical watersheds. Use long-range, low-cost natural succession to restore these important water quality treatment (and storage) elements. Natural treatment methods are the best in the long run and do not include the expensive operation and maintenance costs of traditional engineered structural methods. Fourth, develop and implement in-lake management restoration programs like regular removal of contaminated sediments and so forth. Fifth, raise a lot more money to pay for these actions and programs. Current stormwater utility rates, like it or not, are way too low to do the job even of current system maintenance. A lake-wetland-floodplain restoration bond initiative, based on the expected costs of plans and programs, is the way to go. While there are numerous other items of significance, these five will make a difference and move us a long way toward healthy lakes and surface waters, as well as protecting future ground water supplies.

The alternative is to let these systems fade away like the Longleaf pine-wire grass prairie forests of the Southeastern Coastal Plain and a million other gone and largely forgotten natural things, people and events. Post-modern urbanism will not miss them; Wakulla Springs and the other crystal clear ground water outflows of the region will live on as case studies for future undergraduate ecology, geology and geography textbooks.

WAKULLA SPRINGS WATER CLARITY MODEL

Paul Z. Lee, Ph.D., P.G., Florida Department of Environmental Protection

As part of the State parks system affiliated to a major academic institution – Florida State University, Wakulla Springs is one kind of gem for the Florida panhandle area, a favorite recreation spot, an internationally reputable resort and professional conference site. The glass bottom boats provide a spectacular view of the springs 180 ft. below the water surface. The water is so clear that you feel you and your boat are floating in space. This certainly inscribes an unforgettable memory on the first time visitors. However, the Tallahassee phone book advises that before you bring your guests from Germany or Ghana to visit the springs, it is better to call the Springs management to find out if the glass bottom boats are in operation. Oftentimes, the boats are inoperable due to the poor clarity of spring water caused by recent storms.

The boat operators and most residents in Tallahassee all know that after a heavy rainfall, chances are that the glass bottom boats have to stop operation. However, the mystery is why in some cases, a single medium size rainfall did not necessarily cause dark water discharge, while in other times, a slight rainfall may cause dark water discharge.

What causes the colored-turbid water to replace the otherwise clear spring water? What are the critical conditions to switch on and switch off such unclear water discharge?

CONCEPTUAL MODEL

The Woodville Karst Plain is a discharge area for the Floridan aquifer in general. Springs, rivers, and surficial aquifers all receive certain amount of discharge from the artesian Floridan aquifer during the days with no significant local rainfall (please see the upward arrows in the diagram (Figure 1) showing channels connecting to the shallow sinks). The Floridan aquifer and the shallower receiving hydraulic units maintain a delicate dynamic balance. In this subtropical area, the surface water and water in sinks may be colored and turbid due to suspended sediment and tannic and humic material from the decaying leaves and plants.

During and after a heavy storm, the stream stage and the water table of the shallow part of the aquifer may reach a point that a reverse flow in the connecting channels may occur. Since Wakulla Springs is located quite close to the sea level, the stage of the Wakulla Springs fluctuates between <6 – 11 ft. MSL, and since the Wakulla Springs has a very high base flow, no reverse flow could possibly happen there. Then the colored turbid back flow water at higher locations of the plain may join the base flow and discharges in some large springs which are located in the downgradient or down stream side of the Woodville Karst Plain.

As a consequence, the Glass Bottom Boats would be out of operation. These days are called glass bottom boat “down days” and recorded by the park.

We notice that the dark water discharge relates not only to the rainfall event, it also is related to the previous rainfalls. If the above mentioned mechanism is correct, then a preliminary high water table before the rainfall event will constitute a condition that the release of dark back flow water to the system would be easier to trigger. By the same token, to trigger a back flow with a low preliminary water table, the rainfall should first fill up the storage space in the shallow part of the aquifer, raise up the local water table, then start the back flow.

We also notice that a larger amount and continuing precipitation events all may cause longer period of down days.

SIMPLIFIED MATHEMATICAL MODEL

Based on the above conceptual model, a simple mathematical model is proposed and calibrated with the limited available data. We only use monthly rainfall data and monthly down days data (Figure 2).

The final simple equation is:

$$0.66{*}R_o+P1-(F_b{*}30)-(F_d{*}Dd_1)=R_1$$

Here, R_o**:** the preliminary remaining water (inches) in the system, or DD-index
P: precipitation of the month (inches
F_b: base flow dischargte (inches/day)
F_d: dark water discharge (inches/day)
Dd_1: dark water discharge duration or down days of glass bottom boat (days)
R_1: remaining water in the system (inches)

The R_1 will be used for the next month calculation as the preliminary water:

$$0.66{*}R_1+P_2-(F_b{*}30)-(F_d{*}Dd_2)=R_2\text{, and so forth.}$$

0.66 is an empirical attenuation coefficient to reduce the influence of rainfalls in the previous month.

Using a spreadsheet, one can calculate the monthly remaining water as the DD-index which is used to predict the extent of possibility of next month’s down days depending on the future rainfall amount.

RESULTS AND EXCUSES

Using this algorithm, the error of the initial condition can be minimized gradually through time. The result (Figure 3) shows that after a period of time (1987 – 1988), there is a close match between the calculated DD-index and the actual Down Days of the following month. In general, when the calculated DD-index rises across the zero line, down days occurred; when the DD-index drops across the zero line, the glass bottom boats start full operation.

Some footnotes may help to defend the validity of this model.

1. The monthly precipitation data is quite crude for such analysis. Raining days may happen in the first part of month, connect to the previous month, spread over a month, concentrate in a very short time (in hours), or connect to the next month. The same situation applies to down days of the glass bottom boats.
2. The supply of colored turbid material is limited. After a long, continuous down period, the material may be depleted or diluted in the system.
3. From May 1994 to June 1996, the cumulative error of the calculation shows a plus 2-3 inches from the zero line, when another three month period of operation follows. This is quite close. This can be explained by footnote 2.
4. There is a huge deviation at the initial stage of the calculation. Data of precipitation did not indicate much rainfall between August 1988 and May 1989.
5. Down days might also be caused by mechanical or personnel problems with the boats.

CONCLUSION

DD-Index of Previous month	**Precipitation of this month (Inches)**		
	5	0 to 5	0 to -5
>5	DM	Partial DM	Few DD
0 to 5	Partial DM	Few DD	Few -no DD
0	Few DD	Few-no DD	No DD
0 to -5	Few to no DD	No DD	No DD

DM =Down Month, DD = Down Days

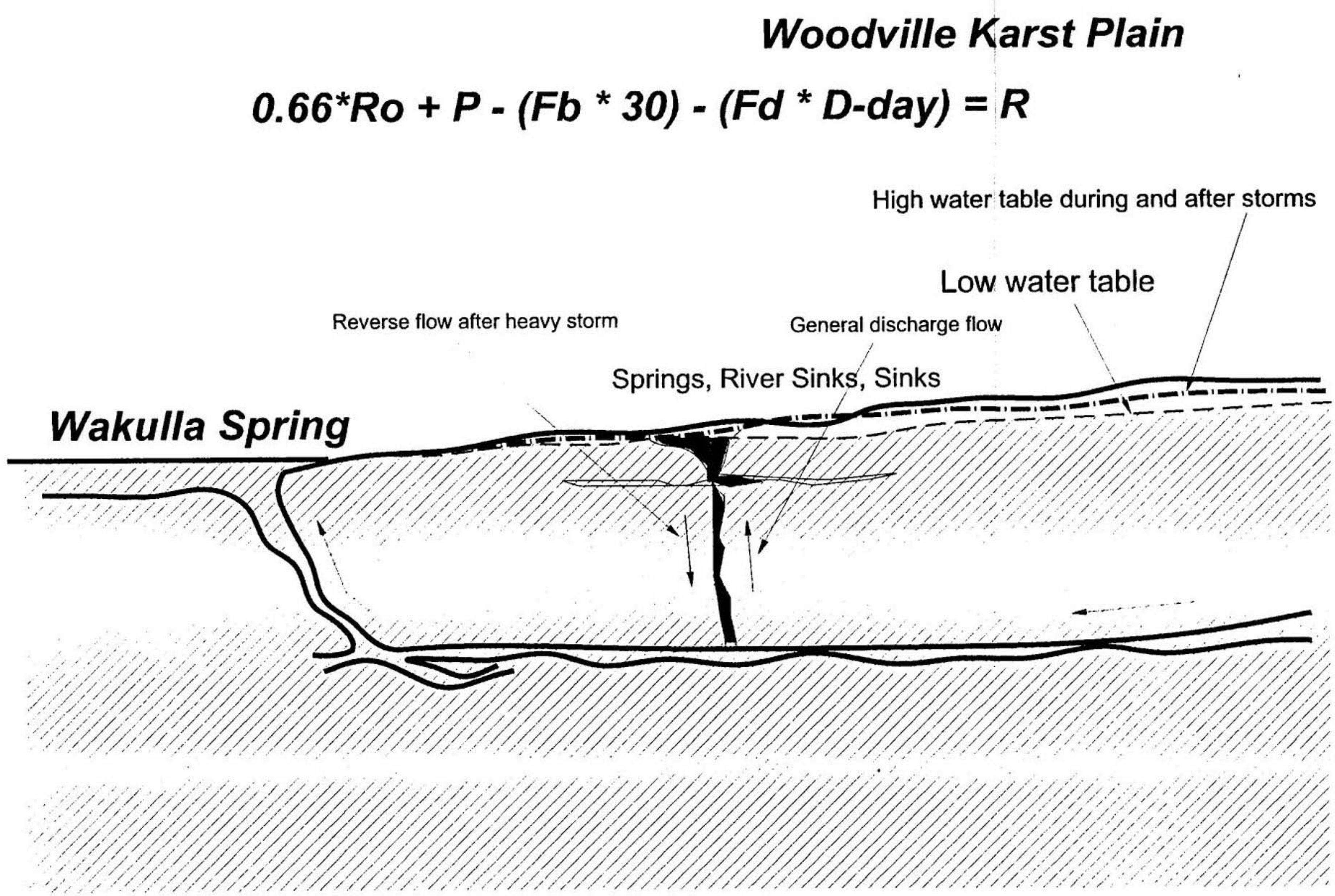

Figure 1. Wakulla Karst Plain Conceptual Flow Model

	0.727	0.0065	year	rpm st	down days	stdev
1			87	6	31	13.99
2			87	6	28	11.22
3			87	9	31	12.51
4			87	8.5	30	4.82
5			87	6	17	5.27
6			87	12	7	11.66
7			87	6	31	9.74
8			87	8	31	11.43
9			87	4	30	7.61
10			87	9	23	1.09
11			87	6	2	2.90
12			87	1	31	-1.13
1			88	3	16	-1.70
2			88	7	17	1.81
3			88	7	31	4.20
4			88	0.5	15	-4.62
5			88	0.5	6	-3.78
6			88	2	5	-4.38
7			88	7	0	0.25
8			88	6	0	2.38
9			88	4	21	1.59
10			88	2	31	-1.01
11			88	4	10	-0.57
12			88	1	15	-3.32
1			89	0.5	18	-5.69
2			89	3	4	-4.65
3			89	4	3	-2.95
4			89	4	4	-1.82
5			89	5	0	-0.03
6			89	17	19	13.01
7			89	6	31	10.64
8			89	6	31	9.06
9			89	5	30	7.00
10			89	3	31	3.62
11			89	4	30	2.38
12			89	5	31	2.51
1			90	3	31	0.61
2			90	7	28	3.38
3			90	3	31	1.18
4			90	3	27	-0.25
5			90	2	0	-1.98
6			90	4	0	-1.14
7			90	3	0	-1.57
8			90	7	0	2.14
9			90	5	0	2.82
10			90	2	0	-0.05
11			90	0.5	0	-3.35
12			90	5	0	-1.05
1			91	19	10	14.40
2			91	1	28	0.60
3			91	13	31	13.35
4			91	6	30	10.90
5			91	10	31	13.22
6			91	6	30	10.79
7			91	10	31	13.16
8			91	4	31	8.74
9			91	0.5	20	2.38
10			91	1	0	-1.22
11			91	0.6	0	-4.03
12			91	2	0	-4.51
1			92	7	0	0.17
2			92	6	8	2.23
3			92	4	22	1.50
4			92	0.5	0	-2.31
5			92	5	0	-0.38
6			92	15	5	10.91
7			92	3	31	6.24
9			92	9	31	9.10
9			92	4	25	6.06
10			92	3	29	3.02
11			92	7	10	5.13
12			92	1	23	8.43
1			93	8	21	4.30
2			93	3	27	1.64
3			93	5	31	2.16
4			93	1	13	-1.47
5			93	0	0	-4.90
6			93	3	0	-4.02
7			93	4	0	-2.51
8			93	4	0	-1.49
9			93	2	0	-2.81
10			93	5	0	-0.69
11			93	3	0	-1.27
12			93	7	0	2.34
1			94	9	1	6.75
2			94	3	29	3.47
3			94	8	31	6.25
4			94	3	28	3.16
5			94	2	0	0.31
6			94	13	12	9.29
7			94	23	31	25.15
8			94	13	31	25.78
9			94	7	30	20.21
10			94	10	31	19.47
11			94	0.5	30	9.49
12			94	2	31	4.28
1			95	5	31	3.79
2			95	3	28	1.49
3			95	6	31	2.93
4			95	6	30	3.90
5			95	7	21	5.62
6			95	7	28	6.74
7			95	6	12	6.60
9			95	7	31	7.25
9			95	2	21	2.94
10			95	7	28	4.94
11			95	4	26	3.28
12			95	5	20	3.21
1			96	4	31	2.08
2			96	4	16	1.45
3			96	9	31	5.90
4			96	5	30	4.89
5			96	2	11	1.37
6			96	5	0	2.11
7			96	4	0	1.60
9			96	8	0	5.26
9			96	5	28	4.55
10			96	7	31	5.97
11			96	2	30	1.84
12			96	7	31	4.22
1			97	6	31	4.78
2			97	5	28	4.14
3			97	2	26	8.74
4			97	8	0	4.69
5			97	8	27	7.10
6			97	10	30	10.59
7			97	12	31	15.09
8			97	6	31	12.04
9			97	1	17	5.11
10			97	5	7	4.55
11			97	5	28	4.00
12			97	4	31	2.51
1			98	5	31	2.67
2			98	9	28	6.74
3			98	7	31	7.44
4			98	1	30	1.92
5			98	1	0	-1.52
6			98	1	0	-3.83
7			98	17	0	10.62
8			98	6	22	9.12
9			98	12	30	14.05

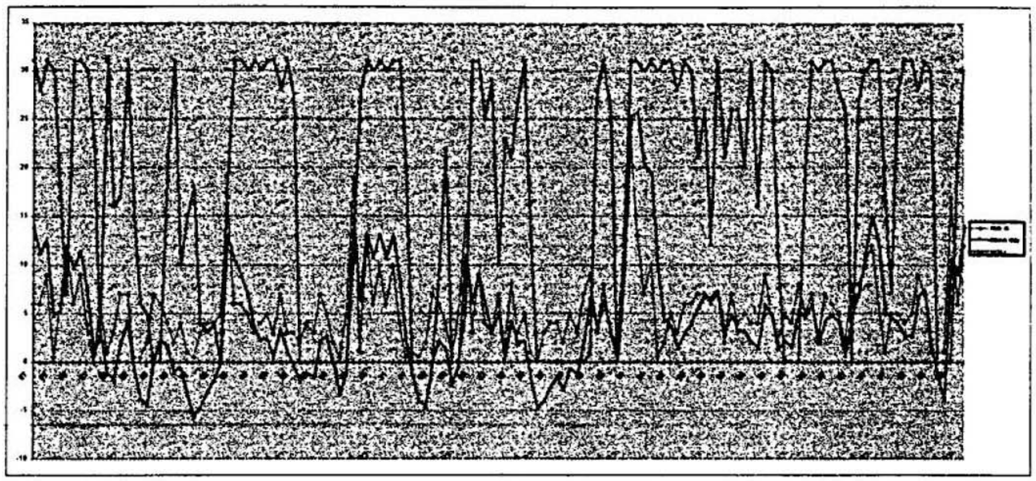

Figure 2. Simplified mathematical model, tabular & graphical output

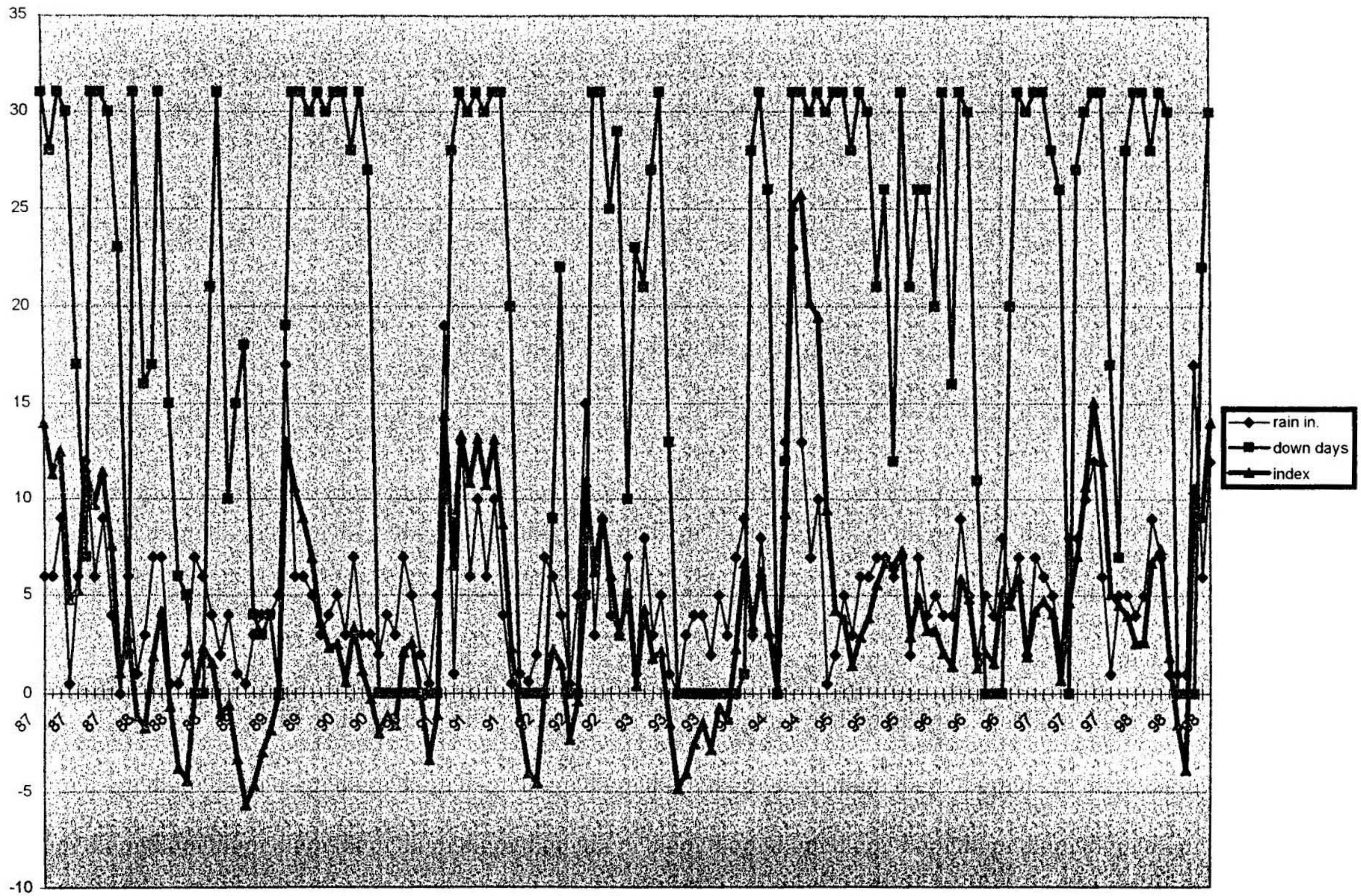

Figure 3. Simplified mathematical output compared with down days and rainfall data

THE POLITICS AND ECONOMICS OF ENVIRONMENTAL NEGLECT

William M. Landing, Department of Oceanography, Florida State University, Tallahassee, FL 32306-4320

ABSTRACT

Florida's explosive population over the past 30 years has been a source of incredible profit for land speculators and developers. Unfortunately for the environment, intelligent growth management and appropriate land-use regulations have not generally been imposed on this process. In our area, we are blessed with a tremendous number of environmentally-conscious scientists and staff at the municipal, county, regional, and state levels, and their efforts are responsible for most of our environmental success stories. One might even imagine that the majority of our local population supports strong environmental protection. The problem is that the majority of our active voters often elect representatives whose vision for our area's future includes poorly constrained growth and the attendant environmental degradation. Some of these elected leaders support two specious concepts; that accelerated growth is "good" for our community because it increases our tax base; and that simple ownership of land carries with it the right to alter the land without appropriate regard for the environmental consequences.

Regarding our economy, Leon County already has an extremely stable base to its economy with the payrolls of the city, county, and state government, the private sector legal and other services supporting government, a community college and two universities, and two large hospitals. We can afford to be careful and move ahead slowly with future growth. After 10 years of service on local environmental committees, it is clear that encouraging growth and economic development will continue to result in environmental degradation because: our current design standards and land-use restrictions are not sufficient, and we don't have the scientific knowledge to intelligently establish adequate ones; and we lack the political will to demand better. The fact that we allow almost anyone to clear 90% of their property, simply because it is cheaper and easier to build from the dirt up, is an embarrassment. We permit someone to spray treated sewage along a sensitive lake-shore because we can't conclusively prove that the lake will suffer in the future. Such a list of examples from recent memory would fill many volumes.

Regarding land-use restrictions, strong laws prohibit the discharge of industrial wastes into the "community" environment, yet the incremental impact of development is ignored in legal decisions supporting individual property rights (so-called "takings" laws that require reimbursement for lost property value due to government regulations). Our power as a community to demand protection of our environment has been subjugated by these policies. And while developers complain about our restrictive (yet certainly inadequate) land-use regulations, the long-term cost to the community far exceeds any short-term costs developers might bear. For example, Leon County plans to spend $16 million in taxpayer money over the next few years to fix a handful of stormwater problems. Had they started 20 years ago, the City and County could have raised an equivalent sum by collecting $300,000 per year from developers and placing it in a trust fund at 10% interest. It's too bad that $16 million only covers a subset of our existing problems, and it won't reverse the intervening 20 years of degradation in the areas that are retrofitted.

Recently, a proposal was circulated to conduct detailed studies of aquifer recharge and flow under Leon County. We know that we can pollute the Floridan aquifer, we know where some of the recharge areas are, but we don't have a very good grasp of how the water flows underground. Considering our reliance on the aquifer to meet 100% of our water needs, it seems prudent to learn as much as possible about the system and to discourage development in recharge areas. Studies like these could be supported from a "developers" trust fund if our elected leaders had the foresight and will to create one.

However, we're not as bad off as many other Florida communities, and we must continue to fight for the protection of our environment by doing at least five things:

1. *Continue to support scientific investigations to learn how our environment functions naturally, and how to protect it during land-use change.*
2. *Recognize that growth will always result in some environmental degradation. Make the land speculators and developers pay into a trust fund to cover this future cost.*
3. *Stop all use of public funds to encourage growth and development in our region. It is foolish to use taxpayer dollars to subsidize activities which result in environmental degradation, then to use taxpayer dollars to try to fix the problems later.*
4. *Accept the concept that land ownership does not confer unrestricted development rights. The community should have the power to make rules on land-use, and to change those rules when necessary.*

5. Educate our friends and neighbors on these issues so that we can elect representatives who embrace these goals of environmental protection ahead of growth and development.

WAKULLA SPRINGS WATER QUALITY WORKING GROUP - AN INTERAGENCY ECOSYSTEM PROCESS

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ABSTRACT

Wakulla Springs was purchased by the State of Florida in 1986 for protection, management and use as a state park. Glass bottom boat tours had been provided for over 50 years by the previous owner and were continued when the state park was established. Park staff determined that the boats were not used 66% of the days during 1991 because the spring water was too dark. This prompted the Department of Environmental Protection, in 1992, to form a working group of all local, state, and federal agencies that have knowledge of water quality issues in the Wakulla Springs Basin (Woodville Karst Plain). Also, industrial land owners, businesses and citizens were invited to participate. The purpose of the Wakulla Springs Water Quality Working Group is to protect the waters flowing to Wakulla Springs by understanding the system, determining the threats to the system and identifying and implementing solutions. The working group has encouraged hydrological research in the basin, exploration and mapping of the cave system, protection of sinkholes, passage of a protection ordinance, acquisition of critical lands, improved stormwater and wastewater management, sensitive land use planning, and public education. Educational activities include newspaper and magazine articles, a "Florida Crossroads" television production, field trips for the press and legislature and this symposium. This ecosystem management process insures that all stakeholders are at the table to enhance communications, avoid duplication and expedite actions.

LAKES AND PONDS IN THE WAKULLA KARST PLAIN; THEIR IMPORTANCE TO LOCAL AND REGIONAL BIODIVERSITY

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ABSTRACT

Sporadically from 1968 to 1993 and rigorously from 1994-1998, about 300 lentic environments were surveyed for aspects of their physical details and vertebrate animals. Here I report preliminary results of monitoring the hydroperiod, local rainfall, temperature, fishes, amphibians, and reptiles for about 265 such pond environments in the Woodville Karst Plain of Leon County and make recommendations for expanding this work south into Wakulla County. Among the vertebrates dependent upon small short-hydroperiod ponds are the striped newt and gopher frog, two amphibians that probably deserve federal threatened status.

BIOLOGICAL ASSESSMENT OF THE ST. MARKS RIVER BASIN IN LEON, JEFFERSON, AND WAKULLA COUNTIES, FLORIDA

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ABSTRACT

A basinwide study, consisting of 30 stations, was performed on the St. Marks River watershed in Leon, Jefferson, and Wakulla counties, Florida. The purpose of the investigation was to determine potential human effects on water quality, habitat, and biological communities.

Habitat factors were important in explaining poor biological community health at Munson Slough at Springhill Road (an urban ditch), Lafayette Creek at US 90 (an urban ditch), Ward Creek (a sluggish, intermittent marsh stream), Sweetwater Creek (where erosion from a dirt road caused habitat smothering), Sally Ward Swamp (a sluggish, intermittent swamp stream), and Boggy Branch (a low velocity, channelized system). Dissolved oxygen was less than the Class III water-quality standard at Ward Creek, Bream Fountain, the St. Marks River below Horn Spring, and the Spring Creek estuary. Low dissolved oxygen at Ward Creek was attributed to the sluggish, marshy conditions there, while the low values seen at the remaining sites appeared to be due to Floridan aquifer spring inputs. Turbidity measurements at Sweetwater Branch (6.2 NTUs) and English Branch (13 NTUs) were higher than the values found in 75% and 90%, respectively, of other Florida streams.

Nitrate-nitrite enrichment (levels higher than those found in 80% of other Florida streams or estuaries) was observed at McBride Slough (0.52 mg/L), Boggy Branch (8.7 mg/L), Sally Ward Swamp (0.35 mg/L), the Wakulla River above US 98 (0.42 mg/L), the Wakulla River below Boggy Branch (0.4 mg/L), the Spring Creek estuary (0.22 mg/L), and the St. Marks River at Indian Point (0.13 mg/L). Nitrate-nitrite enrichment at the majority of the sites appeared to be caused by discharges from Floridan aquifer springs. The springs apparently receive nonpoint sources of nitrogen in their respective recharge areas. The enrichment at Boggy Branch was associated with an industrial facility (Primex).

Fecal coliforms at Munson Slough at Springhill Road (880 organisms/100 mL) and at Sweetwater Branch (830 organisms/100 mL) violated the Class III water-quality standard (which allows a maximum of 800 organisms/100 mL) (Rule 62-302.530(6) FAC). Similarly, total coliforms at Munson Slough at Springhill Road (52,000 organisms/100 mL) and at Sweetwater Branch (3,200 organisms/100 mL) violated the Class III water-quality standard of 2,400 organisms/100 mL (Rule 62-302.530(7) FAC). All other sites in the St. Marks Basin complied with both bacterial standards.

Based on the SCI scores, Sally Ward Swamp and Ward Creek were ranked in the "very poor" category. SCI scores at Black Creek, Munson Slough at Springhill Road, Lafayette Creek at US 90, English Branch, Sweetwater Creek, and Boggy Branch placed these sites in the "poor" category. Alford Arm Creek, Moore Branch, Munson Slough at Oak Ridge Road, Fisher Creek, and the Wakulla River above US 98 had SCI scores in the good range, while Lafayette Creek at Weems Road and Lloyd Creek were classified as "excellent."

The stress observed in the macroinvertebrate communities at several sites may be explained. Ward Creek is a sluggish, marshy system, which intermittently goes dry. Black Creek at Baum Road is another site which occasionally goes dry. Munson Slough at Springhill Road and Lafayette Creek at US 90 are both urban ditches, with extensive habitat degradation. The benthic biota at these two sites are probably suffering from a combination of factors, including poor habitat, periodic abrasive effects from flooding, and sporadically poor water quality. English Branch is a small, first-order, intermittent stream. Based on the turbidity measurement, this stream is apparently also subject to runoff containing suspended solids.

Sweetwater Branch was subject to habitat smothering from significant amounts of soil erosion associated with an unpaved county road (Cody Road) that crosses the stream. Sally Ward Swamp, not being a typical, perennially flowing stream system, probably scored poorly because of the sluggish or intermittent nature of flow through this hardwood swamp. The SCI was developed for flowing streams, and it is not an appropriate measure for wetland systems. Habitat was a limiting factor at Boggy Branch, with respect to low water velocity, habitat smothering, and artificial channelization. This site also was subject to considerable nitrate-nitrite enrichment, which could directly affect algal and macrophyte communities, and indirectly, the benthic populations. A more intensive biological assessment (a "5th Year Study") of the effects of the Primex discharge was carried out in December 1997.

Salinity appeared to be the dominant factor affecting the estuarine biota in this study. Taxa richness at all estuarine sites was better than average for a Florida estuary. The Apalachee Bay taxa richness score was higher than those found in 95% of other Florida estuaries. Compared with other Florida estuaries, three sites had Shannon-Weaver diversities somewhat less than the average value, including the St. Marks at Indian Point, the Spring Creek estuary, and the St. Marks River near Posey's. Low or fluctuating salinity was a factor common to all three of these sites. Low dissolved oxygen (caused by spring inputs) was an additional stressor at the Spring Creek estuary. Urban stormwater inputs may potentially have affected the St. Marks River near Posey's, although low salinity was probably the overriding factor.

INTRODUCTION

A basinwide study, consisting of 30 stations, was performed on the St. Marks River watershed in Leon, Jefferson, and Wakulla counties, Florida, during February 1997. The purpose of the investigation was to determine potential human effects on water quality, habitat, and biological communities.

METHODS

Benthic macroinvertebrate communities in the streams were evaluated by collecting invertebrates from multiple substrates (*e.g.*, snags, leaf packs, roots, vegetation) using 20 discrete dip net sweeps (FDEP Biology Section Standard Operating Procedure #BA-7, FDEP, 1998). Invertebrate populations in areas affected by estuarine conditions were collected with three replicate grabs from a petite Ponar dredge (Biology Section Standard Operating Procedure #BA-9). Habitat quality was determined for each station during an *in situ* assessment (FDEP SOPs #17 and 18). Supplemental physical/ chemical data were also collected on the study sites. Water was also analyzed for nutrients and for total and fecal coliforms. Methods used for all chemical analyses are on file at the Tallahassee DEP Chemistry Laboratory.

RESULTS AND DISCUSSION

The stations situated north of the Cody Scarp were considered in the "upper" basin, those freshwater stations south of the Cody Scarp were classified into the "lower" basin, and the marine influenced sites were considered to be in the estuary. Habitat factors (Figure 1) were important in explaining poor biological community health at Munson Slough at Springhill Road (an urban ditch), Lafayette Creek at US 90 (an urban

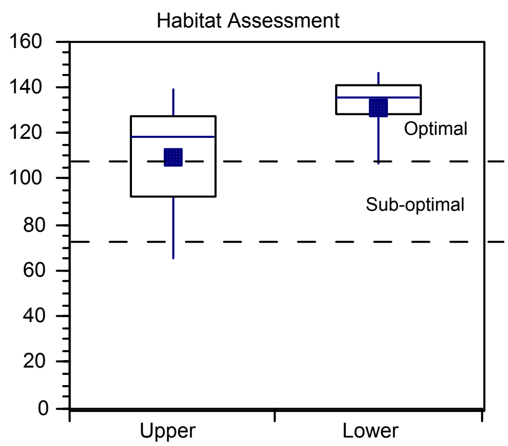


Figure 1. Box plots of habitat assessment scores at the stream station in the St. Marks Basin

ditch), Ward Creek (a sluggish, intermittent marsh stream), Sweetwater Creek (where erosion from a dirt road caused habitat smothering), Sally Ward Swamp (a sluggish, intermittent swamp stream), and Boggy Branch (a low velocity, channelized system). Dissolved oxygen was less than the Class III water-quality standard at Ward Creek, Bream Fountain, the St. Marks River below Horn Spring, and the Spring Creek estuary (Figure 2). Low dissolved oxygen at Ward Creek was attributed to the sluggish, marshy conditions there, while the low values seen at the remaining sites appeared to be due to Floridan aquifer spring inputs. Turbidity measurements at Sweetwater Branch (6.2 NTUs) and English Branch (13 NTUs)

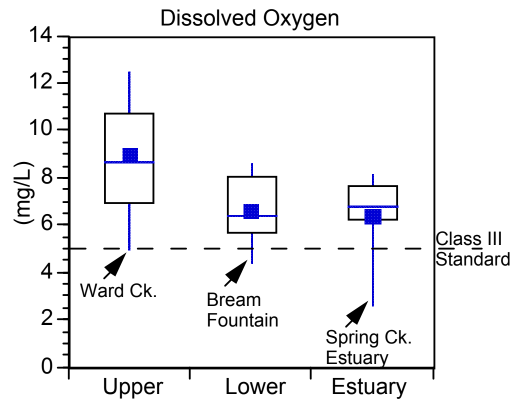


Figure 2: Box Plots of dissolved oxygen concentrations throughout the St. Marks Basin

were higher than the values found in 75% and 90%, respectively, of other Florida streams. Total phosphorus concentrations were generally average or below average for Florida streams and estuaries (Figure 3). Nitrate-nitrite enrichment (levels higher than those found in 80% of other Florida streams or estuaries) was observed at McBride Slough (0.52 mg/L), Boggy Branch (8.7 mg/L), Sally Ward Swamp (0.35 mg/L), the Wakulla River above US 98 (0.42 mg/L), the Wakulla River below Boggy Branch (0.4 mg/L), the Spring Creek estuary (0.22 mg/L), and the St. Marks River at Indian Point (0.13 mg/L) (Figure 4).

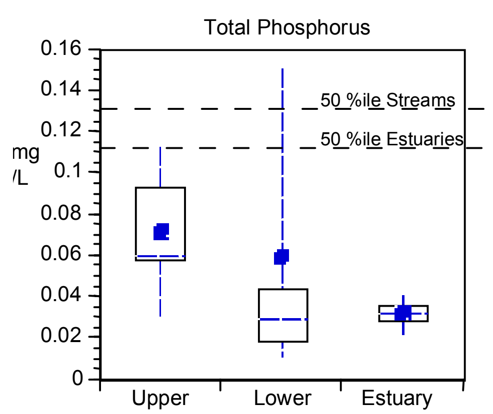


Figure 3. Box plots of total phosphorus concentrations throughout the St. Marks Basin

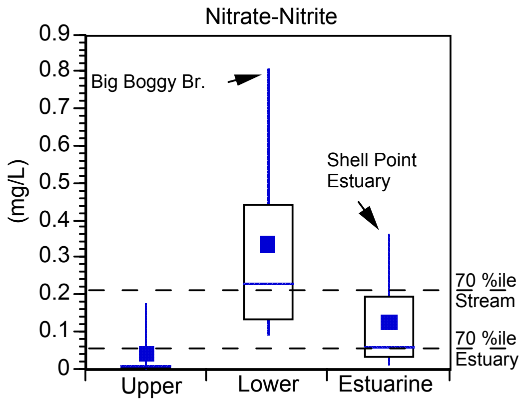


Figure 4: Box plots of nitrate-nitrite concentrations throughout the St. Marks Basin

Nitrate-nitrite enrichment at the majority of the sites appeared to be caused by discharges from Floridan aquifer springs. The springs apparently receive nonpoint sources of nitrogen in their respective recharge areas. Historic nitrate-nitrite concentrations from several springs in the St. Marks basin (Rosenau *et. al* 1977), including Horn, Natural Bridge, Rhodes, St. Marks, Indian, River Sink, and Wakulla Springs, were plotted against the 1997 nitrate-nitrite levels of spring-influenced stations (Figure 5). Note that the 1997 median nitrate-nitrite concentrations were higher than the historic upper quartile values, suggesting significant increases over time. The nitrate-nitrite enrichment at Boggy Branch was associated with an industrial facility (Primex).

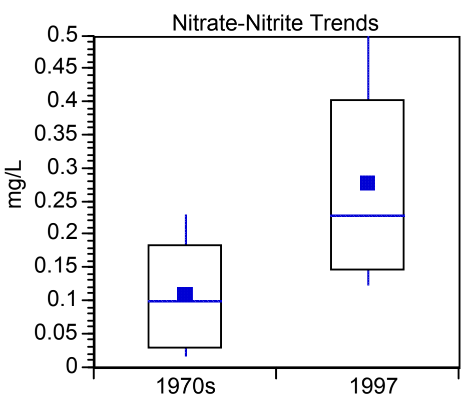


Figure 5: Trends in nitrate-nitrite in the St. Marks basin over time, comparing nitrate-nitrite concentrations in Floridan Aquifer springs (1971-1973) to spring affected stream stations collected in 1997

Fecal coliforms at Munson Slough at Springhill Road (880 organisms/100 mL) and at Sweetwater Branch (830 organisms/100 mL) violated the Class III water-quality standard (which allows a maximum of 800 organisms/100 mL) (Rule 62-302.530(6) FAC). Similarly, total coliforms at Munson Slough at Springhill Road (52,000 organisms/100 mL) and at Sweetwater Branch (3,200 organisms/100 mL) violated the Class III water-quality standard of 2,400 organisms/100 mL

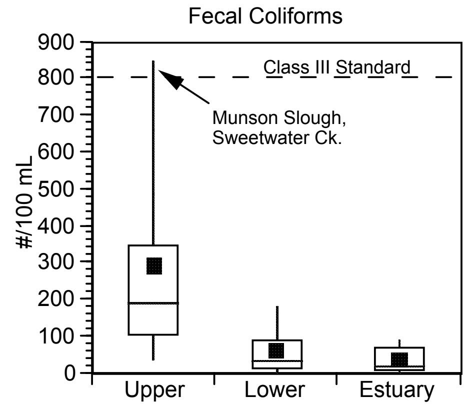


Figure 6: Box plots of fecal coliform concentrations throughout the St. Marks Basin

(Rule 62-302.530(7) FAC). All other sites in the St. Marks Basin complied with both bacterial standards (Figure 6).

The Stream Condition Index for Florida (SCI) is a composite macroinvertebrate metric (Barbour *et al.* 1996). The SCI assigns points to a variety of parameters, depending on how closely each parameter approaches an expected reference condition (Table 1). Based on the SCI scores, Sally Ward Swamp and Ward Creek were ranked in the “very poor” category. SCI scores at Black Creek, Munson Slough at Springhill Road, Lafayette Creek at US 90, English Branch, Sweetwater Creek, and Boggy Branch placed these sites in the “poor” category. Alford Arm Creek, Moore Branch, Munson Slough at Oak Ridge Road, Fisher Creek, and the Wakulla River above US 98 had SCI scores in the good range, while Lafayette Creek at Weems Road and Lloyd Creek were classified as “excellent” (Figures 7 through 9).

Parameter	Response to Disturbance
Taxa Richness	Decrease
EPT Index	Decrease
% Contribution	Increase
Dominant Taxon	Decrease
Florida Index	Decrease
# Chironomidae	Decrease
% Filter-feeders	Decrease
% Diptera	Increase

Table 1: Components of the Stream Condition Index

The stress observed in the macroinvertebrate communities at several sites may be explained. Ward Creek is a sluggish, marshy, wetland system, which intermittently goes dry. Black Creek at Baum Road is another site which periodically goes dry, which local residents speculate is due to hydrological modifications in the basin (*e.g.*, ditching, impoundments). Munson

Slough at Springhill Road and Lafayette Creek at US 90 are both urban ditches, with extensive habitat degradation. The benthic biota at these two sites are probably suffering from a combination of factors, including poor habitat, periodic abrasive effects from flooding, and sporadically poor water quality. English Branch is a small, first-order, intermittent stream. Based on the turbidity measurement, this stream is apparently also subject to runoff containing suspended solids.

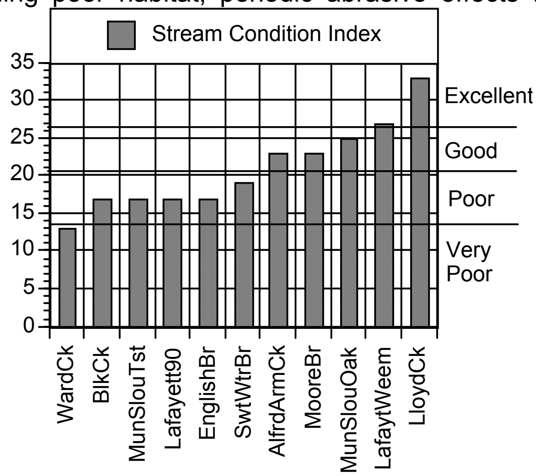


Figure 7: Stream Condition Index results for the upper St. Marks Basin

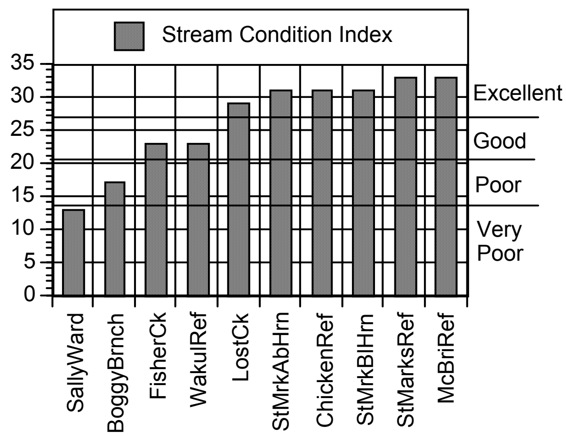


Figure 8: Stream Condition Index results for the lower St. Marks Basin

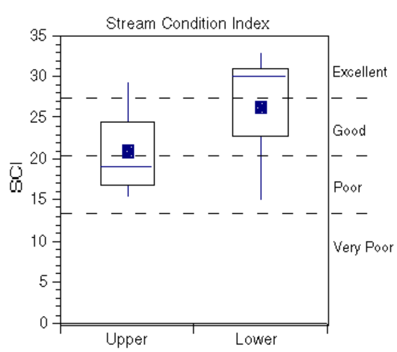


Figure 9: Comparison of the Stream Condition Index results between the upper and lower St. Marks Basin

Sweetwater Branch was subject to habitat smothering from significant amounts of soil erosion associated with an unpaved county road (Cody Road) that crosses the stream. Sally Ward Swamp, not being a typical, perennially flowing stream system, probably scored poorly because of the sluggish or intermittent nature of flow through this hardwood swamp. The SCI was developed for flowing streams, and it is not an appropriate measure for wetland systems. Habitat was a limiting factor at Boggy Branch, with respect to low water velocity, habitat smothering, and artificial channelization. This site also was subject to considerable nitrate-nitrite enrichment, which could directly affect algal and macrophyte communities, and indirectly, the benthic populations.

There were stations above and below impoundments in both Lafayette Creek (Weems Road stormwater treatment pond) and Munson Slough (Lake Munson). Impoundments can potentially improve water quality (through sedimentation of particulates with adsorbed contaminants) and can attenuate extreme flows (reducing abrasion and catastrophic drift in the benthos). Additionally, there were improvements in habitat quality between the upstream and downstream stations (Figure 10). It is likely that the improvements seen in the Stream Condition Index were equally related to enhancements in water quality, flow regime, and habitat.

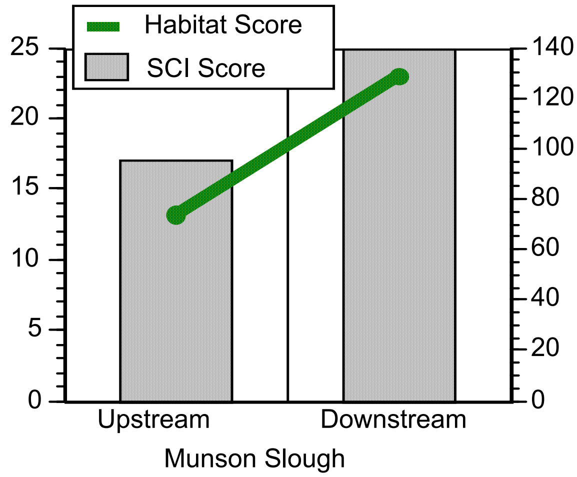
Salinity appeared to be the dominant factor affecting the estuarine biota in this study. Taxa richness at all estuarine sites was better than average for a Florida estuary (Figure 11). The Apalachee Bay taxa richness score was higher than those found in 95% of other Florida estuaries. Compared with other Florida estuaries, three sites had Shannon-Weaver diversities somewhat less than the average value, including the St. Marks at Indian Point, the Spring Creek estuary, and the St. Marks River near Posey's (Figure 12). Low or fluctuating salinity was a factor common to all three of these sites. Low dissolved oxygen (caused by spring inputs) was an additional stressor at the Spring Creek estuary. Urban stormwater inputs may potentially have affected the St. Marks River near Posey's, although low salinity was probably the overriding factor.

CONCLUSIONS

The following are considered the most important findings of his study:

1) Protection or enhancement of stream habitat and adjacent riparian zones throughout the St. Marks Basin is critical to ensure healthy aquatic communitites.

2) Stormwater treatment impoundments, in association with habitat improvements, appeared to have beneficial effects on the biological health of downstream communitities.



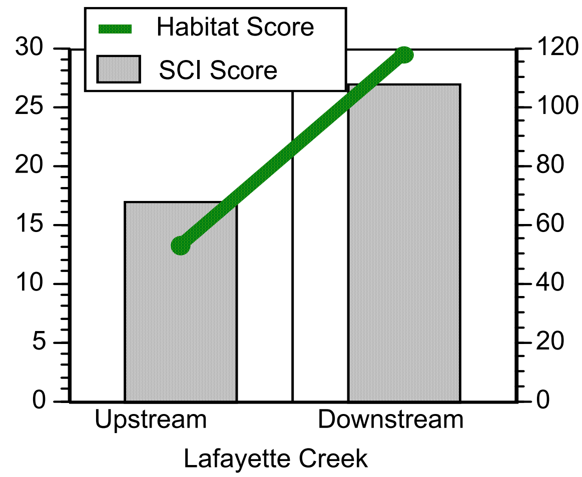


Figure 10: Improvements in the Stream Condition Index as observed between upstream and downstream stations in Munson Slough and Lafayette Creek. These improvements are believed to be related to the effects of impoundments (water quality improvements, flow attenuation) and also to observed improvements in habitat.

3) Nitrate-nitrite enrichment in St. Marks Basin deep aquifer springs has occurred since the early 1970's. This nutrient enrichment may contribute to excess algal or plant growth, such as the nuisance aquatic weeds (*Hydrilla* sp.) present at Wakulla Springs State Park.

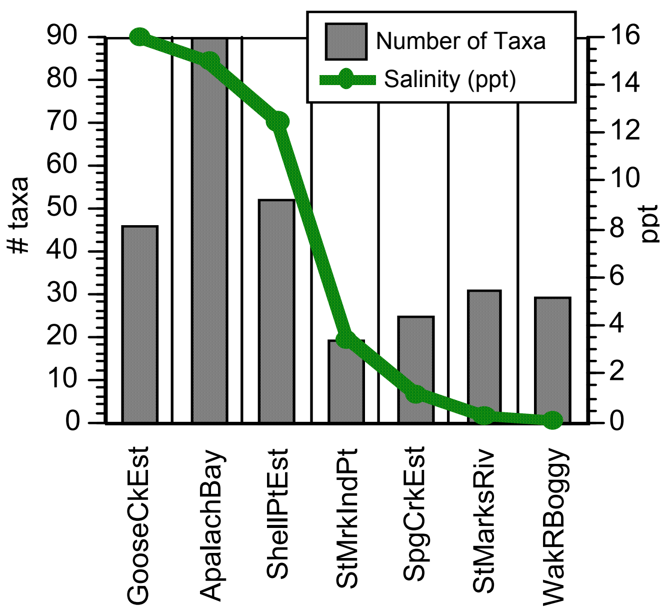


Figure 11: Benthic macroinvertebrate taxa richness vs. salinity at St. Marks estuarine sites

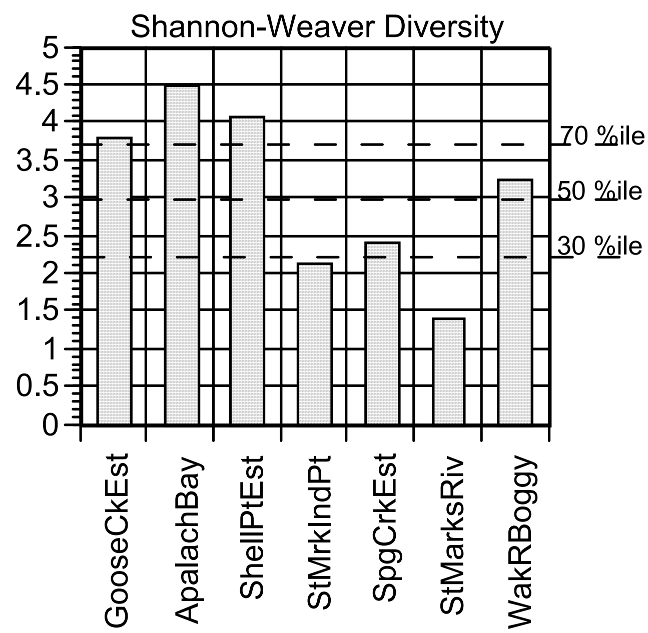


Figure 12: Shannon-Weaver diversity at St. Marks estuarine stations compared with other Florida estuaries

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WATERHYACINTH AS A BIOLOGICAL INDICATOR OF WATER QUALITY

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ABSTRACT

Waterhyacinth production and water quality were measured in four north Florida mesotrophic lakes with existing established populations of this South American invasive plant, to determine if plant growth was related to nutrient enrichment. Intensive sampling in a bay of Lake Iamonia (Leon County) found that waterhyacinth grew faster at sites closest to nonpoint source (NPS) pollution loading. Multiple regression modeling revealed that ammonia was limiting waterhyacinth growth in this portion of the lake:

$$\%Change = -1.301 + 0.0220DAY + 0.0696NH_3 \quad R^2=0.77$$

where %Change is the percent change in waterhyacinth wet weight, DAY is time in days, and NH_3 is the water column ammonia concentration in ug/L. Sampling of three other lakes confirmed that waterhyacinth growth was positively correlated with nutrient levels. Data from this sampling was used to evaluate waterhyacinth growth predictions from the regression model. It was found that the highly variable nature of the water quality data in part caused large confidence intervals around predictions. Results from the four lakes sampled suggest that substantial waterhyacinth growth (doubling times of 30 days or less) occurred when ammonia and ortho-phosphorus concentrations reached values of at least 40 ug/L and 15 ug/L, respectively. Patterns in growth and distribution of established waterhyacinth populations could be an effective clue to detect NPS pollutant sources in mesotrophic lake systems.

INTRODUCTION

One of the worlds worse weeds, waterhyacinth (*Eichhornia crassipes*) has been one of the most studied aquatic plants. The adverse effects stem from its high growth rate, vegetative reproduction, and propensity to form dense floating mats (Debusk and Dierberg, 1989).

Growth rates for waterhyacinth can be phenomenal, reportedly exceeding dry biomass production of any terrestrial, salt water, or freshwater vascular macrophyte (Wolverton and McDonald, 1979). Doubling times in the literature range from 6 to 18 days (Mitchell, 1976; NAS, 1976; Cornwell et al., 1977). Ten plants doubling every 15 days can multiply to exceed 600,000 plants in eight months and cover 0.4 ha (Boyd, 1976). Standing biomass of waterhyacinth can exceed 222 wet tons/a (500 metric tons/ha) (Boyd, 1970; Wolverton and McDonald, 1979; Brower, 1980; DeBusk et al., 1981; Reddy and Bagnall, 1981; DeBusk, 1983; Reddy et al., 1983). Loose-packed waterhyacinth averages 44 wet tons/a (100 metric tons/ha), and dense packs may not experience growth reductions due to crowding until they exceed 222 wet tons/a (500 metric tons/ha).

High growth rates and standing crops translate into high organic sedimentation rates. Brower (1980) found that a dense mat of waterhyacinth sloughs 3.6% (about 20 wet tons/a) of its biomass per year to the sediments. Measurements by Center and Spencer (1981) and Joyce (1985) were much higher; 100-130 wet tons/a per year reached the sediments. In general, a waterhyacinth plant will turn over its biomass 5-7 times per year (Center and Spencer, 1981), and over 20% of this organic biomass is deposited in the sediments (Brower, 1980; Joyce, 1985).

Environmental impacts of waterhyacinth mats involve degraded water quality, organic sedimentation, and dramatic changes in plant and animal communities (McVea and Boyd, 1975; Joyce, 1985; Gopal, 1987; Bartodziej and Leslie, 1998). Diffusion of light and oxygen through the water surface can be significantly reduced (Sculthorpe, 1967; Brower, 1980; Gopal, 1987), and water movements can be reduced by 40-95% (Bogart, 1949; Guscio et al., 1965). Floating mats can physically deprive fishes of spawning areas, or render these areas unsuitable due to anoxia (Lynch et al., 1957; Achmad, 1971). Edges of waterhyacinth mats support large numbers of invertebrates associated with the finely dissected root systems, and the fishes that prey on this resource. However, dissolved oxygen can be limiting throughout the rest of these mats. Drifting mats of waterhyacinth uproot beds of submersed plants and overwhelm marginal plants important to waterfowl (Tabita and Woods, 1962).

Lugo et al. (1979) reported elevated waterhyacinth growth rates in a marsh receiving sewage effluent compared to waterhyacinth growth in a nearby pond system. Experiments in the St. Marks River revealed that waterhyacinth had a doubling time of 10 to 17 days in the unshaded pool (0.2 to 1.0 km south of the head spring) where ambient nutrient concentrations were naturally high -- total phosphorus and nitrogen averaged 60 ug/L and 280 ug/L, respectively (Bartodziej and Leslie, 1998). Tank studies on waterhyacinth in central and southern parts of Florida indicate that nutrient-rich waters increase plant productivity (Reddy et al., 1983). And anecdotal evidence from Florida Department of Environmental Protection (FDEP) field biologists suggest that certain plant species (e.g. waterhyacinth and duckweeds) grow especially well in nutrient-rich waters.

Because of its high growth rate in nutrient-rich conditions, waterhyacinth has been commonly exploited to remove nitrogen and phosphorus from the water-column in sewage treatment facilities (Wolverton, 1987). FDEP currently permits the possession and use of waterhyacinth in eight industrial and sewage treatment facilities (J. Schardt, FDEP, personal communication, 1996). Waterhyacinth has also been evaluated as a potential method for treating eutrophic lake water (Fisher and Reddy, 1987).

Eutrophication is a term generally used in describing a water body that has received nutrient inputs, resulting in an increase of productivity and the structural simplification of its biotic components (Wetzel, 1983). Baker et al. (1981) and Huber et al. (1982) summarized Florida lake data in an attempt to evaluate “nonpoint source” (NPS) exports of phosphorus and nitrogen from urbanized or agriculturally developed drainage basins. It is generally accepted that in nutrient limited lakes, an increase in phosphorus and nitrogen will cause a shift in phytoplankton community structure and an increase in productivity (Brenner et al., 1990). Glooshcenko and Alvis (1973) found in a study of water collected from Lake Jackson (Leon County, Florida) that the addition of nitrogen, phosphorus, or silica resulted in higher numbers of algal cells and shifts in community structure. Vascular aquatic plants are also an important component of total plant biomass and primary productivity in Florida waters (Canfield et al., 1983). For example, Fontaine and Ewel (1981) found that macrophytes and their associated epiphytes accounted for 56 percent of the gross primary production in Little Lake Conway, near Orlando, Florida.

Certain aquatic plant species may be good indicators of nutrient enrichment. Floating plant species, like waterhyacinth, extract nutrients from the water-column and their growth rates are directly associated with recent nutrient inputs. Hoyer et al. (1996) correlated historical Florida lake water quality data with the presence of selected aquatic plant species. Generally, they found that common floating species (e.g. giant duckweed *Spirodela polyrhiza*, common duckweed *Lemna minor*, and azolla *Azolla caroliniana*) were more likely to be present in nutrient-rich systems. They reported that waterhyacinth can

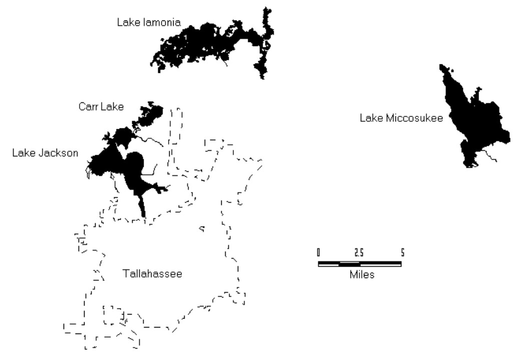

Figure 3. Location of the four study lakes in relation to Tallahassee.

grow in a wide range of water quality conditions, and its distribution did not seem to favor nutrient-rich waters. However, neither waterhyacinth production nor the level of waterhyacinth control was compared to the historical water quality data. FDEP Bureau of Invasive Plant Management reports more waterhyacinth control in mesotrophic to eutrophic than in oligotrophic waters (J. Schardt, FDEP, pers. comm. 1996).

Numerous published studies and field observations suggest that waterhyacinth and other floating plant species grow especially well in nutrient-rich lake water. However, current available data do not allow for the computation of nutrient thresholds in natural systems. Being a large conspicuous plant, waterhyacinth may be an ideal biological indicator of nutrient enrichment if generalizations can be made about its response to water-column phosphorus and nitrogen concentrations in certain lake types. Also, waterhyacinth-nutrient correlations from field-collected data will be useful in predicting the effects of NPS pollution on aquatic plant management efforts.

The object of this study was to determine waterhyacinth growth rates under varying nutrient concentrations in several north Florida mesotrophic lakes. First, this involved measuring waterhyacinth biomass accumulation along a nutrient gradient in one lake, developing predictive capability. And then to test the predictions, we collected additional data in selected lakes of the same overall trophic state.

METHODS

An intensive six-week study of a bay in Lake Iamonia (Leon County, Florida) and monitoring in three other lakes were initiated in May 1996 to assess the relationship between water quality parameters and waterhyacinth growth. The first phase of the investigation was designed to correlate waterhyacinth data with varying nutrient concentrations and to generate a nutrient-waterhyacinth growth regression model. The second phase of the study focused on collecting water quality and waterhyacinth growth data in Lake Iamonia and three other mesotrophic lakes in Leon County to validate the statistical model.

Phase I

Phase one of the study was conducted in a bay (Lester Cove) of Lake Iamonia (Fig. 1). Lester Cove receives varying degrees of NPS inputs from a sewage wastewater sprayfield complex, a golf course, and residential development. Small mats of waterhyacinth were present in several areas of Lake Iamonia, but the largest and most robust concentration was found in Lester Cove. The relatively large population of waterhyacinth in this part of the lake suggested elevated nutrient levels. The possibility of a spatial nutrient gradient and the remote location of Lester Cove, only accessible by airboat, provide an ideal study area.

Four sample sites were positioned in Lester Cove, Site 1 being nearest the southern shore and Site 4 was closest to the bay opening; Site 5 was approximately 300 m north of the bay opening, in the main body of the lake. Sites 1 and 2 were dense waterhyacinth mats. Site 3 contained an equal mix of waterhyacinth and fragrant waterlily (*Nymphaea odorata*). Fragrant waterlily was the dominant plant at Sites 4 and 5; Site 4 had a sparse cover of individual waterhyacinth plants and no waterhyacinth were found at Site 5.

At each site, three 1-m^2 PVC quadrats were stocked with approximately 500 g (wet weight) of waterhyacinth (0.1 m tall) collected from surrounding areas. Quadrats were spaced at least 10 m apart and were anchored in place. At Site 1, frame placement was 150 m from the bank to avoid shading effects from large trees. Waterhyacinth growth was determined by measuring plant weight (wet) in the field approximately weekly. Initial stocking of frames was on 16 May; the monitoring duration was 42 days (six sampling events).

Water samples were collected 0.3 m below the water surface at each site on every sampling date. Total nitrogen, total phosphorus, ortho-phosphate, nitrite-nitrate, and ammonia were analyzed at the central FDEP Analytical Laboratory in Tallahassee using standard methods. Conductivity, dissolved oxygen, and temperature were measured in the field using YSI (models 51B and 33) water quality meters.

Phase II

In addition to Lake Iamonia, lakes Jackson and Carr (Leon County), and Miccosukee (Jefferson County) were chosen to obtain data for the validation phase of the study (Fig. 1). Reference and NPS areas were chosen in lakes Iamonia, Jackson, and Carr. In Lake Miccosukee, only a reference area was identified. A NPS area was defined as a portion of a lake receiving NPS pollution runoff. In these instances, storm water runoff from residential and commercial developments seemed to be a substantial contributor to NPS pollution. Conversely, all reference areas were adjacent to relatively undisturbed portions of watersheds, receiving less NPS runoff. Reference areas in lakes Jackson, Carr and Miccosukee were located near large tracts of relatively undisturbed privately held land. The reference area in Lake Iamonia was located in a bay directly to the west of Lester Cove. This portion of the lake had less residential development around the south shore, and was not directly influenced by runoff from the sprayfield or golf course. The treatment area was in Lester Cove, close to Phase I Site 3; the delineation of this treatment area was based on results from Phase I.

Our *a priori* assumption was that lake areas adjacent to watershed disturbances, would receive NPS runoff elevating nutrient levels compared to reference areas with less watershed disturbances. All of the reference areas were dominated by fragrant waterlily. The Lake Carr treatment area had a mix of waterhyacinth and American lotus (*Nelumbo lutea*).

Table 1. Peak Nutrient Concentrations and waterhyacinth growth rates in four north Florida lakes. IAM-1 through IAM-5 are from Phase I sampling in Lester Cove of Lake Iamonia. JAX-NPS (Lake Jackson), CAR-NPS (Lake Carr), and IAM-NPS (Lake Iamonia) are Phase II sites receiving non-point source pollution. CONTROLS are the average peak concentrations from reference sites in lakes Iamonia, Carr, Jackson and Miccosukee. COND=conductivity umhos/cm; ALK=total alkalinity mg/L $CaCO_3$; OP=ortho-phosphorus ug/L; NH_3=ammonia ug/L. DOUBLE DAY = time required for waterhyacinth biomass to double (days). % PER DAY = percent increase in waterhyacinth biomass per day over the course of the study.

Study Site	----------Water Chemistry Peak Concentrations------------ COND	ALK	OP	NH3	---Waterhyacinth Growth Rates--- DOUBLE DAY	% PER DAY
IAM-1	120	35	23	470	6.5	15.3
JAX-NPS	72	26	43	61	7.7	13.0
CARR-NPS	30	11	43	54	29	3.4
IAM-2	120	29	12	49	7.8	12.8
IAM-NPS	61	24	6	49	45	2.2
IAM-3	83	23	11	26	59	1.7
IAM-4	47	18	8	24	250	0.4
IAM-5	30	10	7	19	>250	<0.1
CONTROLS	<25	<13	<7	<40	>52	<2.0

Waterhyacinth was common around floating mats of bur-marigold (*Bidens* spp), swamp loosestrife (*Decodon verticillatus*), maidencane (*Panicum hemitomon*), and water primrose (*Ludwigia* spp) in the Lake Jackson treatment site.

The same general protocol outlined in Phase I was used in this segment of the project. Three 1-m^2 quadrats were randomly placed in each reference and treatment area. Starting on 6 August, waterhyacinth (approximately 550 g wet weight total) were placed in each frame, the last measurements were taken on 25 September. The study areas were monitored four times after the initial stocking of waterhyacinth. Water quality was measured along with the weighing of plant material on each sampling date.

RESULTS

Lester Cove of Lake Iamonia proved to be a suitable location to study the effects of NPS pollution on waterhyacinth growth. Values of key water quality parameters suggest the greatest NPS pollution influence at sites closest to watershed disturbance. For instance, total phosphorus and ortho-phosphorus declined from an average of 166 ug/L and 14 ug/L at Site 1 to 24 ug/L and 5 ug/L at Site 5, respectively. The variance around mean concentrations also showed a decline from Site 1 to Site 5, suggesting that sites near shore were exposed to pulses of nutrient inputs (Fig. 2). This same trend held true for nitrogen.

Elevated total nitrogen concentrations were detected at Sites 1, 2, and 3, and then significantly declined ($P<0.05$) at Sites 4 and 5 (Fig. 2). Variances around mean total nitrogen concentrations were also relatively higher at Sites 1, 2 and 3; the peak total nitrogen concentration recorded at Site 1 was 3300 ug/L. Ammonia concentrations behaved similarly. Mean ammonia at Site 1 was 122 ug/L, while Site 5 had a concentration of 13 ug/L. Sites 1 and 2 had relatively higher ammonia concentrations and larger variances than were detected at Sites 3, 4 and 5. Again, the same general trend was evident for turbidity and alkalinity. Significantly higher ($P < 0.05$) alkalinity and turbidity levels were detected at Site 1 compared to Site 5; values for Sites 2, 3 and 4 fell in the range set by Sites 1 and 5 (Fig. 2).

Waterhyacinth in the PVC quadrats responded to the elevated nutrient levels close to the NPS pollution inputs. At Sites 1 and 2, waterhyacinth grew at a faster rate compared to levels measured at Sites 3, 4 and 5 (Fig. 2; Table 1). At day 42, waterhyacinth had grown at a rate of 15.3 and 13.0 percent of their biomass per day (biomass doubling times of 6.5 and 8 days) at Sites 1 and 2, respectively. The same declining trend, found with key water quality parameters, was evident in the waterhyacinth growth data; waterhyacinth in quadrats further away from NPS inputs had lower growth rates.

Best subset regressions were run to determine a statistical model that explained the relationship among waterhyacinth growth, time, and nutrient concentrations. Percent waterhyacinth change in wet weight was used as the dependent variable; however, waterhyacinth wet weight was also found useful. Untransformed and transformed water quality data described above were entered as unforced independent variables into the models. Our goal was to produce a straightforward model that explained the response of waterhyacinth to varying water quality conditions. Results of the best subset regression exercise and several other correlation analyses revealed that time (DAY) and ammonia concentration (NH_3) best explained the percent change (%Change) in waterhyacinth wet weight:

- $\%Change = -1.3 + 0.022DAY + 0.07NH_3$
- $R^2 = 0.77$

The overall equation was highly significant ($P < 0.00001$) as well as the DAY coefficient ($P < 0.0498$) and the NH_3 coefficient ($P < 0.00001$). The NH_3 variable had a greater influence in the model; this was likely due to the low rate of waterhyacinth growth measured at Sites 3, 4 and 5. Ortho-phosphorus and total phosphorus did not significantly add to the model, suggesting that phosphorus was not limiting waterhyacinth growth at these sites. By graphing the standardized residuals versus the fitted values, it was apparent that the variances were constant (Weisburg, 1985). A Wilk-Shapiro/Rankit Plot indicated normality in the model (Daniel and Wood, 1971). Although the data set is restricted by a limited number of sampling events through time, preventing time series regression analysis, residual analyses suggest a sufficient multiple regression model.

Water quality and waterhyacinth data collected in Phase II of the project was used to validate the multiple regression model. The selection of reference and NPS sites in lakes Miccosukee, Carr, and Jackson was primarily based on land use patterns (the degree of anthropogenic watershed disturbance) and the abundance of waterhyacinth. Data collected during Phase II generally showed elevated nutrient levels at the sites we labeled as NPS compared to the reference sites (Table 1; Fig. 2).

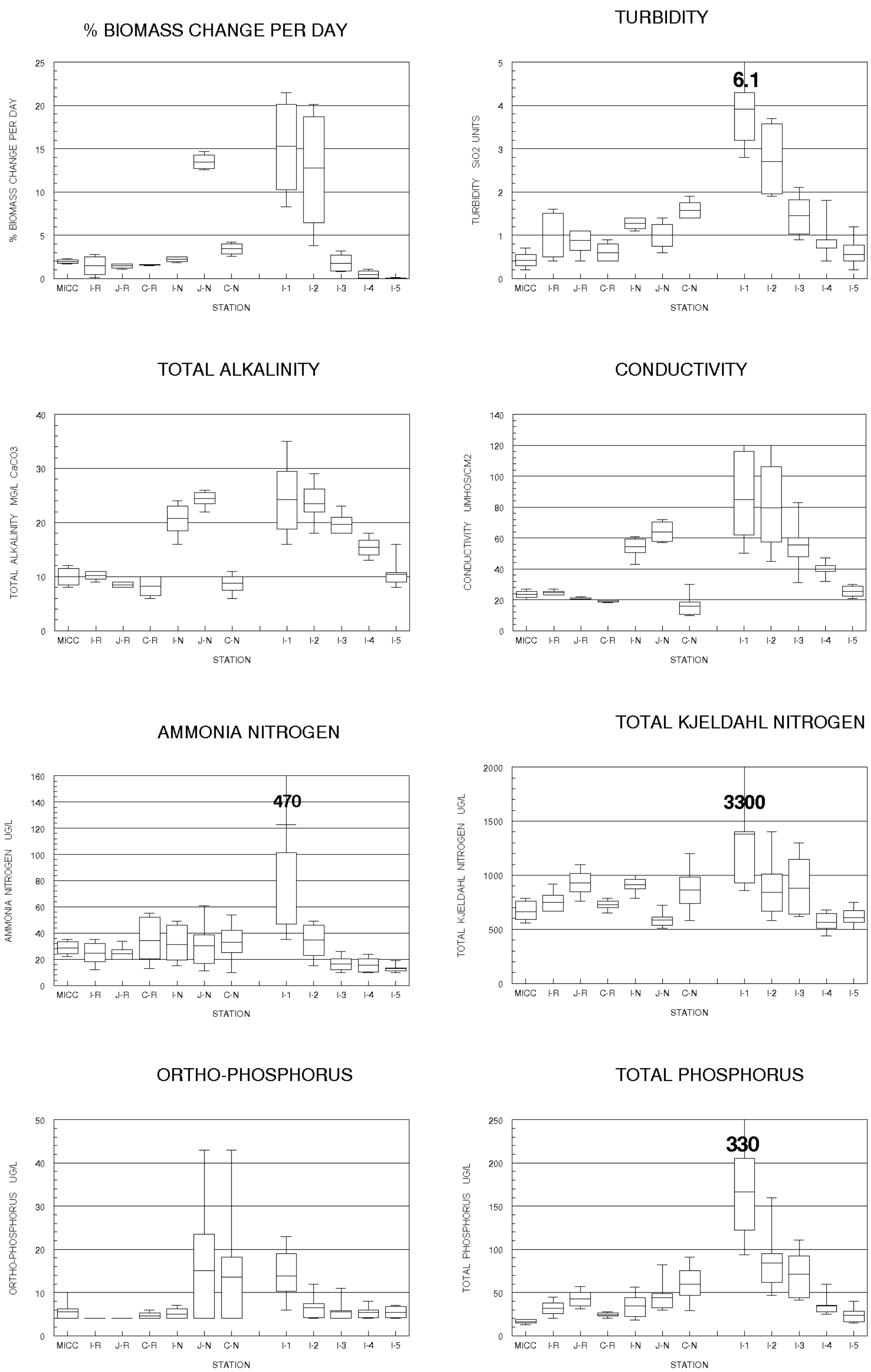

Figure 2. Box and whisker plots for waterhyacinth growth and selected water quality parameters at Phase II sites on lakes Iamonia (I), Carr (C), Jackson (J) and Miccosukee (M). Sites labeled N receive nonpoint source pollution, those labeled R are the reference sites. Sites I-1 through I-5 are Phase I data from Lester Cove, Lake Iamonia.

In Lake Iamonia, the bay considered a reference to the west of Lester Cove, had lower nutrient concentrations, but not significantly lower than the NPS site. The one NPS site chosen in Lester Cove was close to Site 3 in Phase I of the study. This location was chosen because of the significant decline in waterhyacinth growth that was detected between Phase I Sites 2 and 3. It was thought that more data collected in this part of the cove may help explain the differences in waterhyacinth growth. The Lake Miccosukee reference site had similar water quality to that of the Lake Iamonia reference site, except for total phosphorus, which was higher ($P < 0.05$) in Lake Iamonia.

Lake Carr differed from Lake Iamonia in that total nitrogen and ammonia were similar between reference and NPS sites. Detectable nutrient differences were in the form of phosphorus; total phosphorus was lower ($P < 0.05$) in the reference site averaging 25 ug/L, whereas in the NPS site, mean total phosphorus was 60 ug/L. Also differing from the pattern seen in Lake Iamonia was that water true-color was found to be lower (19 versus 16 Pt-Co units, $P < 0.05$) at the NPS site.

True-color was also lower ($P < 0.05$) at the NPS site in Lake Jackson compared to the reference site (20 versus 39 Pt-Co units, respectively). This lake was similar to Lake Iamonia in that nutrient concentrations in the NPS site varied widely due to pulses of nutrient inputs. For instance, peak ortho-phosphorus in the NPS site was 43 ug/L while values were 4 ug/L or less in the reference site on all dates. The highest ammonia level detected at the NPS site was 61 ug/L versus 34 ug/L in the reference site. Interestingly, total nitrogen was significantly higher in the reference site, which was unique to Lake Jackson.

Waterhyacinth grew faster at the NPS sites in all lakes (Table 1; Fig. 2). Plant growth at the Lake Jackson NPS site was similar to that found for Sites 1 and 2 in Phase I of the study (Lake Iamonia). Waterhyacinth growth in Lake Carr and Lake Iamonia NPS sites were significantly lower ($P < 0.05$) than values measured in the Lake Jackson NPS site, but higher ($P < 0.05$) than levels for the reference sites in all lakes.

The regression model from Phase I was used to compare patterns in waterhyacinth percent wet weight increase values at the end of Phase II (day 35) with predicted values. Figure 3 shows the relationship between waterhyacinth growth and ammonia concentrations when the independent time variable remains constant (DAY equals 35) in each equation. Only for reference sites in lakes Miccosukee (1), Iamonia (3) and Jackson (5), were the ending waterhyacinth growth values within two standard errors of the predicted values. Waterhyacinth at Lake Iamonia-NPS (2), Lake Carr-NPS (6) and Lake Carr-

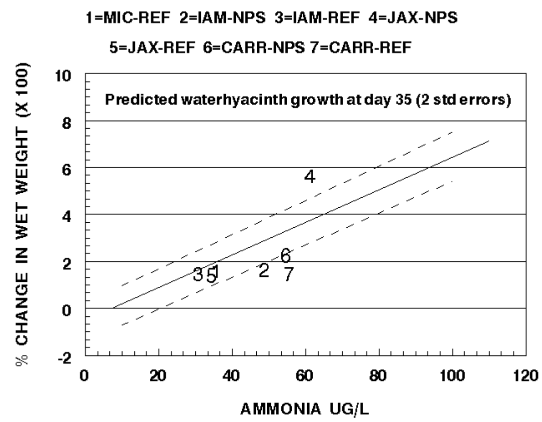

Figure 3. Multiple regression model predicted percent change in waterhyacinth wet weight (solid line) versus ammonia concentrations with time constant (DAY=35). Dashed lines are $\pm$2 std errors. Numbers are data from Phase 2 sites.

REF (7) sites grew at rates much lower than predicted by the model, possibly indicating one or more other nutrients were below a threshold value. The Lake Jackson NPS (4) site was unique in that it grew waterhyacinth the fastest with relatively moderate mean ammonia concentrations over the duration of Phase II sampling. With this data set, there also seems to be a positive correlation between waterhyacinth growth and ammonia concentrations.

DISCUSSION

This study demonstrated that waterhyacinth production can be correlated with certain water quality parameters under field conditions. We found that waterhyacinth growth rates were significantly higher in areas of mesotrophic lakes receiving NPS inputs.

The regression modeling exercise was helpful in determining that ammonia was limiting waterhyacinth production in Lake Iamonia. When added as independent variables, total phosphorus and ortho-phosphorus did not significantly contribute to the model. This finding suggests that the extremely high waterhyacinth production near the south shore of Lester Cove was due to nitrogen inputs from one or more of the watershed disturbances. Other studies have found that nitrogen limits waterhyacinth growth in natural systems (Lugo et al. 1979; Carignan and Neiff 1992). The decline in waterhyacinth production from Phase I Site 2 to Site 3 and the corresponding reduction of ammonia (Table 1; Fig. 2) suggest that the large waterhyacinth mat covering Sites 1 and 2 may have acted as a nitrogen sink. This is supported by the fact this plant is widely used in wastewater treatment.

Phase II of the study confirmed the NPS pollution-waterhyacinth relationship. Data from lakes Miccosukee, Carr and Jackson generally supported the multiple regression model. In these systems, ammonia was also correlated with waterhyacinth growth. The Lake Jackson NPS site had high waterhyacinth growth, yet moderate mean ammonia concentrations. This waterhyacinth response was not explained by the regression model. Overall, this site had unique water quality characteristics. The peak ortho-phosphorus concentration was 43 ug/L, and ammonia reached 61 ug/L in Lake Jackson, the highest recorded for Phase II sampling. It is likely that waterhyacinth were reacting to these pulses of nutrients, but since mean concentrations were modest, the model proved ineffective in predicting the magnitude of plant growth.

The results from the Lake Jackson NPS site suggest that pulsed nutrient input events can have a significant effect on waterhyacinth growth, making predictions from incrementally collected field data quite challenging. In addition, the predictions generated from the regression model have inherently large confidence intervals, and this was in part due to the variability in the water quality data, especially from Sites 1 and 2, closest to the Phase I NPS inputs. This variability in water quality data, however, gives support to the idea of using waterhyacinth as a biological indicator. Large expanses of lush green waterhyacinth in oligotrophic or mesotrophic lake systems may be more useful in detecting NPS pollution than one or two water quality samples in time. If such waterhyacinth mats are present, our sampling suggests that ammonia and ortho-phosphorus concentrations likely reached values of at least 49 ug/L and 12 ug/L, respectively, with total alkalinity greater than 12 mg/L (Table 1). These threshold nutrient concentrations are reasonable starting points, and hopefully further study will refine these estimates.

Our study demonstrates that waterhyacinth may be an effective tool that could be used to detect NPS pollutant sources in north Florida oligotrophic and mesotrophic lakes. For instance, managers could distinguish specific lake areas with recurring waterhyacinth infestations and work with water quality experts to identify nutrient sources. Also, if lakes are under plant management programs, tracking the number of acres of waterhyacinth controlled may be a way to assess trends in nutrient inputs over time.

Reducing the nutrient loading below threshold levels could ultimately save resources by alleviating the need for intensive plant management activities. This study has profound implications in this regard. Waterhyacinth are a very real threat to the integrity of native aquatic habitats. As such, it is essential that the biomass of these plants be maintained at the lowest feasible level in areas where they are able to proliferate. The regression in Figure 3 indicates that in Lake Iamonia, a potential 100 percent increase in waterhyacinth growth rate for every 14 ug/L increase in available nitrogen may be possible. Thus costs of plant management, including the amount of herbicidal materials used, can quickly escalate with even modest increases in NPS loading.

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FRESH WATER IMPACTS IN COASTAL ECOSYSTEMS

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ABSTRACT

Groundwater discharge contributes significant amounts of fresh water into coastal ecosystems in the Apalachee Bay region, helping to maintain estuarine conditions. These estuaries are currently in relatively good ecological health. As a result, the area supports diverse marine ecosystems, extensive marine sea grass beds and healthy populations of several endangered species. In particular, the Kemp's ridley sea turtle, Lepidochelys kempi, congregates in estuarine areas, feeding on large populations of blue crabs, Callinectes sapidus.

Groundwater discharge to estuaries is known to be extensive, but it is still poorly understood and nearly unmapped. As the aquifer develops elevated nutrient levels, it becomes a delivery system for excessive nutrient loading into coastal waters which can lead to major ecological degradation, particularly to sea grass ecosystems.

In addition, because of the diffuse and unmapped pattern of coastal groundwater seepage, it is virtually impossible to model and predict precisely any impacts to marine ecosystems resulting from major diversions of groundwater resources from their current status to human use. However, based on experience in Florida Bay, such impacts could be expected to be harmful and substantial.

Apalachee Bay, the coastal region adjacent to the Woodville Karst Plain, is the northern and western limit of the Florida Big Bend Coast, a little developed and nearly pristine coastal region stretching from approximately Crystal River in the south to Ocklockonee Bay in the north. Marine communities of the region are currently in relatively good ecological health. The Big Bend's diverse marine ecosystems include one of the largest coastal salt marshes in the US, dominated by the rush *Juncus roemerianus*; one of the most extensive marine seagrass beds in the world composed primarily of turtle grass *Thalassia testudinum*; and extensive limestone bottoms that support tropical coral reef associated species of fishes and invertebrates (FDEP, 1988; Iverson and Bittaker, 1986). Near the mouths of streams and in the vicinity of large coastal springs and groundwater seepage areas such as Spring Creek, estuarine conditions prevail, supporting large populations of commercially important blue crabs, *Callinectes sapidus*, stone crabs, *Menippe mercenaria*, and oysters, *Crassostrea virginiana*, as well as other estuarine species.

The economic value of the marine resources of the region exceeded $10 million, based on 1997 commercial fishery landings of pink shrimp, gag grouper, blue crabs, stone crabs, and oysters (FDEP, 1998). The value of the seagrasses and marshes as nursery habitat to these and other marine species is enormous, with published estimates ranging from approximately $6500/acre for sports fishing revenues in Florida to a value of $242-313 million per year for New England salt marshes (Bell, 1997; Stevens et al., 1995).

These diverse marine habitats currently support healthy and growing populations of several endangered marine species. The Kemp's ridley sea turtle, *Lepidochelys kempi,* congregates in estuarine areas, feeding on large populations of blue crabs, *Callinectes sapidus* (Rudloe et al., 1991). A growing population of the West Indian manatee, *Trichechus manatus*, forages in coastal seagrass beds in the summer and overwinters in Crystal River to the south (Powell and Rathbun, 1984). The present healthy populations of these well-publicized species are dependent on the presence of intact ecosystems with thousands of other more obscure species of marine plants and animals. Their future survival is equally dependent on the continued health of these ecosystems and their wealth of smaller species.

Perhaps because of its limited accessibility, this area has in the past been the subject of surprisingly little ecological investigation. Most notably, Livingston and his students (Hooks et al., 1976; Livingston, 1982; Hock and Orth, 1980) contributed greatly to our knowledge of the seagrass fauna in the 1970s and 1980s and some studies of the unusual *Juncus roemerianus* dominated salt marshes were done (Durako et al., 1985). At this time, however, the area is receiving more attention from researchers. The Florida Big Bend Coastal Research Workshop, held in 1997, highlighted a wide variety of marine investigations of the region, ranging from physical oceanography to geological processes to habitat investigation (Lindberg, 1997). In these studies, academic researchers have been joined by staff from the various state and federal agencies with management responsibilities in the area. This affords the opportunity for eventual development of long term, region-specific data sets that will be critical to the preservation of the area's resources.

Most of the coastal area is incorporated into a series of public preserves, including the St Marks National Wildlife Refuge, a series of state preserves, and the Lower Suwannee and Cedar Keys National Wildlife Refuges. State waters are included in the Big Bend Seagrasses Aquatic Preserve, a program designed to give extra legal protection to waters of exceptional ecological value. It might be assumed that these preserves would protect the marine resources of the region. However, like most marine ecosystems, they are highly vulnerable to decline due to pollution originating outside the immediate area and transported into the region by land drainage and coastal currents.

Maintaining the ecological integrity of these coastal areas is dependent on a number of factors. Among the most important is the preservation of the freshwater flow into the region, both to maintain the estuarine components of the system and to protect the seagrass meadows from developing periodic hypersaline conditions during summer when evaporation rates are high. Equally important is the protection of the grassbeds from the injection of excess nutrient loads that lead to algae blooms, reduced light penetration and the resultant decline and eventual disappearance of the grasses that are the foundation of the ecosystem.

In many coastal areas, coastal groundwater discharge contributes a remarkable component of the total freshwater delivered to coastal ecosystems. Studies in South Carolina (Moore, 1996) indicate that groundwater contributes just under 50% of the amount provided by area rivers. Similar work in the Apalachee Bay region is reported by Burnett and his students (Cable et al., 1996 and elsewhere in this symposium). This extensive groundwater discharge currently contributes significant amounts of fresh water into coastal ecosystems in the Apalachee Bay region, helping to maintain both estuarine conditions and healthy seagrass communities. However, it is still poorly understood and nearly unmapped.

As the Floridian aquifer develops elevated nutrient levels from human activities such as improperly treated sewage, use of agricultural fertilizer and concentrated dairy and poultry farming, the most immediate damage is the degradation of the globally unique and beautiful spring ecosystems themselves. Such elevated nutrient loads have been reported in recent years from many of the freshwater springs in the aquifer. Staff from the Suwannee River Water Management District have found elevated nitrate levels in several major coastal springs, including Chassahowtzka, Homosassa, Weeki Wachee, and Rainbow as well as in many springs along the Suwannee River. Similar problems exist in Wakulla Springs. Some have reduced rates of flow as well (Ceryak and Rupert, 1997). Concurrent declines in water clarity, excessive levels of epiphytic algae and the explosive growth of exotic species of aquatic vegetation are now apparent in many of these springs relative to the mid 1970s when the last major survey of all the Florida springs was conducted (Rosenau et al., 1977). The major source of these elevated loads in the Suwannee River Valley appears to be agricultural development, (Ceryak, pers. comm.) while urbanization in the Tallahassee area and possibly forestry practices are candidates at Wakulla Springs.

Beyond impacts to the springs, polluted groundwater also becomes a delivery system for excessive nutrient loading into coastal waters. Eventually there is the potential for elevated nutrients in coastal ecosystems down stream, excessive plankton blooms and turbidity and the subsequent loss of those ecosystems as well. Seagrasses in particular are extremely vulnerable to such damage due to their dependence on high light levels and good water clarity. The potential vulnerability of coastal ecosystems to elevated nutrient loading in incoming freshwater is becoming apparent from studies conducted throughout the world. Coastal areas of chronic hypoxia, toxic algae blooms and resultant fish kills have been reported in increasing numbers in recent years. They are typically associated with elevated nutrient loading delivered via freshwater input. Fish kills resulting from nutrient loading and hypoxia now exceed those from any other single agent, including oil spills (Summers et al., 1997; Diaz and Rosenberg, 1995; Rosenberg and Diaz, 1993; Diaz et al., 1992).

The largest and best-studied example of this phenomenon in the Western Hemisphere occurs in coastal waters of the Gulf of Mexico west of the Mississippi River drainage. The river is currently carrying three times the levels of nitrates that it did in 1960, over 80% of which is from agricultural sources. Surface plankton blooms result and that in turn results in elevated organic levels on the sea floor as planktonic remains and fecal matter fall to the sea floor. Bacteria levels are then elevated, depleting oxygen from the bottom water. Benthic fish and invertebrates die en mass, further increasing the load of decaying organic matter. Eventually the sea floor may become coated with mats of sulfur oxidizing bacteria (Justic et al., 1996).

Blooms of toxic planktonic microalgae and resultant fish kills are also increasing concurrently with increasing nutrient loading, low oxygen and alterations in salinity regimes. In the Chesapeake Bay and in North Carolina, algae blooms have appeared in the last several years that are toxic to the point of being human health threats as well as sources of fish kills (Burkholder and Glasgow, 1997). Studies to improve methods of fertilizer application and reduce runoff are currently underway, particularly in the Mississippi River.

In addition to problems associated with eutrophication, the diversion of freshwater to human use and resultant declines in the volume of freshwater entering coastal ecosystems can also lead to environmental degradation. In particular, the reported severe declines of seagrass in Florida Bay, seaward of the Florida Everglades, are concurrent with and may be partly attributed to massive diversion of freshwater away from the coastal areas as well as altered hydroperiods due to human flood control activities (Smith and Robblee, 1994; Robblee et al., 1991). In the case of Florida Bay, other anthropogenic changes in the region, particularly development in the Keys, may also be involved as well as long term climate variables. At this time, an intensive research effort is underway to elucidate these factors (University of Miami, 1998). Research in the Waccasassa Bay area of the Florida Big Bend coast (Williams, 1997) suggests that the loss of coastal wetland forests, and particularly of coastal sabal palm, *Sabel palmetto*, is more immediately due to elevated salinity than it is to changes in levels of inundation experienced by the trees.

In short, the combination of eutrophication and/or diversion of freshwater, together with climatic variability typically leads to massive ecological damage and loss of the marine ecosystems whose freshwater supply is affected. In addition, because of the diffuse and unmapped pattern of coastal groundwater seepage, it is impossible at this time to model or predict exact impacts to the marine ecosystems of the Big Bend resulting from major diversions of groundwater resources of the Woodville Karst Plain from their current status to human use. However, based on experience in Florida Bay, Chesapeake Bay, North Carolina, the Mississippi coast, and many other coastal locations all over the world, such impacts may be expected to be substantial and devastating to the marine life of the Florida Big Bend and Apalachee Bay.

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A GEOLOGICAL INVESTIGATION OF SEDIMENTATION AND ACCRETION RATES OF MARINE COASTAL WETLANDS WITHIN APALACHEE BAY

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ABSTRACT

An investigation of the relationship between changes in sea level and sedimentation rates within the marine coastal wetlands of Apalachee Bay has been conducted through an ongoing cooperative agreement between the Florida Geological Survey and the U.S. Geological Survey. This study used sediment erosion table (SET) and cryogenic coring/marker horizon techniques to characterize the marsh surface and short-term marsh stability. To accomplish this, a number of sediment erosion table (SET) sites were established within the Juncus marshes of Apalachee Bay, including the Aucilla and St. Marks Estuaries, to determine present day erosion/accretion rates. Accretion rates of 4.9 mm/yr and 0.7 mm/yr, respectively, were measured over a four-year interval. Sea level measurements, as determined from tide gauge records at Cedar Key (approximately 50 miles south of the study area), indicate a rate of 1.24 mm/yr for sea level rise for the period from 1909-1980. Comparing this rise to the above measured SET elevation and cryogenic accretion values shows that, at least in the short term, each site is maintaining respective elevations relative to sea level. Carbon and Pb-210 dating of core sediments were conducted to provide estimates of longer tern sedimentation rates. Sedimentation rates derived from Pb-210 ranged from ~3.6 mm/yr to ~0.72 mm/yr for Aucilla and St. Marks Estuarine cores, respectively. These low accretion rates can be attributed primarily to drainage basins comprised of gently sloping coastal lowlands and associated reduction of rivers velocities and sediment load, and a coastal shelf of approximately 1.5 feet drop in bathymetry per mile, which significantly reduces wave energy.

INTRODUCTION

A quarter of Florida's Gulf shores are coastal wetlands located along the "Big Bend", connecting the Florida Panhandle and the Peninsula. Located within the Big Bend, Apalachee Bay can be characterized as a relatively pristine area which to-date has experienced minimal coastal development. These extensive wetlands represent one of the few remaining undeveloped coastal wetland areas in Florida. Researchers have just begun to assess the physical, chemical and biological processes which determine energy and matter fluxes through its littoral environment. Of concern are estimates of losses of coastal wetlands in the last 25 years that range from 20,000 hectares (Frayer et al., 1983), to 32,000 hectares (Day and Craig, 1981) per year nationwide. These wetlands process and filter wastes and nutrients derived from uplands, sustain the health and abundance of life in estuaries, and buffer coastal areas against storm and wave damage (NOAA, 1988).

Understanding the dynamics of sediment availability and sea level rise is essential to the formulation of effective land-use policies to preserve Florida's remaining coastal wetlands. In response to this need, the FGS has focused investigations on evaluating the present health and stability of wetlands within Apalachee Bay, specifically the Aucilla and St. Marks Estuaries. These on-going studies include the establishment of sediment erosion tables (SET) within the Aucilla and St. Marks coastal marshes to measure elevation changes at the marsh surface. This value when compared to tidal gauge data at Cedar Key gives a snapshot of the marsh surface stability over a short period of time. Meaningful trends will require longer- term monitoring.

STUDY AREA

The SET sites are located within coastal wetlands and lowlands near the mouths of the Aucilla and St. Marks Rivers. Two USGS (1:24000) topographic maps cover the location of these sites: Snipe Island and Sprague Island respectively. Both of these sites are located in salt marshes comprised predominantly of *Juncus roemerianus* and fringed by *Spartina alterniflora*. The areal extent of these salt marshes is a function of tidal range (Stickney, 1984). The geographic distribution of natural communities also reflects the duration and extent of tidal flooding.

The low continental-shelf gradient protects the coastline from large, landward-propagating waves formed in the Gulf, except during storms. Other factors contributing to this (normally) low wave-energy environment include: less common and weaker frontal (extratropical) storms than those that occur at higher latitudes, offshore dominant storm wind direction (northerly), and relatively small fetch from the offshore tidal flats to the Gulf shoreline (less than 5 miles). Because sand is available offshore, and very high waves and tides are necessary to setup sand movement in this area of normally small fetch, large storms build beaches that are not subsequently reworked. Gulf shore locations near the mouths of the Aucilla and St. Marks River's support high berms with water tables high enough to support ridges of fresh-water vegetation, including trees.

The shoreline bounding the study area is irregular and tide-dependent. High tides can be as much as 1.2 meters above mean sea level (MSL), although 0.76 to 1 meter tides are more normal. Rising tides flood the marsh grasses with water from several centimeters to one-third meter deep, and deepen the numerous, meandering, tidal creeks that cross the shoreline. At high tide the upper reaches of these creeks attain widths of 30 meters or more in the marshes, although in their incised channels nearer the Gulf, creek widths change much less. Falling tides expose shallow tidal creek-beds, oyster bars, and mud flats.

GEOLOGIC SETTING

The SET study areas lie in the northwestern portion of the Suwannee Basin (Figure 1). This basin is located southeast of a graben-horst-graben sequence thought to have formed during the middle Mesozoic when rifting separated the African, South American and North American continents during the breakup of Gondwanaland. The graben northwest of the Suwannee Basin linked with the South Georgia Basin to form the Suwannee Straits during the Triassic. A large carbonate platform began forming in this basin in the Early Jurassic. Carbonate, anhydrite, and fine-grained clastic, postrift sediments formed a platform sequence approximately 2 km thick in this basin by the middle of the Cenozoic (Klitgord et al., 1984).

By the late Paleogene, the trough separating the Florida Platform from North America had filled with sediments. Siliciclastic and authigenic sediment infilling terminated widespread, shallow-water carbonate-platform sedimentation and allowed quartz sand coastlines to develop on the platform interior (Riggs, 1979). The quartz-rich sands were later transported and reworked during Quaternary sea-level fluctuations and were ultimately deposited in terraces which have been identified above and below present sea-level. Healy (1975) identified three marine terraces on the basis of elevation in the NW Florida region including the upper reaches of the Aucilla River and St. Marks River basins.

A number of wells were used to construct a local stratigraphic cross-section depicting the shallow stratigraphy of the immediate onshore area (Figures 2, 3 and 4). To the east of the area depicted on the cross sections, but still within the study area, the oldest formation exposed is the Suwannee Limestone. The Suwannee was deposited approximately 35 million years before present during the Oligocene. Although often covered by a veneer of Plio-Pleistocene siliciclastic sediments in southern Jefferson and Taylor Counties, the upper surface of this limestone is frequently exposed in the Aucilla River and its tidal creeks. Lithologically, the Suwannee Limestone ranges from pale orange, finely crystalline, fossiliferous limestone to highly indurated dolostone.

Overlying the Suwannee Limestone is the Lower Miocene St. Marks Formation which has limited occurrence within the Aucilla estuary and is the oldest formation exposed in the St. Marks Estuary. These sediments, which were deposited approximately 25 million years before present, range from a white to very pale orange, finely crystalline, sandy, silty, clayey limestone to silicified or dolomitized limestone. Additionally, the St. Marks Formation is rubbly and highly fossiliferous.

Undifferentiated sand and clay unconformably overlie the St. Marks Formation and Suwannee Limestone in the area contiguous with the lower reaches of the Aucilla and St. Marks Rivers and the adjacent coastal marshes. These sediments comprise surficial clays, silts, sands and organic material deposited during the Pleistocene and Holocene Epochs, and range from absent to less than 5 meters thick.

METHODS

Two SET sites consisting of three individual SET's each were established in wetlands of the Aucilla and St. Marks Estuary's respectively (Figures 5 and 6). SET's were constructed in the following manner:

1. Small platforms were constructed at each site to allow access to, without disturbing, the marsh surface site. Locations were chosen at least 50 feet from the nearest channel, and in areas of like vegetative cover and composition.
2. Aluminium vibracore pipes were driven into the marsh substrate until bedrock is reached or refusal of the tube to be driven to any greater depth.
3. For each measurement session, the SET is placed in the tube and leveled in the horizontal plane. Nine pins are lowered to the marsh surface, locked into place (care is taken to place the measuring rods on the hard surface and are to avoid forcing them into the substrate), and measurements from the nine pins are recorded. The measurement is repeated in the three remaining quadrants for the station total.
4. Elevations are compared to show total change at each SET location. Figure 7 is a schematic representation of a SET.

Cryogenic coring, which was conducted at each site to measure accretion/erosion at the marsh surface, was accomplished as follows:

1. White feldspar marker horizons were established at each SET station. Two plots, measuring approximately 0.5 meter by 0.5 meter, were placed at each station when the SET pipe and platform was installed.
2. Over time, tidal sediments cover the powdered feldspar layer. To measure the accretion, a copper tube pumped full of liquid nitrogen is inserted into the feldspar plots to freeze sediments surrounding the tube (Figure 8). Upon removal of the copper tube, measurements of sediment accretion above the feldspare horizon in the frozen core are made using a caliper.

Lead 210 dating was conducted on selected cores for the study areas as follows:

Sediments were obtained with a coring apparatus. Six 3.5" diameter cores were taken in the Big Bend estuaries from different sedimentary environments: four from the Aucilla and two from the St. Marks. Each core was sampled at 0.5 cm intervals for the upper 10 centimeters, and then at 5 cm intervals for the remainder of the cores.

Lead-210 geochronology has become a commonly used technique for ascertaining rates of sedimentation in lakes (e.g. Robbins and Edgington, 1975), estuaries (Goldberge et al., 1977), and coastal marine sediments (Koide et al., 1973). An excellent extensive review by Robbins (1978) includes discussions of the geochronological applications of ^{210}Pb to these environments, the principles behind the technique, and the alternative analytical methodologies.

Of the radioactive isotopes of lead derived from the decay of uranium and thorium, only ^{210}Pb has received serious attention in the environment because the short half-lives of the others make them difficult to measure. Lead-210 ($t_{1/2}$ = 22.26 y) occurs naturally as one of the radioisotopes in the ^{238}U decay series. Disequilibrium between ^{210}Pb and its parent isotope, ^{226}Ra ($t_{1/2}$ = 1602 y), arises through diffusion of the intermediate gaseous isotope, ^{222}Rn ($t_{1/2}$ =3.8d). The desorption of ^{226}Ra as these particles enter the estuary may cause an apparent excess of ^{210}Pb activity (Helz et al., 1985). Sources of ^{210}Pb are atmosphere, groundwater, and terrestrial. Generally, possible sources of ^{210}Pb in Florida are atmosphere and groundwater.

The basic analytical procedure used to analyze ^{210}Pb in the cores is modified from Eakins and Morrison (1978). For each core, the intervals were dried, wet sieved, leached with concentrated HCl, and spiked with a ^{208}Po tracer of known activity. Each sample was placed in a large Pyrex test tube and heated to 550^{o} C in a tube furnace for 30-40 minutes. This volatilized the polonium, which condensed on a moist plug of glass wool in the top of the test tube. The glass wool was then placed in a beaker containing 0.5 N HCl and a silver disk was suspended in the solution. Autoplating of the polonium then proceeded for 5-7 hours. Activity of ^{210}Po and ^{208}Po on each silver planchet was then counted using an alpha spectrometer. Secular equilibrium between ^{210}Pb and its daughter product ^{210}Po was assumed.

In many cases sediment accumulation rates are variable and there are two models that take this into consideration in ^{210}Pb- age determination. The first is the CIC (constant initial concentration) model assumes that the initial activity of excess ^{210}Pb is the same at all depths in a core and is independent of sedimentation rate (Shukla and Joshi, 1989). The second model, the CRS (constant rate of supply) model which assumes that there is a constant flux of excess ^{210}Pb to the sediment (Appleby and Oldfield, 1992). In the present study we used the CIC model which allows for a straightforward method of dating buried sediments as well as quantifying sedimentation rates.

The age dating equation is: $A_i = A_0 e^{-\lambda t}$ where λ_{210} = 0.03114 y^{-1} is the ^{210}Pb radioactive decay constant. By measuring A_i, the age t can be calculated if the initial activity A_0 can be deduced from the model by plotting the log of A vs. depth in core. From this plot, the slope of the regression line is the average long-term sedimentation rate.

Carbon-14 dating was conducted on selected cores from the Aucilla River study area as follows:
Four wood fragments were sampled from cores for C-14 dating and analyzed by Krueger Enterprises, Inc., of Cambridge, Massachusetts. Samples were prepared by cleaning away sediment or other foreign debris and then splitting them into small pieces. Each was treated with hot, dilute HCl to remove carbonate and with hot, dilute NaOH to remove humic acids and other organic contaminants. After drying, the samples were combusted to recover carbon dioxide for dating. Samples were counted from two to four days. Resulting ages were corrected for C-13.

RESULTS AND DISCUSSION

Elevation and Accretion Data

The St. Marks SET site, consisting of three stations, established in May of 1992 by the USGS, has been monitored by the FGS since June of 1995. The Aucilla SET site consisting of three stations was established two years later in September, 1994 by the FGS. Measurements at both sites have been taken at three to four month intervals. Table 1 shows elevation and accretion data for the Aucilla and St. Marks sites respectively.

The total site elevation change at the three Aucilla stations averages 3.5 mm/yr. All three stations experienced both negative and positive readings throughout the period of measurements. Average accretion for the site totaled 4.9 mm/yr. Accretion consists primarily of organic sediments deposited in a low energy Estuarine environment. Sediment contributions from the area's rivers is minimal as they are low sediment load spring fed rivers. In contrast, the extensive marsh grasses, consisting primarily of *Juncus roemerianus* and fringing *Spartina,* represent an abundant source of organic deposits. Figure 9 is a graphical depiction of elevation and accretion over time.

The total site elevation change at the three St. Marks stations averages -0.6 mm/yr. In contrast to the Aucilla stations, all of the St. Marks stations showed negative total change in elevations. Sediment accretion measurements were consistently conducted at stations 1 and 3. These stations exhibited different trends, with station 1 showing larger accretion values over time, while station 3 experienced both accretion and erosion events over the same period of time (Table 2). Station 2 yielded less data due to the loss of the feldspar marker at this site during the last two monitoring cycles.

One goal of this study is to determine the effects of storm events on sedimentation at the marsh surface. Fortunately, the measurements conducted at the Aucilla site on June 13, 1995 and October 26, 1995 enabled an evaluation of the impact of Hurricane Allison and Hurricane Opal respectively. Measurements were conducted just before and after the passage of Hurricane Allison on June 5, 1998 which affected the area with winds of 65 knots. Similarly, measurements were conducted just days after the October 4th passage of Hurricane Opal, which hit the area with tropical force winds.

All three Aucilla stations showed accretion increases after the passage of Hurricane Allison. In contrast, these stations had mixed results for Hurricane Opal. Aucilla station 1 showed an increase in accretion while stations' 2 and 3 showed slight decreases.

Lead-210 Geochronology

One of the important results of the dating of estuarine and salt-marsh sediments using ^{210}Pb is that the sedimentation rate closely matches the rate of sea-level rise (Church et al., 1981, Goldberge et al., 1979, McCaffrey and Thomson, 1980, Sharma et al., 1987). This implies that marshes are steady-state features, accreting sediment in response to sea-level rise. As such they are important recorders of deposition of natural and anthropogenic substances. In the present study we have utilized ^{210}Pb geochronology in the Apalachee Bay, a low-energy embayment in the northeasternmost Gulf of Mexico of the Florida Big Bend, for the purpose of establishing sedimentation accumulation rate at six sites of the Aucilla and St. Marks Rivers.

The results of the ^{210}Pb are shown in Figures 10 and 11. Linear regression of these data yield sediment accumulation rates (Table 3) ranging from ~0.72 mm/yr. to ~3.6 mm/yr. for St. Marks and Aucilla cores, respectively. These sedimentation rates were variable, but within acceptable limits when compared to rates reported from estuarine and salt marsh environments. Highley (1995) reported mean sedimentation rates ranging from 0.5 mm/yr. in Big Bend intertidal *Juncus* marshes to 5.1 mm/yr. for subtidal environments in the same area. Sedimentation rates from intertidal environments in this study area averaged 0.94 mm/yr. whereas sedimentation rates from the subtidal environments averaged 3.3 mm/yr. This lower rate of sedimentation is consistent with the findings of Highley (1995). These low rates of sedimentation are mainly due to the unique geologic environment of the Big Bend coast of western Florida. It is a low-energy and sediment-starved environment. Hess (1995) analyzed nine cores from the Apalachicola Bay subtidal environment. The average sedimentation rate for these nine cores was 4.2 mm/yr. which is considerably higher than the intertidal sedimentation rate.

Carbon-14 Dating

Table 4 shows the core number, core length, depth sampled, and radiocarbon age for the four samples. Dates were based on the Libby half-life (5570 years) of C-14. Dates ranged from approximately 3800 to 6900 years and appear to be representative of the time of deposition of the enclosing sediments. The four data points were plotted on the revised Florida submergence curve of Scholl et al. (1969). Figure 12 shows the revised Florida submergence curve with the Aucilla River data points superimposed. Also, it shows that the radiocarbon data points lie above the regional sea-level curve. This confirms sea-level rise.

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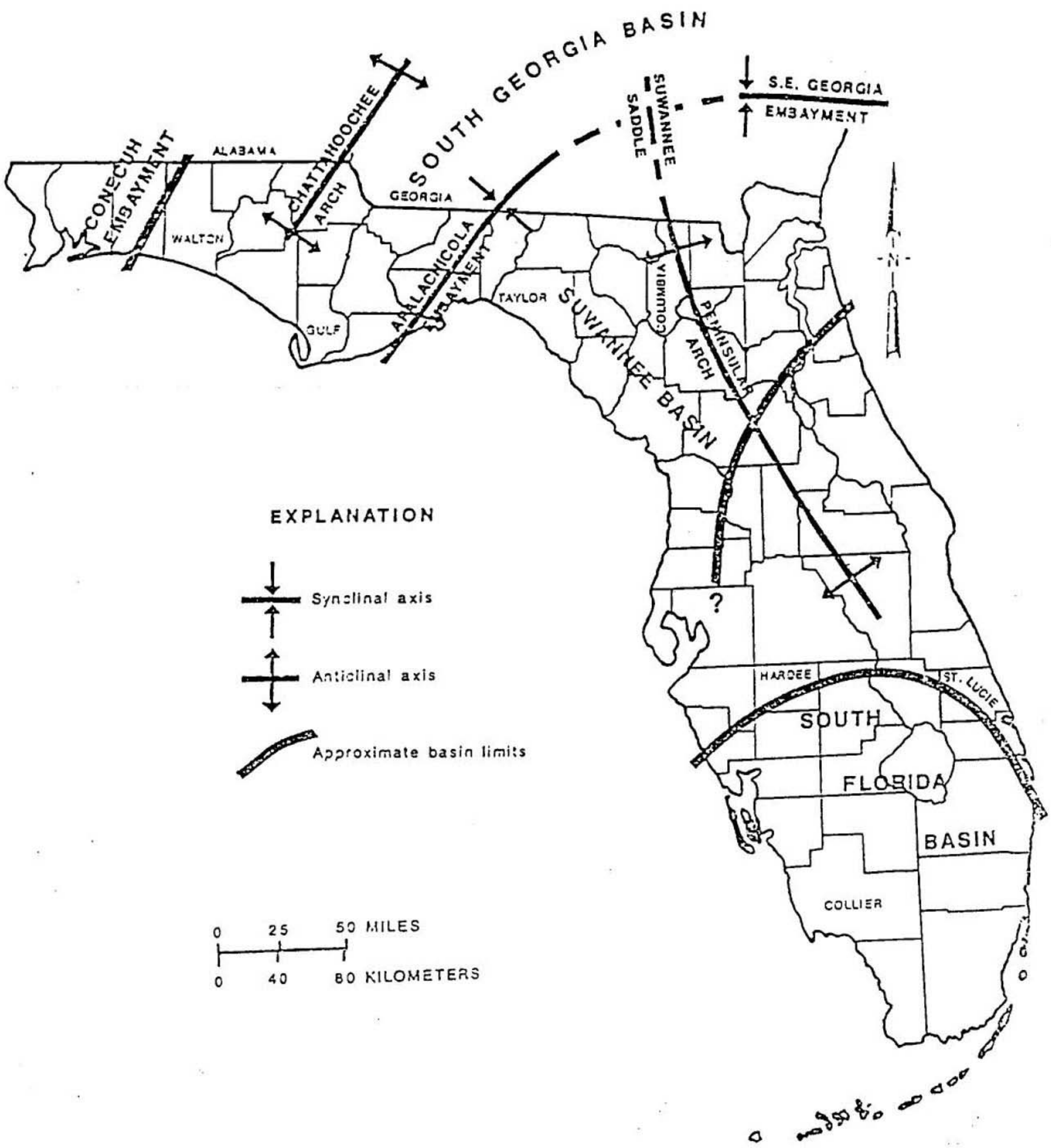

Figure 1. Florida basement pre-Middle Jurassic tectonic features (Arthur, 1988)

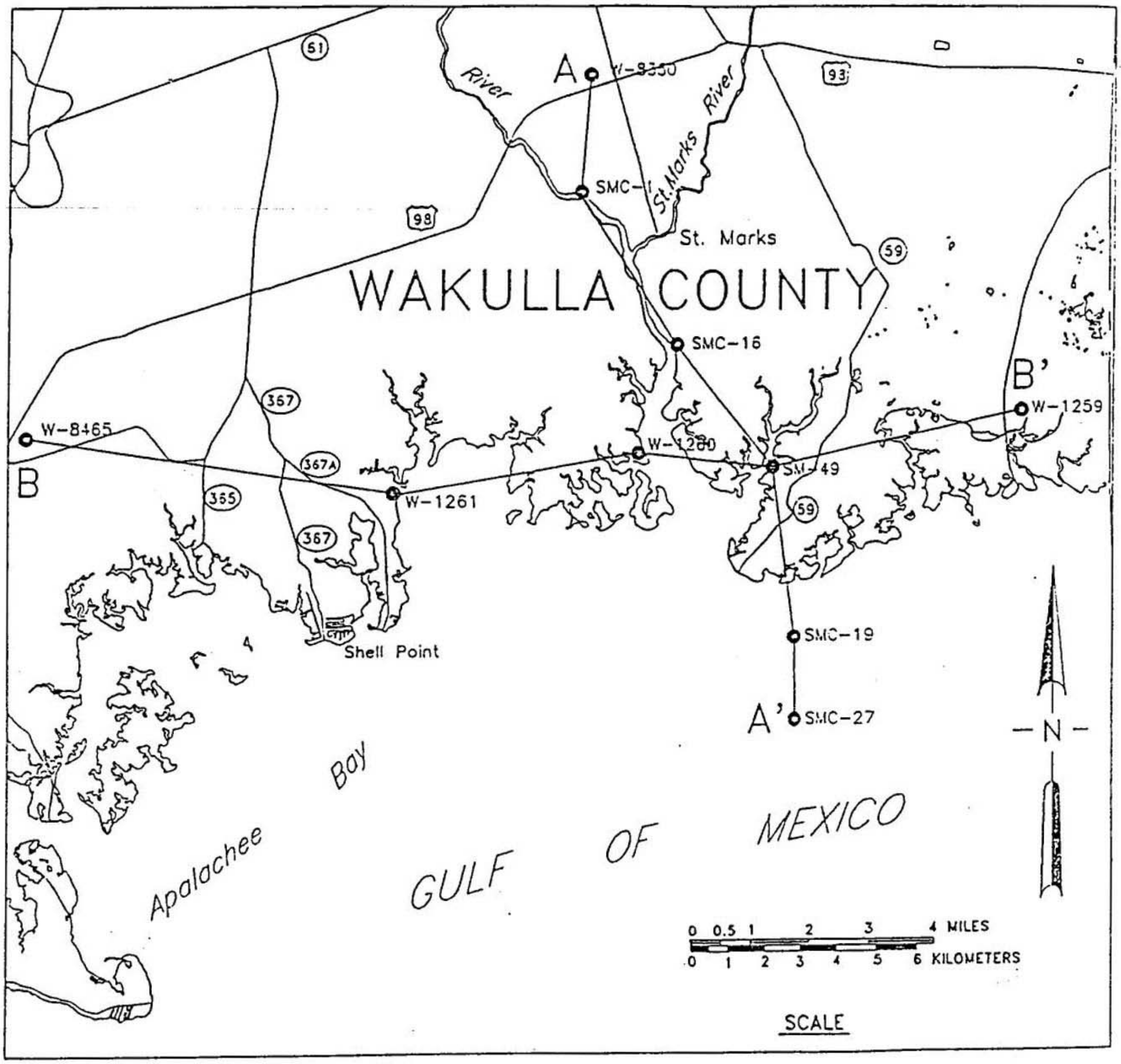

Figure 2. Well Locations for Regional Geologic Cross-sections.

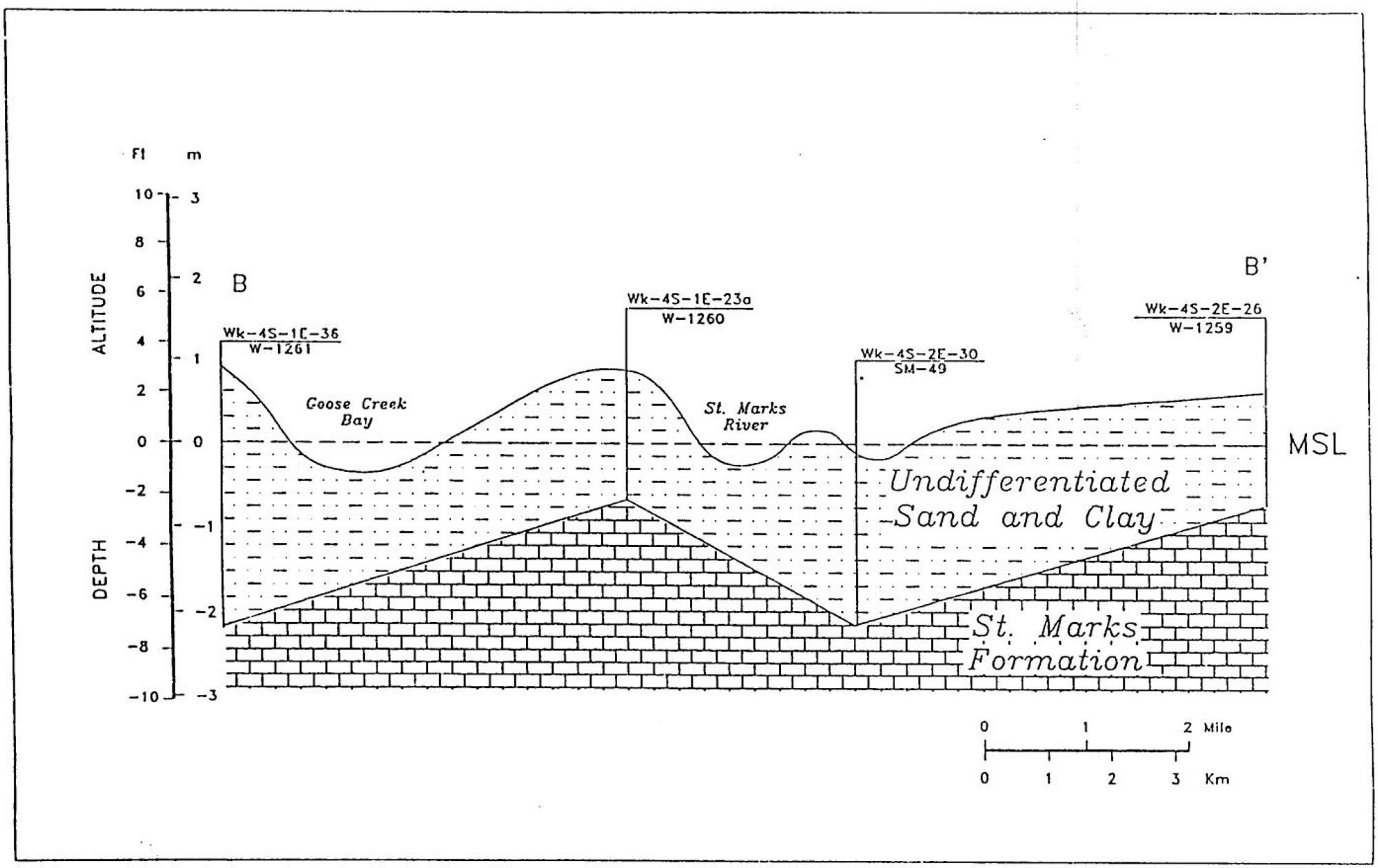

Figure 3. Geologic Cross-section B-B'

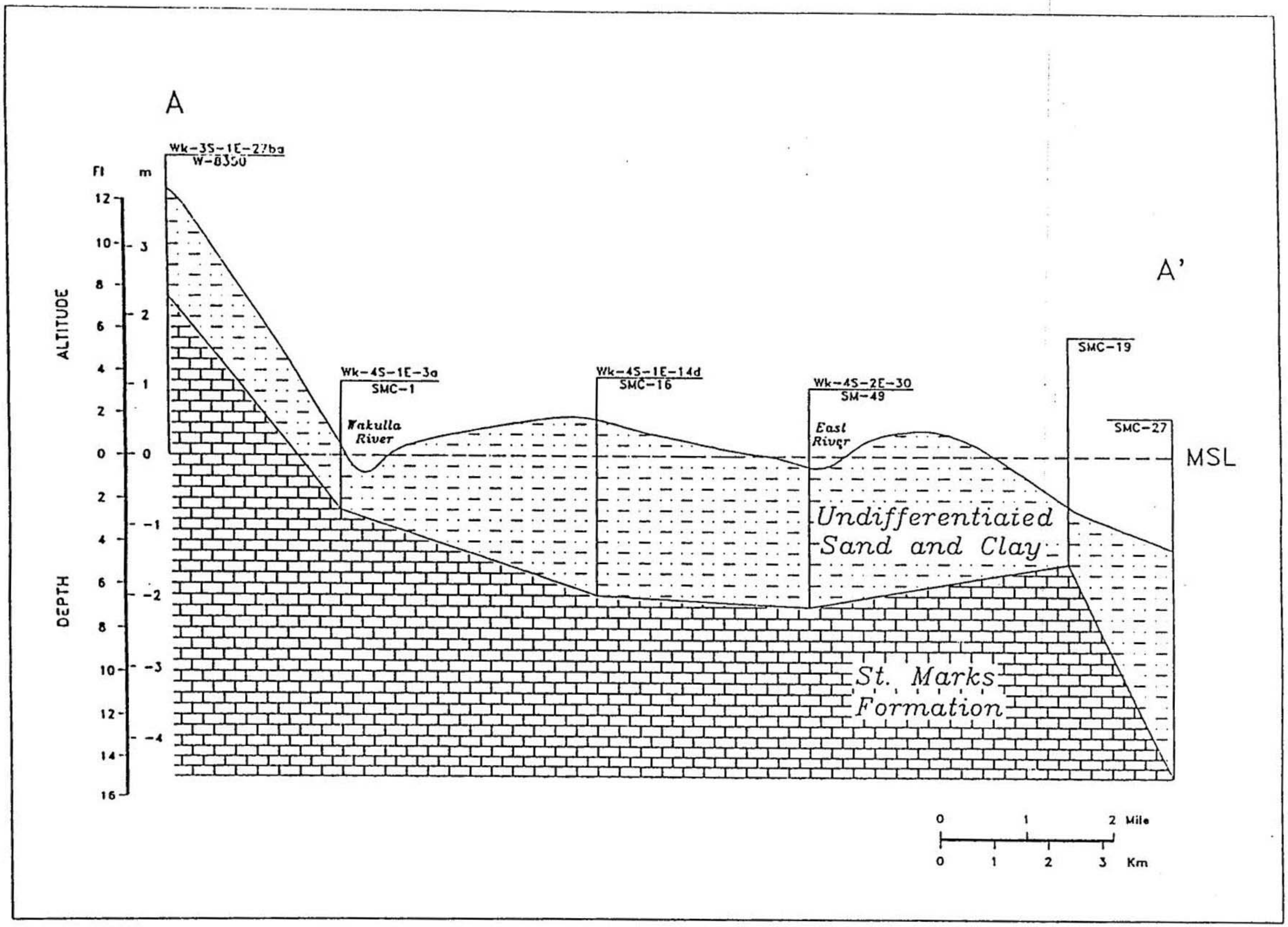

Figure 4. Geologic Cross-section A-A'

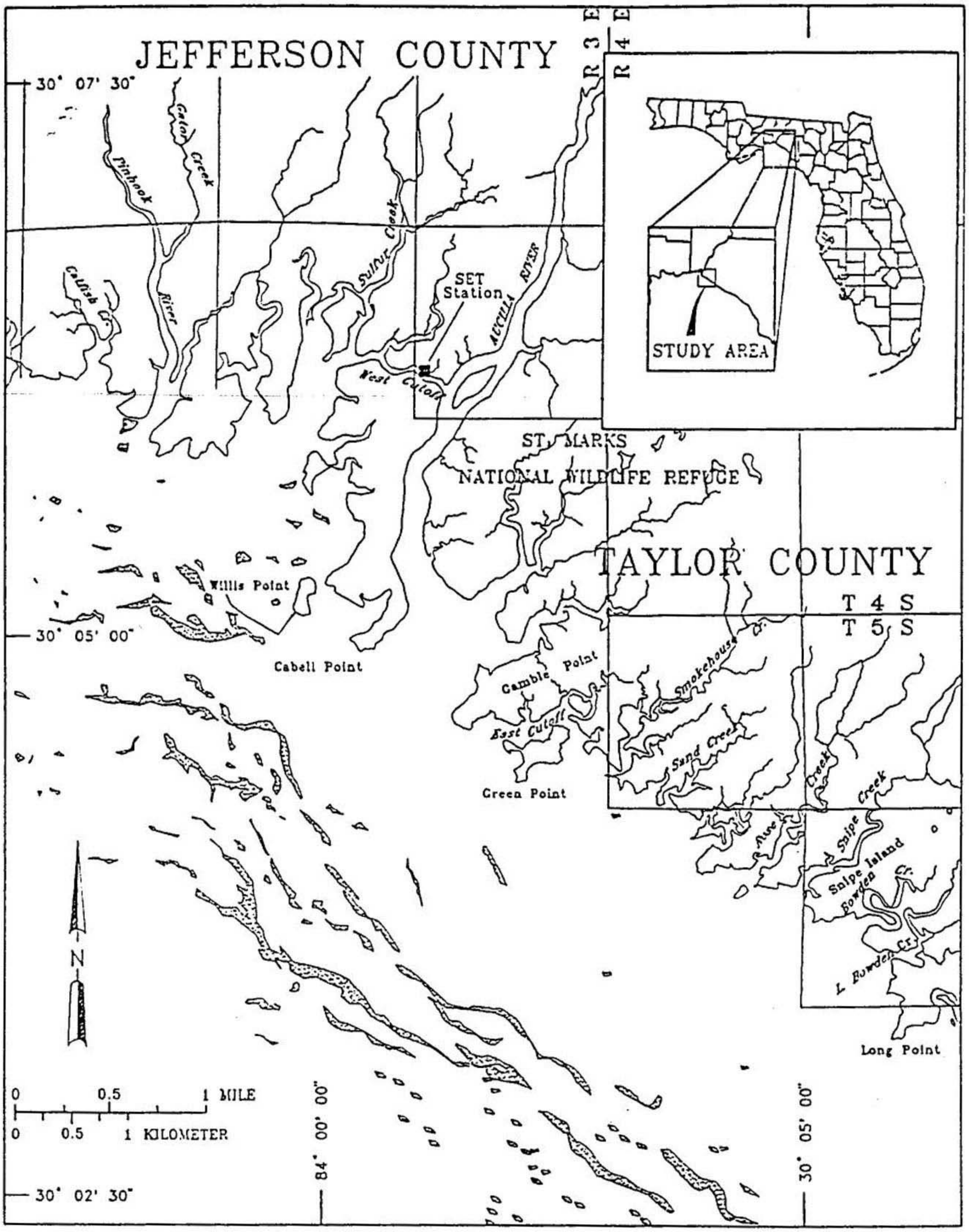

Figure 5. SET station location in the Aucilla River study area

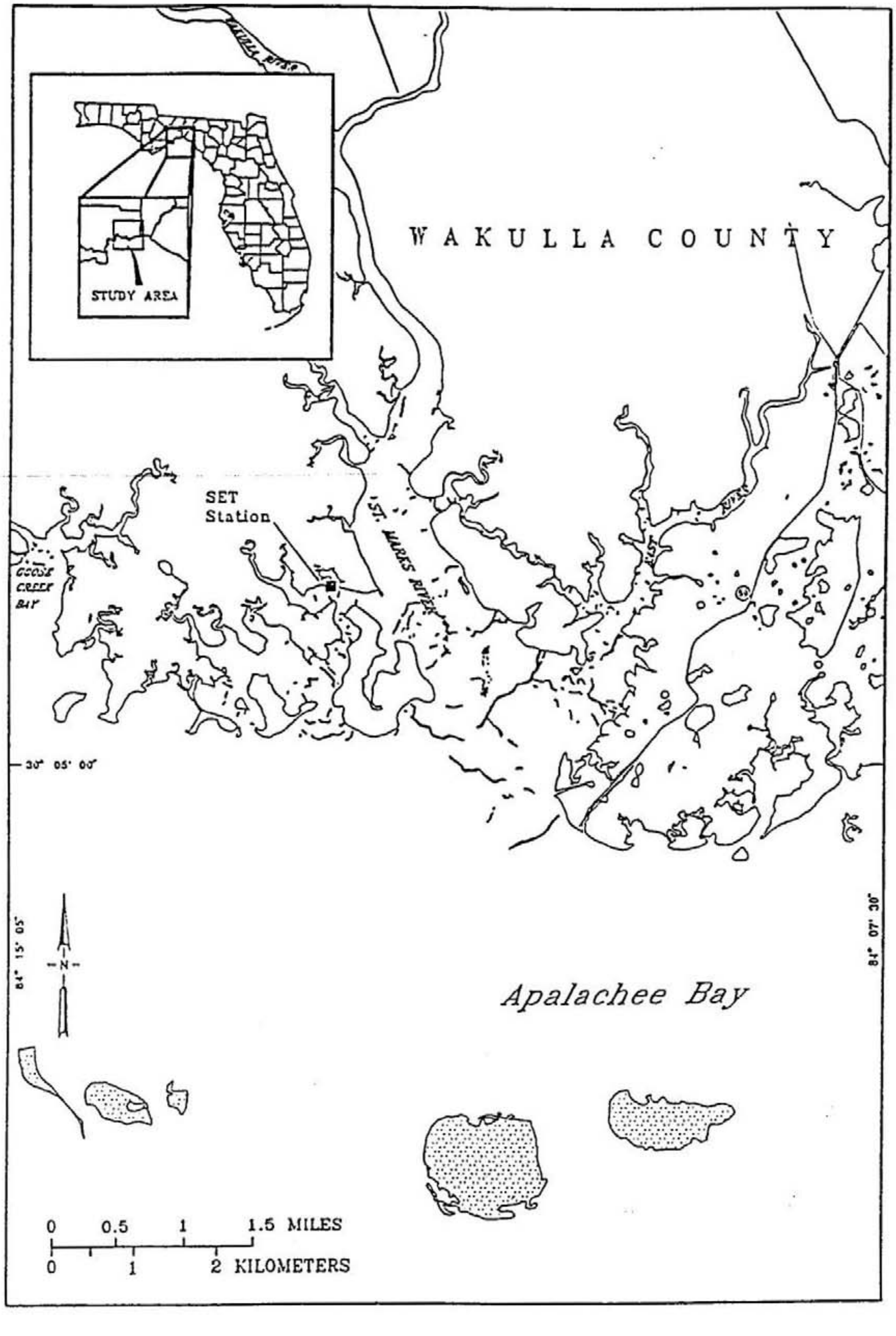

Figure 6. SET station location in the St. Marks River study area

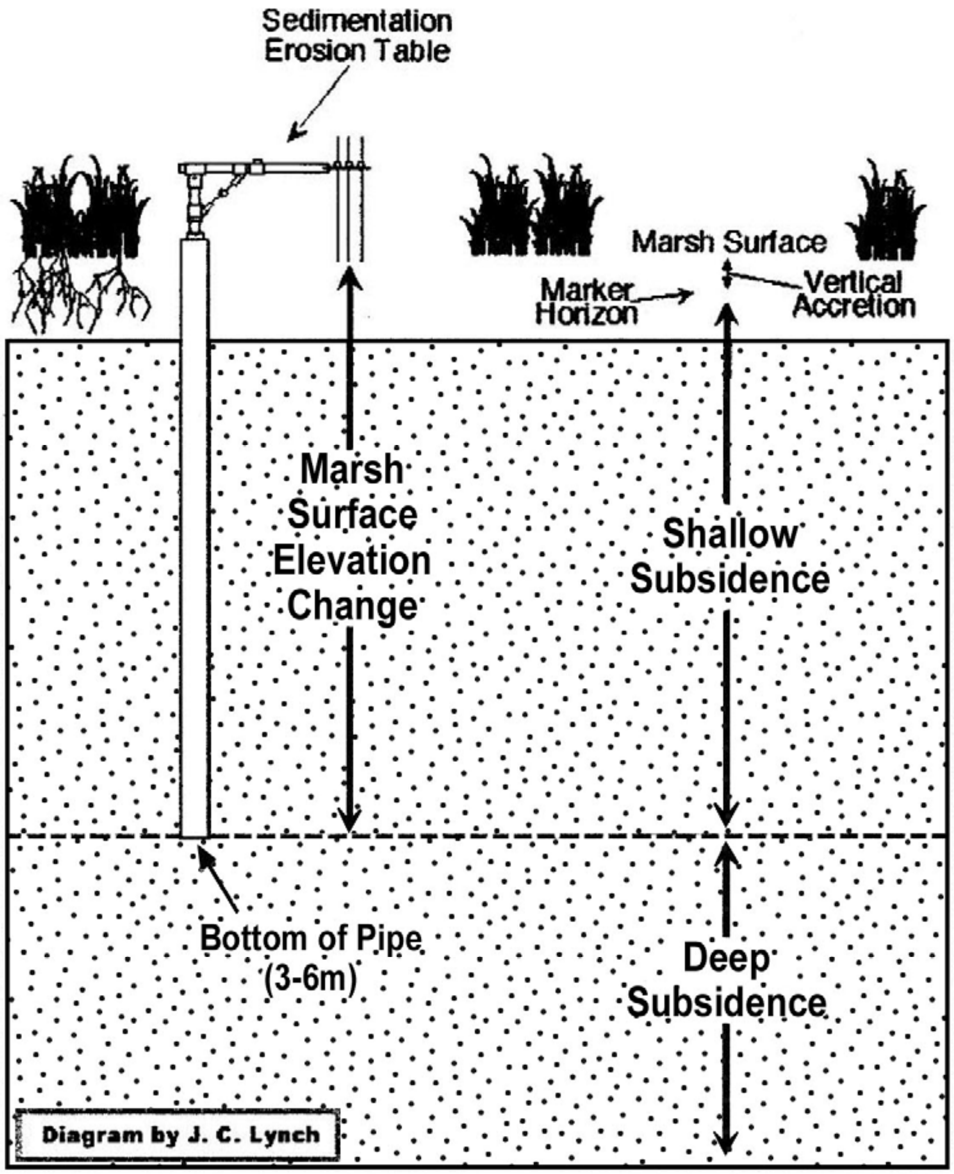

Figure 7. Plan view of Sediment Erosion Table (SET) (Lynch, 1999; Cahoon et al., 1995)

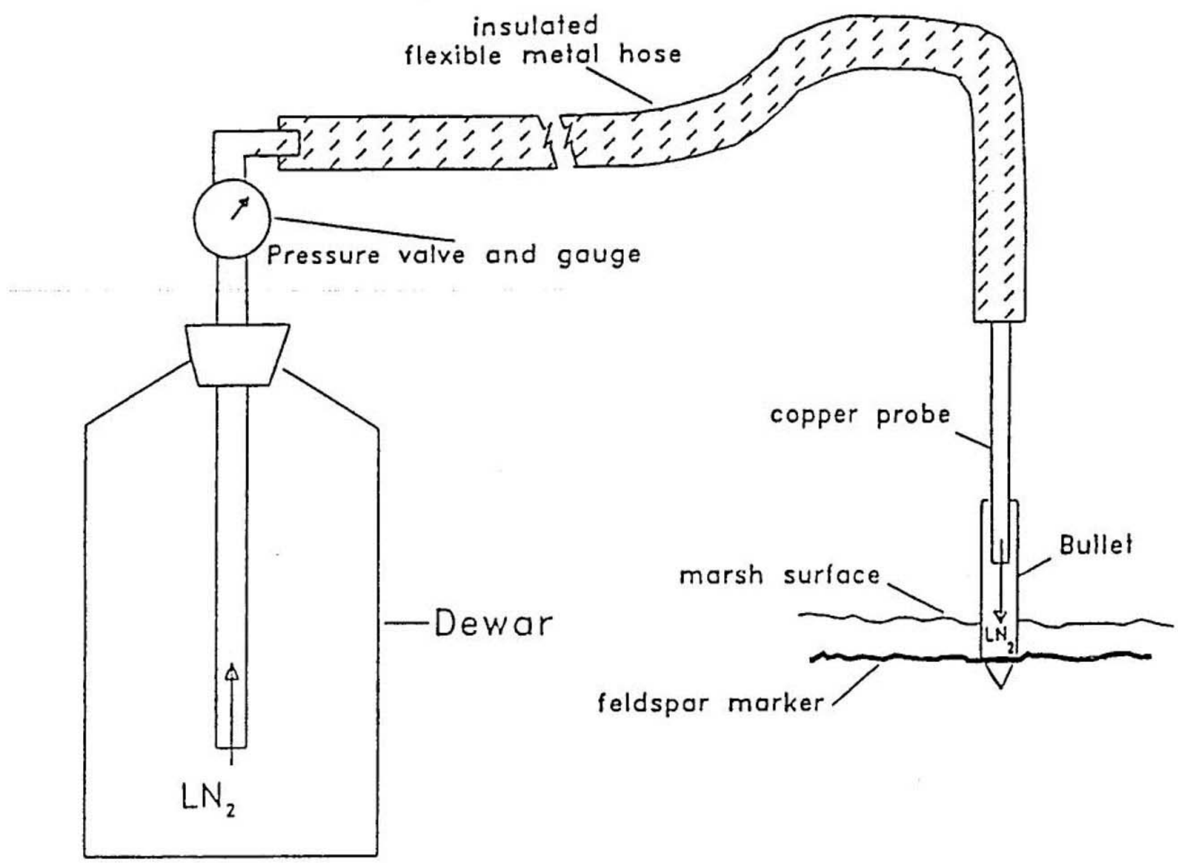

Figure 8. The cryogenic coring device of a fifteen-liter dewar filled with liquid nitrogen. A length of copper tube with a 30-30 bullet welded to its base is inserted into the marsh sediments and through the white powdered feldspar marker bed. The insulated metal hose and probe is inserted into the copper tube and is filled with liquid nitrogen, causing the surrounding sediments (and feldspar) to freeze to the walls of the copper tube. The cryogenic core or "bullet" is removed from the marsh and accretion measurements are made from the top of the feldspar horizon to the surface of the marsh (Knauss and Cahoon, 1990).

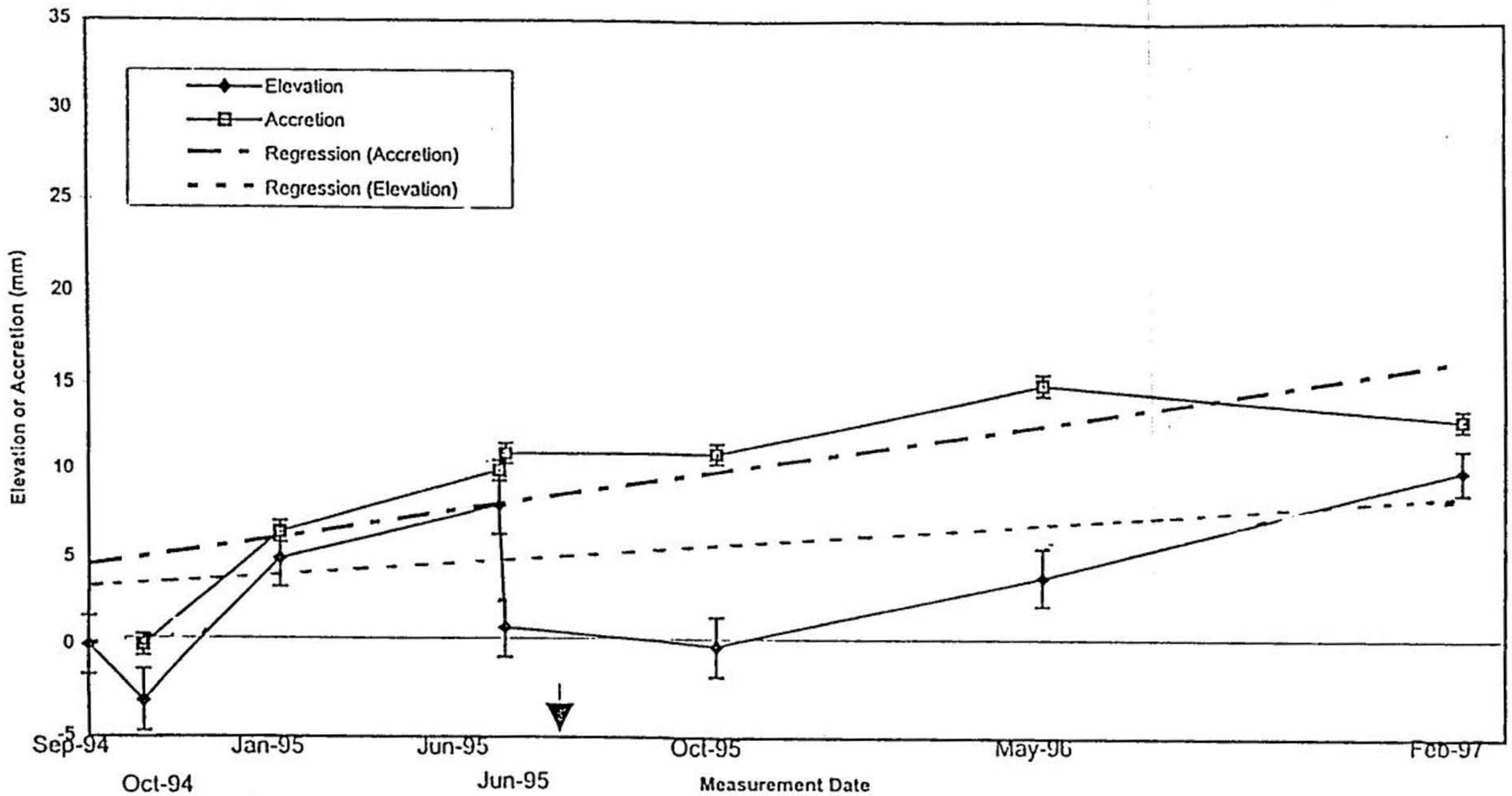

Figure 9. Elevation and Accretion vs. Time for the Aucilla River estuary site. Elevation change rate (dotted regression line) measured 3.5 mm/yr and accretion change rate (dot-dash regression line) measured 4.9 mm/yr. The arrow represents landfall of Tropical Storm Allison on 8/4/95. Note the small decrease in elevation change between measurement events surrounding the landfall of Tropical Storm Allison.

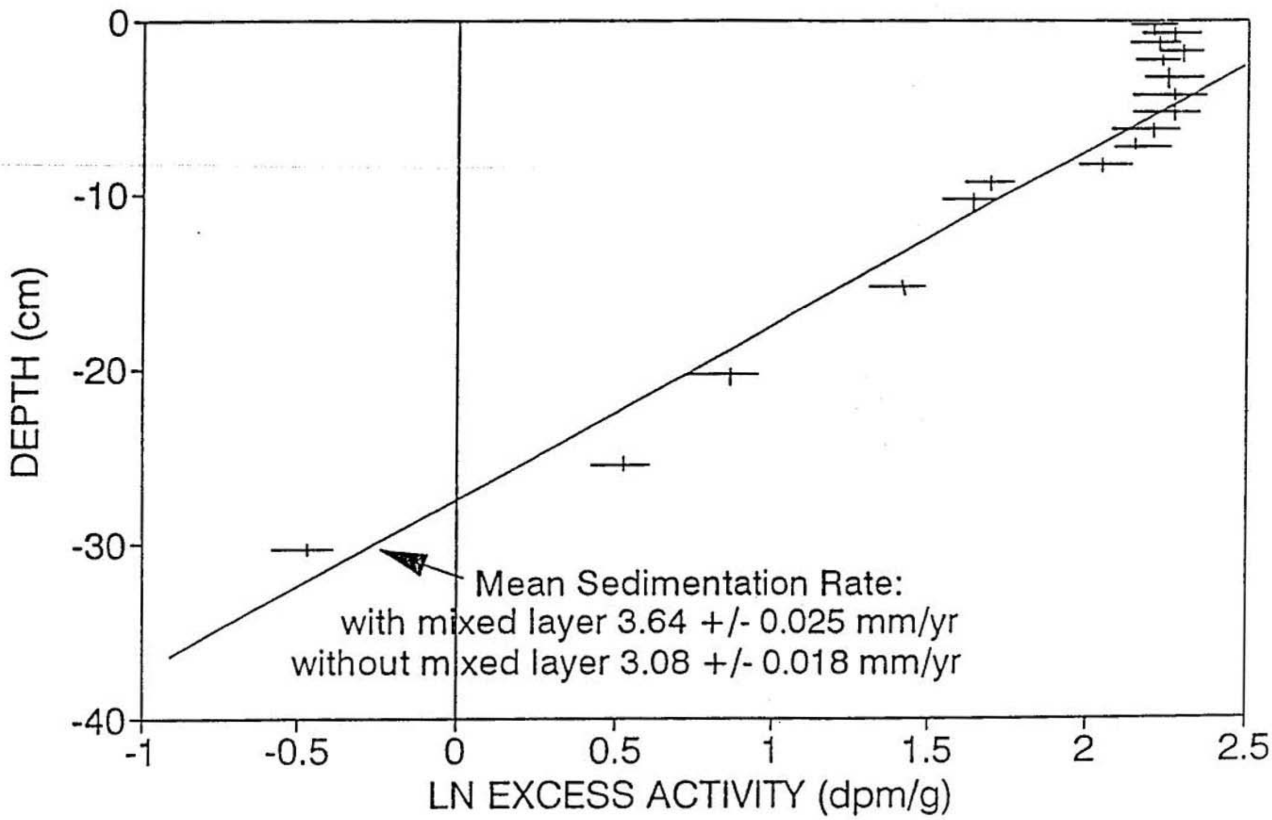

Figure 10. Excess Pb-210 activity profile for Aucilla River core (ARC-32)

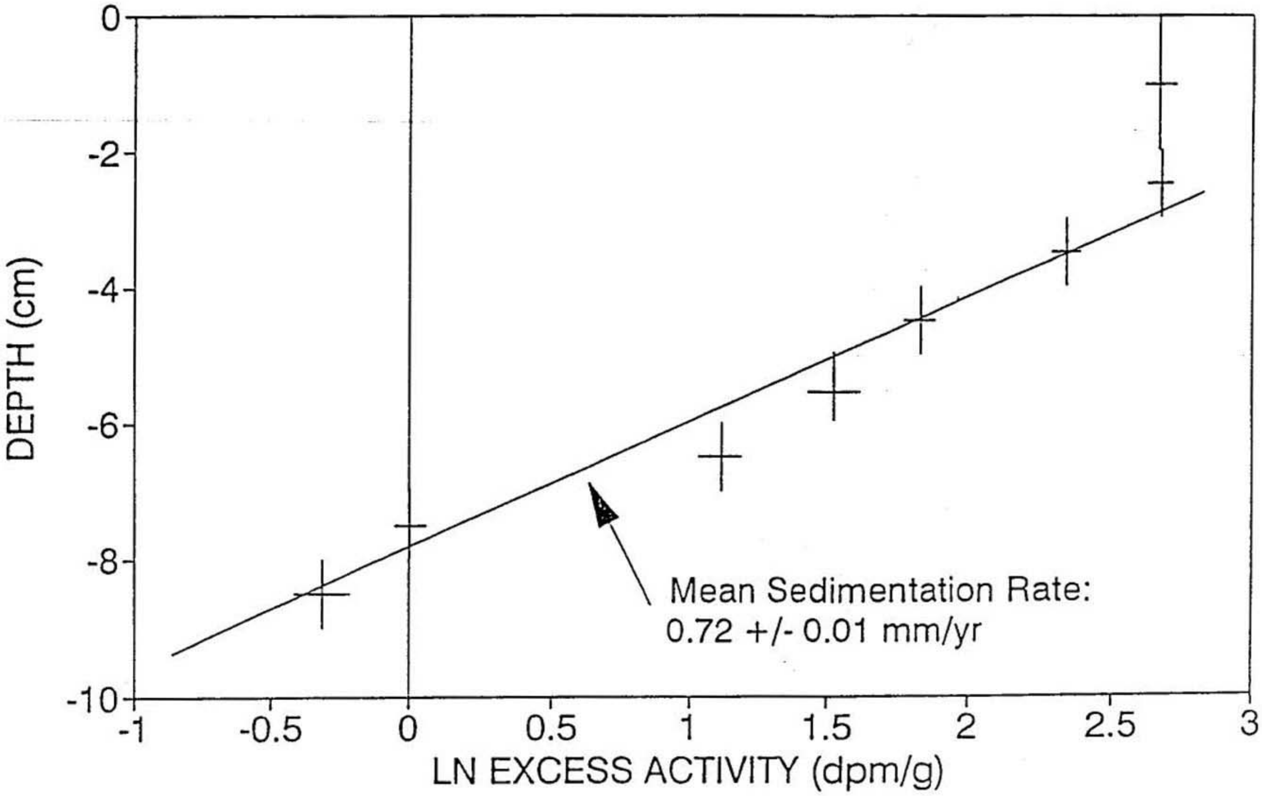

Figure 11. Excess PB-210 activity profile for St. Marks River core (SMRC-17)

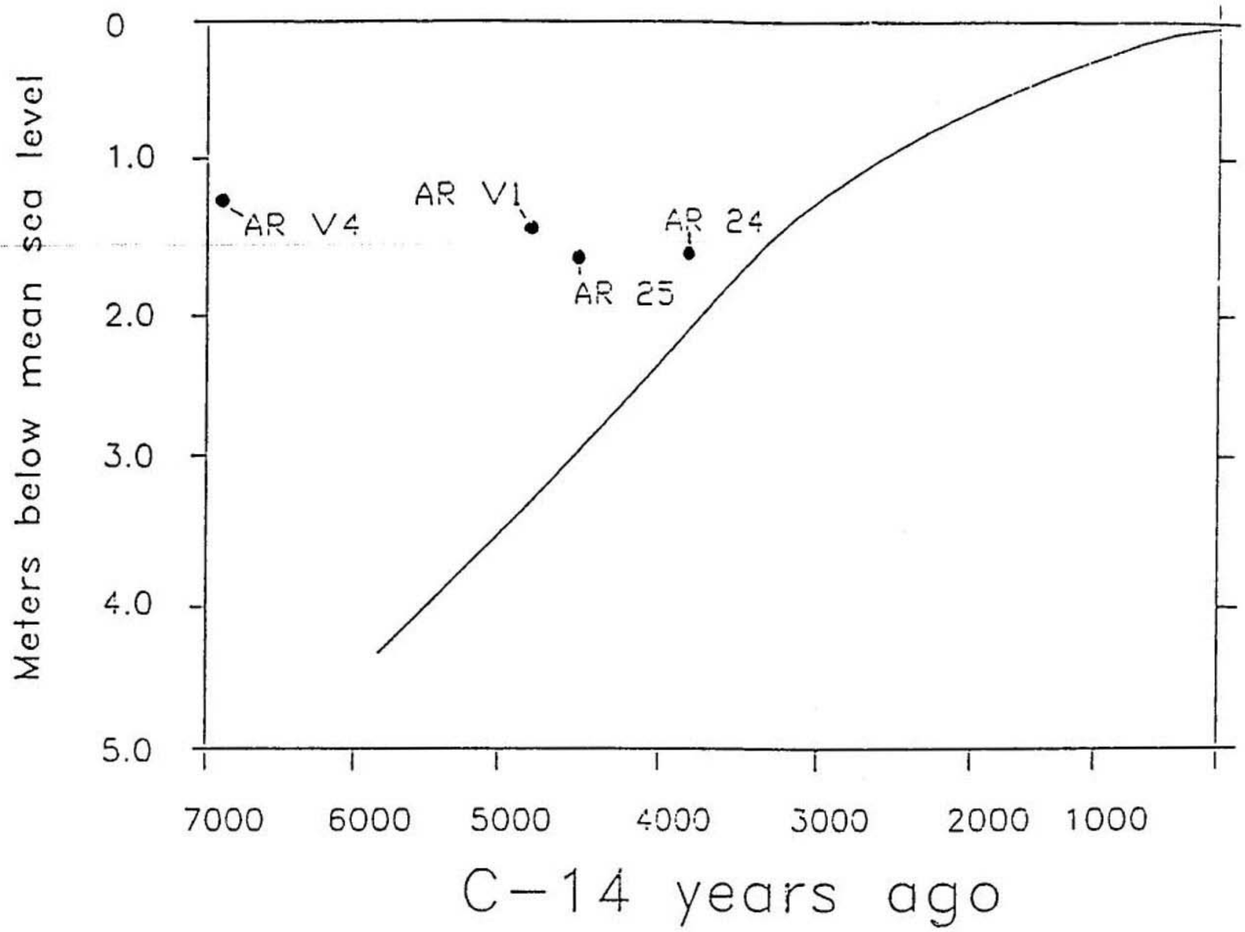

Figure 12. Southwest Florida sea-level curve (redrawn from Scholl et al., 1969) with Aucilla River radiocarbon data superimposed

Table 1. Summary table of elevation and accretion data. Elevation and accretion change measurements based on a zero datum, or the elevation of the marsh on the date the site was established. Elevation change rates calculated from linear regression of elevation and accretion change vs. time plots.

SITE	DATE	ELEVATION CHANGE (mm)	ACCRETION CHANGE(mm)	years elapsed	Elevation Change Rate (mm/yr)	Standard Error for Elevation Values	Accretion Change Rate (mm/yr)	Standard Error for Accretion Values
ST. MARKS	12-May-92	0.0	0.0	0.0	#'s based on		#'s based on	
	15-Oct-92	11.0	7.0	0.3	linear regression		linear regression	
	06-May-93	-3.0	8.5	0.7	of change data		of change data	
	03-Nov-93	4.0	10.9	1.0				
	11-May-94	-1.0	8.9	1.3				
	19-Jul-94	18.0	11.1	1.8				
	15-Sep-94	-3.0	10.3	1.9				
	29-Nov-94	1.0	10.2	2.0				
	17-May-95	2.0	12.8	2.4				
	09-Jun-95	2.0	11.7	2.6				
	27-Jun-95	3.0	n.d.	2.8				
	25-Oct-95	-3.0	5.4	3.0				
	04-May-96	-1.0	9.0	3.5				
	30-Aug-96	0.0	10.0	4.0				
	08-Jan-97	1.0	9.2	4.6				
	21-Apr-97	51.0	6.8	5.0				
				avg (mm/yr)	-0.6	0.1	0.7	0.9
SITE	DATE	ELEVATION CHANGE (mm)	ACCRETION CHANGE(mm)					
AUCLLIA	23-Sep-94	0.0	n.d.	0.0				
	27-Oct-94	-3.0	0.0	0.8				
	20-Jan-95	5.0	6.5	1.3				
	09-Jun-95	8.0	n.d.	1.7				
	13-Jun-95	1.0	11.0	1.7				
	26-Oct-95	0.0	11.0	2.1				
	17-May-96	4.0	15.0	2.3				
	12-Feb-97	10.0	13.0	2.4				
				avg (mm/yr)	3.5	0.6	4.9	0.7

Table 2. Summary table of the cryogenic data

ST. MARKS RIVER

SUMMARY OF CRYOGENIC DATA

Date	Total Days Feldspar	Station 1 Total Change Accretion (mm)	Station 2 Total Change Accretion (mm)	Station 3 Total Change Accretion (mm)	Site Average Total Change Accretion (mm)	1st Der Site Average Total Change Accretion Rate (mm\day)	2nd Der Site Average Change in Change Total Change in Elevation Rate	Station 1 Total Accretion Rate (mm\day)	Station 2 Total Accretion Rate (mm\day)	Station 3 Total Accretion Rate (mm\day)
6/9/95	0	0.00	0.00	0.00	0.00	0.00	x	0.000	0.000	0.000
6/27/95	18	x	x	x	0.00	0.00	x	x	x	x
10/25/95	138	x	4.43	6.29	5.36	0.04	0.039	x	0.032	0.048
8/30/96	309	6.60	11.20	12.23	10.01	0.03	-0.008	0.021	0.036	0.040
1/8/97	578	x	8.95	9.13	9.04	0.02	-0.017	x	0.015	0.016
1/8/97	578	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate
1/8/97	578	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate	duplicate
4/21/97	681	x	8.24	6.23	4.82	0.01	-0.009	x	0.012	0.009
1/28/98	825	14.25	x	6.90	10.58	0.01	0.006	0.017	x	0.008
6/16/98	1102	20.08	x	13.38	16.73	0.02	0.002	0.018	x	0.012

ESTUARY	CORE #	DEPOSITIONAL ENVIRONMENT	MEAN SEDIMENTATION RATE (mm/yr)
Aucilla	ARC 30	subtidal	4.20-5.12
Aucilla	ARC 31	intertidal	1.56
Aucilla	ARC 32	subtidal	3.08-3.64
Aucilla	ARC 33	intertidal	0.53
St. Marks	SMRC 17	intertidal	0.72
St. Marks	061796-01	subtidal	2.5

Table 3. Pb-210 sedimentation rates for selected cores in the Aucilla and St. Marks River

CORE #	CORE LENGTH (m)	DEPTH IN CORE (m)	DEPTH BELOW MSL (m)	UNCORRECTED C-14 AGE (yr BP)
AR 24	0.73	0.61	1.59	3885 +/- 145
AR 25	1.07	0.7	1.62	4475 +/- 130
AR V1	1.47	0.34	1.41	4810 +/- 169
AR V4	1.46	0.91	1.22	6920 +/- 195

Table 4. C-14 data for Aucilla River wood samples

WAKULLA SPRINGS -- QUALITY OF LIFE

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ABSTRACT

People have been attracted to Wakulla Springs for thousands of years for the same reasons; clear cold water. Their purpose for coming has changed from providing basic food and drinking water to an outlet for recreation and relaxation.

Early Native Americans used the Springs and the surrounding area for hunting and gathering food. Evidence, such as stone tools, unearthed during several archaeological excavations has proven that the site has been inhabited by people for over 10,000 years.

By the mid 1800's people came to the springs for a different reason. Leisure time activities were becoming more popular and the springs provided an opportunity to experience something unique. Providing these outlets for people has now become essential to their well being and state of mind. Recreation, whether it is in the form of swimming, hiking, picnicking, wildlife observation or relaxing, can improve the psychological and physical health of societies. On the other hand the lack of these outlets increases societal problems.

The resources that are necessary to provide these quality recreational experiences must be preserved through research and proper planning. Maintaining the water quality, the focal point of Wakulla Springs, is the most important. However, maintaining the rural character of the area surrounding the park also provides a soothing effect.

Protection of this resource is an issue of not only environment but also quality of life.

People have been attracted to Wakulla Springs for thousands of years for the same reasons; clean, clear water. Their purpose for coming has changed from providing basic food and drinking water to an outlet for recreation and relaxation.

Early Native Americans used the springs and surrounding area for hunting and gathering food. Randomly collected flint scrapers and stone tools give us clues to the spring's first human visitors. Evidence suggests that Wakulla Springs was occupied from the Paleo-Indian period (15,000 – 8,000 BC) through the Archaic period (8,000 – 5,000 BC). Visits by some of the first European explorers have also been well documented. The reason for being there and their quality of life was sustained based on the availability of clean water.

Some early visitors may not have been as impressed with the sight. In the early 1800's a topographical engineer from Tennessee was instructed to prepare a report of General Andrew Jackson's route through Florida. With an eye towards development, he noted that land around this basin is second rate: *"the growth hickory and oak with some cane, the surface agreeably uneven and having charming spots for settlement."*

Growth for what was then called Middle Florida, the area between Apalachicola and Suwannee Rivers, was inevitable. The East and West Territories had agreed on locating the new capitol in Tallahassee. Publications frequently began providing reports on Wakulla Springs and its natural wonders. In 1835 one anonymous author wrote:

> *But the most singular of all the greatest natural beauty, and I may say, the greatest curiosity of the whole South, is the source of the Wakulla, before mentioned in Middle Florida, six miles distant from St. Marks. Its origin, be it remembered, is said to be Lake Jackson, at 15 miles distance. This lovely sheet of water is 120 yards in diameter so still and of such perfect transparency, that the smallest object is seen at the immense depth of water below; and the spectator upon it surface, sits and shudders as if suspended in empty air. On some future, and not distant day, these banks will be studded with private residences, as indeed even now the country round it is full of plantations.*

During the second Seminole war the springs was visited by a clergyman who was staying at Ft. Stansbury near the dividing line of Leon and Wakulla counties. Accompanied by soldiers, their visit included a leap in the spring that felt as though you were leaping out of the earth in a single bound. A ride over the spring gave him the familiar feeling of dizziness and floating on air. Afterwards he declared *"The Wakulla is one of the lions in Middle Florida, it will* *attract many visitors into the country, as soon as we shall be rid of certain wild animals."* Now-a-days a visit to the park may make you wonder if the wild is still present. Field trips bring 14,000 students annually for educational purposes, thousands more each summer to swim.

By 1873 the spring had changed hands again and J.W. Dugger was able to capitalize on Wakulla's commercial value. The weekly Floridan announced a new attendant who is provided with several good, safe boats and is always on hand to accommodate private and picnic parties with a row over the bosom of the springs. Although the oars have been changed to electric motors, generations of people have both driven the boats, as well as, rode as passengers over the spring. Many people then and now have a sense of ownership of the Springs.

Through luck or fate several proposed commercial ventures for the springs were never accomplished. A Cincinnati physician selected and purchased the site to build the most beautiful sanitarium in the nation. A natural place for the soul. In an effort to maintain local support, he proclaimed the old fountain as still belonging to Wakulla County.

Thankfully enough the sanitarium and yet another proposed commercial venture for a paper processing plant failed. The spring water had just the right qualities for processing saw palmetto to make paper. We might have ended up much like the Fenholloway River had the project be completed.

By the early 1900's rapid changes were occurring in Florida due to improved transportation and the Florida land boom. Opinions were divided, with some citizens anxious to see economic development and others fearful of destructive exploitation. Hummmmmmm? Sound familiar? I've heard the same comments made in recent years. And now Wakulla County faces that rapid growth period.

After much anticipation, in 1937 Edward Ball finally completed the development of the spring area including the lodge. The facilities were well received. Now people could stay for longer periods and have all the needed comforts. The lodge had many amenities not available in other areas such as advanced systems of sewage removal, waterworks and power plants. But it was not enough for some people. Articles in both the Wakulla News and Tallahassee Democrat promoted expansion of the facilities and more publicity. Comparisons were made to Silver Springs & Weeki Watchee. They wanted to use Wakulla Springs to attract more people to the area. Ed Ball refused and continued to operate Wakulla Springs in a park-like manner. The Tallahassee Democrat editor later paid him a tribute. The Coney Island atmosphere and inappropriate three-ring circus shows so prevalent at many large springs in Florida have been avoided.

Visitors to Wakulla Springs as early as the 1800's came for the same reasons they visit today – recreation, relaxation and something different. Leisure time activities became more popular and the springs provided an opportunity to experience something unique. Providing these outlets for people is essential to their well being and state of mind. Recreation, whether it is in the form of swimming, hiking, picnicking, wildlife observation or relaxing, can improve the psychological and physical health of societies. On the other hand the lack of these outlets increases social problems. Law enforcement, Correctional Facilities and health care are essential. Recreation in a more subtle way is also important and reduces the need for those other government services.

Many activities associated with Wakulla Springs might be considered a cultural experience. Adults who bring their children to swim and jump from the tower reminisce about coming with their parents and their first jump. Of course, they proclaim the tower "was much taller back when I was a child" (and it was). Others reminisce on the boat tours. I remember going on Luke's tour. He was great. My grandparents would tell me how the boats were guided over the spring using long oars. The driver would chant to Henry, the pole vaulting fish and sing up the Catfish Convention. Some of today's drivers claim it's the same fish and they only respond to certain singing.

Whether through luck or fate Wakulla Springs has had numerous close calls and managed to escape being completely commercialized. It is our responsibility to continue to protect its resources that are necessary to provide these quality recreational experiences so that future generations can watch Henry pole vault, swim in an untainted spring or bail off the tower. Through continued research and proper planning of the surrounding area, damage to the resources can be minimized. One might argue that a single landowner has certain rights to do whatever he wishes with his property. However, that argument will not hold water when a single landowner's actions interfere with many individuals rights to lead healthy, normal lives.

Protection of a natural resource is not only an issue of environment but also one of quality of life.

TWO CYCLES OF LATE PLEISTOCENE SINKHOLE FILLING IN THE MIDDLE AUCILLA RIVER, JEFFERSON COUNTY, FLORIDA

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ABSTRACT

During the past decade the Aucilla River Prehistory Project (ARPP) has intensively explored the middle reaches of the Aucilla River in search of relatively thick, continuous sections of late Pleistocene sediments. Teams of paleontologists and archaeologists have successfully excavated more than a dozen such sections using SCUBA, dredges and underwater lights. The sections studied by ARPP range from about three to more than five meters thick and represent nearly continuous deposition of fine-grained, highly-organic clastic sediments, including peats, clays, silts and fine sands. Most of these sections lie immediately adjacent to relatively deep holes in the uneven bottom profile of the river. Evidently these sediment packets in the Aucilla River represent sinkhole fillings in the Suwannee Limestone, now partially exposed by the river.

In the course of its excavations, the ARPP has acquired more than 60 radiocarbon dates on river-bottom sections from the middle reaches of the Aucilla River. We anticipted that the dates would represent the last deglacial hemicycle, driven by a rising piezometric surface geared to the latest glacial sealevel rise. For a majority of dated sections that expectation was fulfilled. For example at the Page-Ladson site sediments record fine details of back-filling history between 15,000 and 9,000 radiocarbon years. Quite unexpectedly, however, nearly 40 percent of the sediment packets samples and dated by ARPP represent a previous interval of sinkhole filling with dates between about 28,000 and 34,000 radiocarbon years before present. This earlier cycle of sinkhole filling correlates with the next highest oxygen isotopic peaks (before the latest Pleistocene) in the Greenland Ice Core record. The abundance of such sediments in the Aucilla River, despite being overprinted by a later cycle, suggests that they played an important role in regional karst history.

For nearly two decades the Aucilla River Prehistory Project (ARPP) has intensively explored the middle reaches of the Aucilla River in search of relatively thick, continuous sections of late Pleistocene sediments. In the course of this project, teams of underwater paleontologists and archaeologists developed new techniques by which they can concisely excavate long records of fossils and cultural remains. Multidisciplinary analyses of the ARPP results record essential features in the extinction of the megafauna, early arrival and cultural change in human populations, and late Quaternary environmental prehistory in the northern peninsula.

Stratigraphic sections in the Aucilla River, studied by the ARPP, range in thickness from about three to six meters and represent gradual deposition of fine-grained, highly organic, clastic sediments dominated by peats, clays, silts and fine sands. Most of these sections lie within relatively deep holes in the uneven bottom profile of the river. Evidently these sedimentary sections represent sinkhole fillings in the Suwannee Limestone, subsequently exposed by river erosion.

In the course of its explorations in the middle Aucilla River the ARPP has identified and sampled several dozen sites, and worked intensively at a handful. As part of this prehistory program the project has submitted more than 60 samples from these sediments for radiocarbon dates. This is the first extensive set of dated sediments from the bottom of a Florida karst river. We anticipated that the dates would represent the last deglacial hemicycle driven by rising piezometric surface geared to sealevel rise during the latest glacial interval. That expectation was fulfilled in a majority of dated sections, most notably at the Page/Ladson site where back-filled sediments record much of the interval from more than 15,000 to less than 9,000 radiocarbon years before present.

Quite unexpectedly, however, nearly 40 percent of the sedimentary sections sampled in the middle reaches of the Aucilla River represent an earlier interval of sinkhole filling, with a predominance of radiocarbon dates between 28,000 and 34,000 radiocarbon years before present. Representation of these older sediments becomes proportionally more abundant in the lower (downstream) portions of the studied area. This earlier cyle of sedimentation correlates with the next highest oxygen isotopic peaks in the Greenland Ice Core record. Thus, stage 3, the penultimate sealevel rise, is nearly as well represented by backfilled sediments in the middle Aucilla River, as stage 2, the latest sealevel rise. The abundance of these older sediments in the Aucilla River, despite being overprinted by a later cycle, suggests that they played an important role in regional sealevel and groundwater history in the Woodville (Wakulla) Karst Plain.

INTRODUCTION

Sealevel changes undoubtedly have played a major role in the geologic history of Florida. Such changes are intensely focused in the Gulf Coastal Plain, where the shallow gradient of the coastal lowlands exaggerates the effect of even minor transgressions and regressions of the sea. Textbook descriptions of eustatic changes in coastal lowlands are usually set in clastic sedimentary regimes, where the effects of terracing and longsshore drift predominate. Equivalent processes pertaining to karstic coasts are less readily described, and inherently more obscure.

North peninsular Florida, and especially the Woodville Karst Plain, clearly represent a region with a low coastal gradient and an important history of rising and falling sealevels during the Quaternary (Donoghue, 1993; Lane, 1989). In this tectonically stable area, eustatic changes, driven by global glacial and interglacial cycles, must be a primary mechanism forcing patterns of deposition and erosion. A simple verbal model posits two opposite phases of a glacial/interglacial cycle. During a glacial phase, as the sealevel falls, local sinkholes and other karst features are increasingly exposed by a declining piezometric surface. Accordingly the subterranean conduit systems are enlarged, interconnected and conducted farther into the Gulf of Mexico at ever-lower baselines. On the other hand, during a deglacial hemicycle, as the sea and the piezometric surface rise, local sinkholes and other karst features in the coastal plain would begin to backfill with locally derived sediment, until they attained the local baselevel. Then springs would spill onto the land surface and sinkholes and other conduits would become integrated into stream systems.

Recent research on late Quaternary sediments in the middle reaches of the Aucilla River by the ARPP exemplifies some of the patterns suggested by this verbal model. In this paper, I present some preliminary results from that research, and suggest that the general history of erosion and deposition for the middle Aucilla River may exemplify the effects of glacial to interglacial sealevel cycles for the entire Woodville Karst Plain. That hypothesis requires fuller testing both in marine and in other freshwater sites.

GEOMORPHIC STATUS OF MIDDLE AUCILLA RIVER

The Aucilla River drains the upland region of north peninsular Florida and adjacent parts of southern Georgia, breaks across the Cody Scarp onto the Woodville karst plain, and flows southwestward into the Gulf of Mexico. Its source area consists of the predominantly red clay sediments in the Tallahassee Hills and adjacent parts of north Florida and south Georgia. The river defines the eastern boundary of Jefferson County, the only Florida county that extends all the way from Georgia to the Gulf of Mexico.

Figure 1 maps the middle reaches of the Aucilla River featured in this report. Within this area the river is notable for its discontinuous nature. It disappears from the land surface, reappearing in a rise at some considerable distance at Half-Mile Rise, then at Little River Rise, and finally at Nutall Rise. The Aucilla bears a complex relationship to the Wacissa River which rises at the foot of the Cody scarp and sends multiple tributaries to the Aucilla. The most headward of these tributaries enters the middle of Half-Mile Rise over a natural race (small waterfall). Numerous sinkholes dot the adjacent karst plain throughout the middle reaches of the Aucilla River and adjacent segments of the Wacissa River. An apparent former watercourse runs parallel to the Half-Mile Rise and the Little River segments of the present Aucilla River. All of these features indicate that the middle reaches of the Aucilla River, as well as adjacent parts of the Wacissa River, represent an immature stage of geomorphic evolution.

METHODS AND PURPOSE OF THE AUCILLA PREHISTORY PROJECT

In 1983 a team of paleontologists and archaeologists initiated a long-term project to investigate the late Quaternary history of the middle Aucilla River. Specific impetus for this project was discovery of a Bison kill-site in the adjacent Wacissa River (Webb et al., 1984), but the more general motivation was our sense that this river system held a major prehistoric resource that warranted serious exploration. This team has conducted its underwater investigations for an average of more than one month during each year for the subsequent decade and a half. This report is one of a series of ongoing studies by the Aucilla River Prehistory Project (ARPP), covering the geology, paleontology and archaeology of this area.

We developed teams of SCUBA divers working in pairs to explore the most promising areas previously identified by hobbyist collectors. Our initial surveys of the river bottom were followed by vibracoring in selected areas to determine the depth, age and nature of source sediments. The goal was to find bones and teeth of late Pleistocene megafauna in association with Paleoindian lithic artifacts in thick sections of organic sediments. It soon became evident that the promising areas were deep circular areas often associated with relatively wide segments of the river. The intervening stretches of riverbottom were shallower, often narrower, and consisted of Oligocene Suwannee Limestone. Thus our exploration revealed that the river bottom consisted of the regional limestone alternating with eroding, sediment-filled sinkholes.

The first major site that the ARPP developed was the Page/Ladson site (Dunbar et al., 1989), located in Figure 1. The site complex is about 60 meters long by 45 meters wide, and was explored by opening diverse test pits in the deeper exposures, typically at depths of seven to ten meters. In order to conduct detailed excavations in darkwater settings, we used 1,000 watt snooper lights, a two-by-three meter track measuring device to control the site, and induction dredges with floating screens to capture sediments after they were removed from the bottom. Vertical control was maintained by measuring depths from bank gauges, and by excavating in regular 20 cm increments, giving way to natural stratigraphic breaks. The walls of our test pits stood intact from season to season, although the river filled the depressions with loose leaf litter. In this way we developed reliable methods for developing in-place collections from well-stratified late Quaternary sediments in submerged sinkhole settings. Figure 2 illustrates the major stair-step section below the west bank at the Page/Ladson Site.

DEPOSITION DURING LAST DEGLACIATION

The sedimentary section repeatedly sampled in the Page/Ladson site is about six meters thick . The sediments consist mainly of fine-grained organic clastics, predominantly peaty clay and silt. The richest bone and stone producing sediments, however, are fine to medium calcareous sands which appear at two levels in the lower third of the section. A continuous chronological record, based on 44 carbon dates, indicates the schedule and rates of sedimentation in this back-filled sinkhole. Evidently late glacial backfilling of this sinkhole began at a little before 15,000 years ago, and was largely completed a little after 9,000 years ago. Only one reversal in the filling sequence is evident: that is represented by a brief stillstand and dark paleosol at about 10,000 radiocarbon years ago. This corresponds almost surely to the Younger Dryas cooling episode. Sinkhole filling resumed in about a thousand years. Finally, as indicated in Dunbar et al. (1989), evidence of stream-flow and extensive collapse of adjacent limestone appeared about 5,000 years ago. The important point, in the present context, is that virtually all of the Page/Ladson sinkhole filling corresponds to the last deglacial hemicycle and to corresponding sealevel rise. Even the brief reversal of the Younger Dryas is reflected in the local sedimentation history of the Page/Ladson sinkhole.

OXYGEN ISOTOPES AS SEALEVEL PROXIES

During the Quaternary records of sealevel changes are clearly recorded in the last glacial cycle in many coastal regions around the globe. Older cycles are more problematic, however, except in some tectonically active oceanic islands where such evidence is emergent. A proxy record of sealevel changes, however, can be read from cooling and warming cycles represented by oxygen isotope ratios recorded in deep-sea cores. Even more detailed records of the last few glacial cycles are preserved in ice cores from Greenland and Antarctica. The oxygen isotope chronology of glacial cycles and corresponding sealevel cycles are well known and widely accepted (Grootes et al., 1993). On this basis one can determine schedules of earlier sealevel cycles.

RECORD OF PENULTIMATE DEGLACIATION

In its underwater explorations and excavations in the middle reaches of the Aucilla River, the ARPP has developed approximately a dozen sites from which we have acquired more than 60 carbon dates. We anticipated that all of the sinkhole sediments would record the same last deglacial hemicycle, representing the same general history as that documented at the Page/Ladson site. As indicated in Figure 4, however, there is also a second cluster of much older radiocarbon dates.

This earlier cluster of sinkhole filling in the Aucilla River correlates with the next older peak in oxygen isotope ratios in the deep sea and Greenland ice core records (Grootes et al., 1993). The ultimate glacial is known as oxygen isotope stage 2; while the penultimate glacial is stage 3. Oxygen isotope stage 3 extends from over 30,000 to about 28,000 years ago. In the Woodville Karst Plain, one might expect sinkhole filling to occur in conjunction with rising sealevel during any glacial termination. This new evidence indicates that the penultimate deglacial hemicycle was nearly as well represented as the final deglaciation.

COMBINED EVIDENCE OF LATE QUATERNARY DEPOSITION

The correspondence between sealevel and the surface appearance of streams and springs in the coastal lowlands is not a simple horizontal relationship. Rather there is a graded surface that rises toward the interior. This piezometric surface is defined as the level to which water rises in a cased well. Figure 6 represents the contours of the present piezometric surface in eastern Jefferson County along the western margin of the Aucillla River. A surface of similar slope may be assumed to have existed in the past, although it presumably tracked upward or downward in synchrony with transgressive or regressive changes in sealevel. Increased regional rainfall and other major freshwater inputs may also have increased the slope somewhat in the past. As sinkholes and solution pipes in the Woodville Karst Plain were filled during successive deglacial hemicycles, there may have been a gradient in the timing of sediment accumulation. As cycles of filling and removal were repeated throughout the late Quaternary, one might expect that the record would not be synchronous from place to place.

In order to search for gradient-related differences we divided the dated sediments recovered by our project into three segments, corresponding to the natural divisions of the present Aucilla River. The most headward segment is the Half-Mile Rise; the middle segment is known as Little River; and the most seaward set of dated samples comes from the West Run below Nutall Rise. The results of this subdivision are indicated in Figure 7.

There is a decided difference between the upstream and the downstream records. The upstream records, represented by the sediments from Page/Ladson site, are exclusively from the last deglacial interval. This is the thickest set of sinkhole-filling sediments. The minor reversal in transgression of the sea correlated with the Younger Dryas cooling interval is also reflected, as shown above, by a minor break in deposition. The two more seaward segments of the Aucilla River sample many older sediments, even though they do not greatly exceed 40,000 years, falling well within the range of carbon-dating. The older sediments frequently underly sediments from the last deglacial. Both sets of sediments are invariably thinner in the down-river sections than at Page/Ladson, although the details are too complex to present here.

It should be emphasized that these data are preliminary. Larger samples of dated sediments from a broader area of the coastal lowlands may alter the patterns presented here. It will be of special interest to compare more dates on the sediment packets now submerged within the marine portion of the Woodville Karst Plain with those from the middle reaches of the Aucilla River.

CONCLUSIONS

The age and disposition of late Quaternary sediments in the middle reaches of the Aucilla River, studied over the past fifteen years by the ARPP, may provide a useful outline of the depositional cycles that have prevailed the in the Woodville Karst Plain. At present, simple geomorphological observation indicates that the Aucilla River is not fully integrated; instead, the river intermittently rises from and sinks into the regional karst plain. And its tributary, the Wacissa River, has multiple confluences, of which one spills over a race to enter Half-Mile Rise.

Stratigraphic evidence of massive limestone collapse at the Page/Ladson Site indicates initiation of a fluvial regime there at about 5,000 years b.p. (Dunbar et al., 1989). Bottom surveys reveal that the river presently consists of a string of sinkholes filled with fine clastic sediments alternating with stretches of shallow limestone bottom.

The deepest section of sinkhole sediments exposed in the Aucilla River (six meters at Page/Ladson Site) was filled between about 15,000 and 9,000 years b.p. This is the last deglacial hemicycle, suggesting that the backfilling sedimentation of this sinkhole is driven by a rising sealevel and rising piezometric surface. The results of more than 60 carbon-dated sediment samples from the middle and lower Aucilla River show, as expected, many additional records from the last deglacial hemicycle. Unexpectedly, howeveer, they also include an older cluster of dates from the penultimate deglacial hemicycle. The two clusters indicate extensive deposition during the terminal (deglacial) phases of oxygen isotope stage 3 as well as oxygen isotope stage 2. These same data suggest tentatively that the lower reaches of the Aucilla River system retain more of the older set of sediments, whereas the middle reaches yield thicker sections of the latest deglacial hemicycle. If the present slope of the piezometric system is applied to the past depositional data presented here it yields a simple model that can be applied to other parts of the Woodville Karst Plain. In principle this allows one to interpolate eustatic sealevel history of the late Quaternary with cycles of deposition and erosion. These preliminary depositional data from the Aucilla River indicate that one can extend the piezometric surface downslope and upslope in past and future reconstructions of the karst drainage system in the coastal lowlands of Florida.

ACKNOWLEDGEMENTS

The Aucilla River Prehistory Project owes its success to several granting agencies, a number of private supporters, many collaborators and students, and a very long list of dedicated volunteers. For multiple grants that have sustained the ARPP research program for fifteen years we are indebted to the National Geographic Society's Committee on Research and Exploration and to the Florida Department of State, Division of Historical Resources, assisted by the Historic Preservation Advisory Council. Also in Tallahassee we have received vital cooperation and encouragement from colleagues at the Bureau of Archaeological Research (Jim Dunbar and Roger Smith) and at Florida State University (Joe Donoghue and Michael Faught). Key Florida officials who have supported our work and visited our project include the late Governor Lawton Chiles, and representatives Janegale Boyd, Carl Littlefield and Marjorie Turnbull. And finally I thank Dr. Walt Schmidt of the Florida Geological Survey and the other organizers of the Wakulla Springs Karst Plain Symposium for the opportunity to participate.

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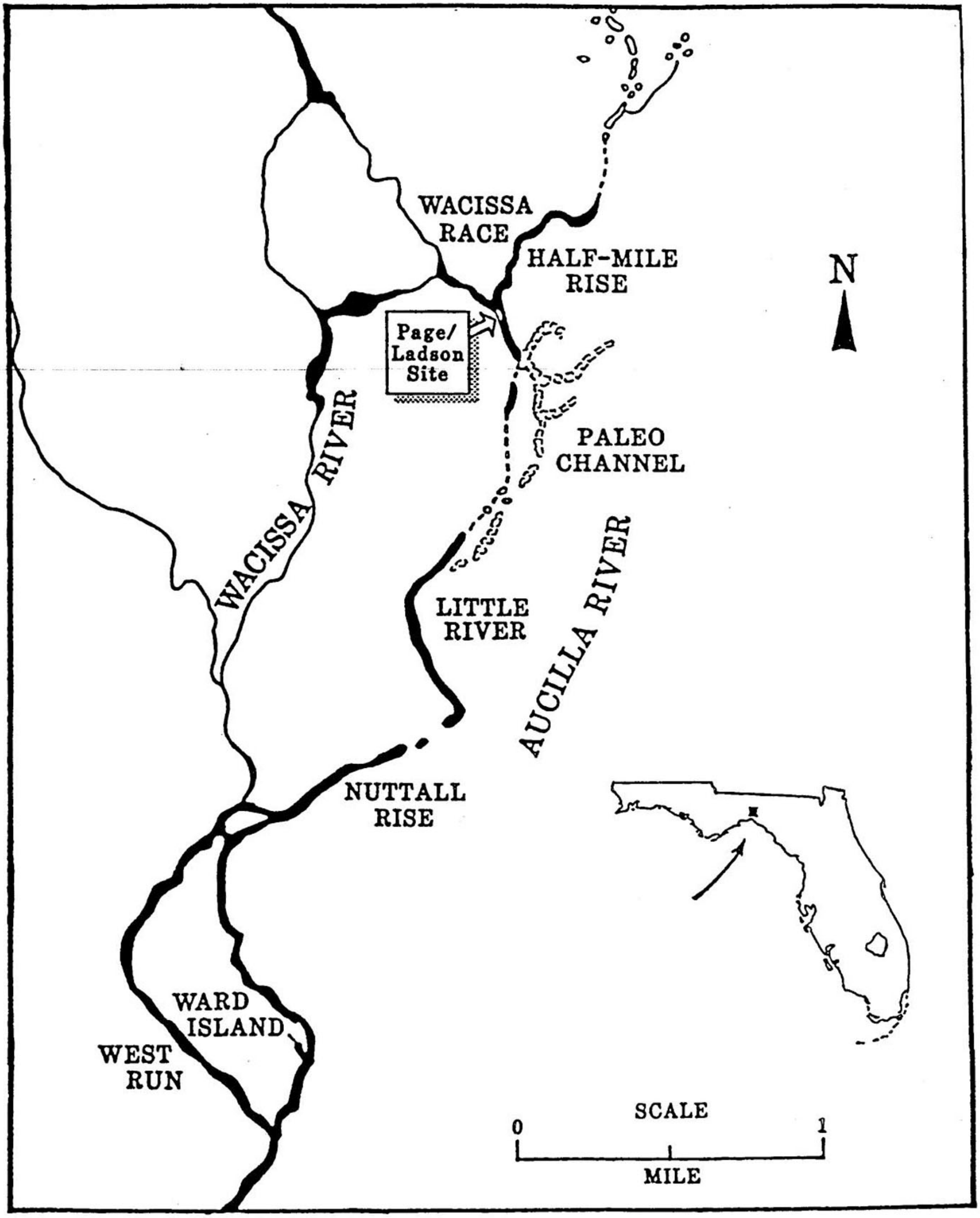

Figure 1. Location map for middle reaches of Aucilla River.

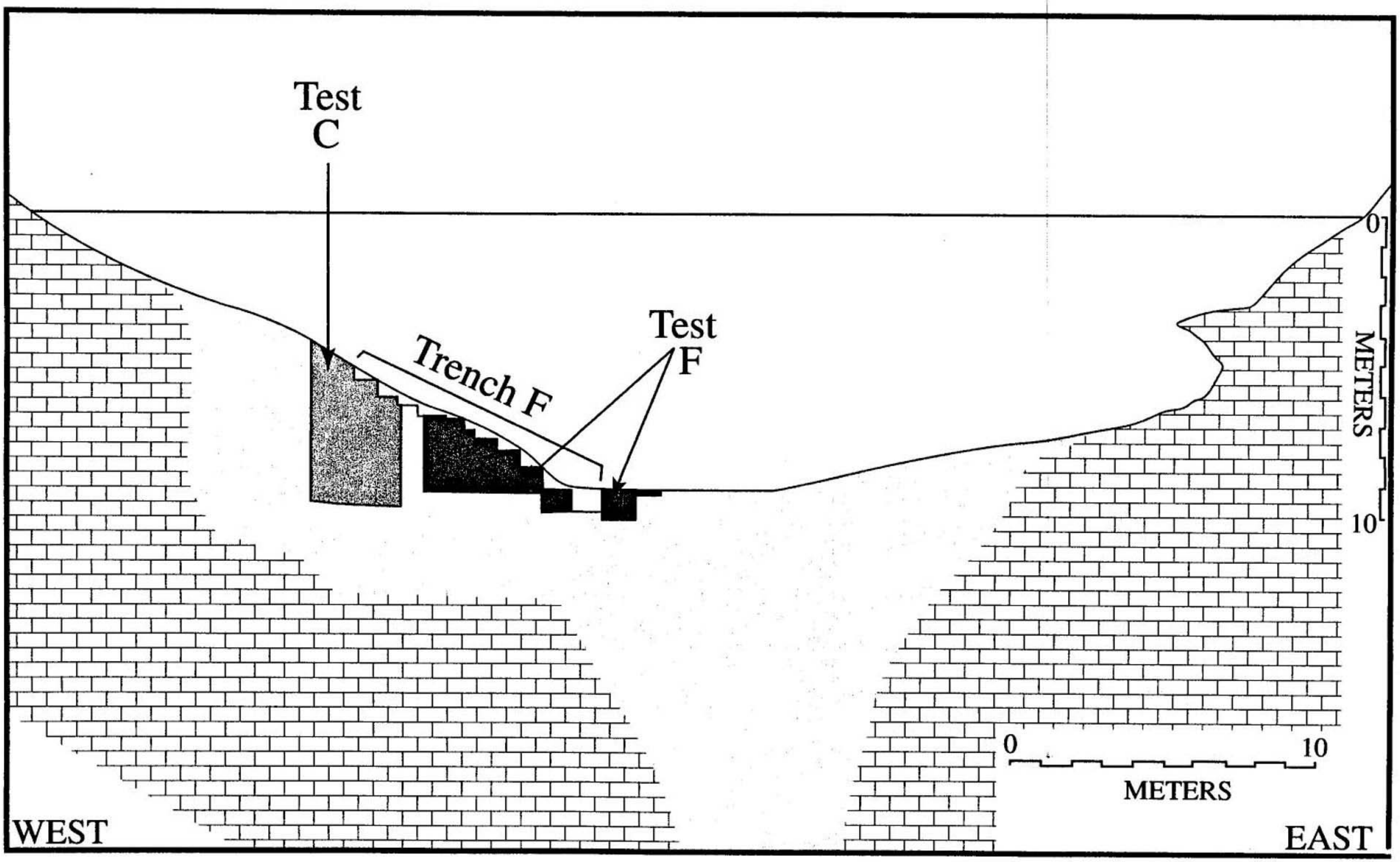

Figure 2. West-East Cross Section, Aucilla River, Page-Ladson Site

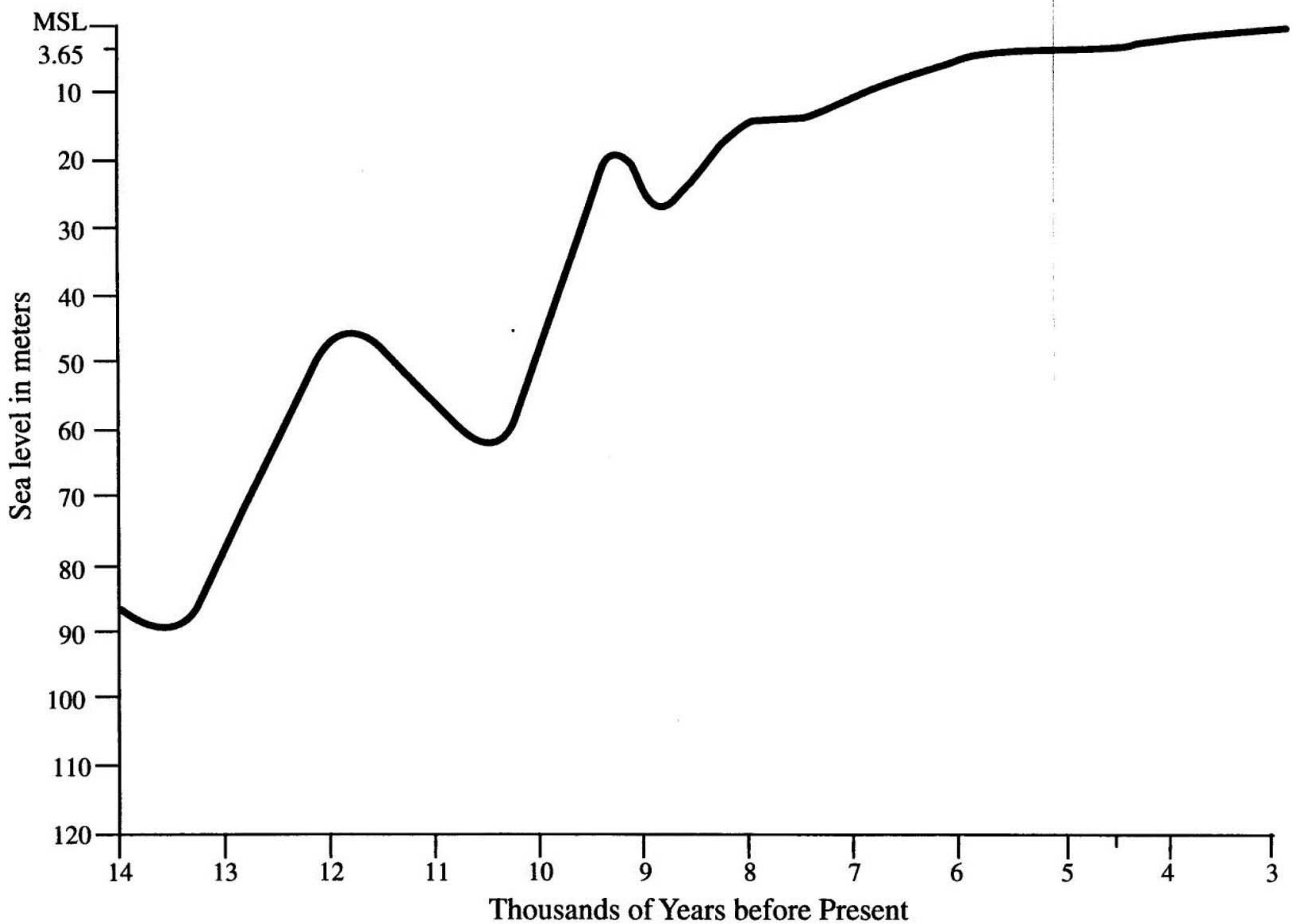

Figure 3. Late Pleistocene Sea Level Curve for eastern Gulf of Mexico

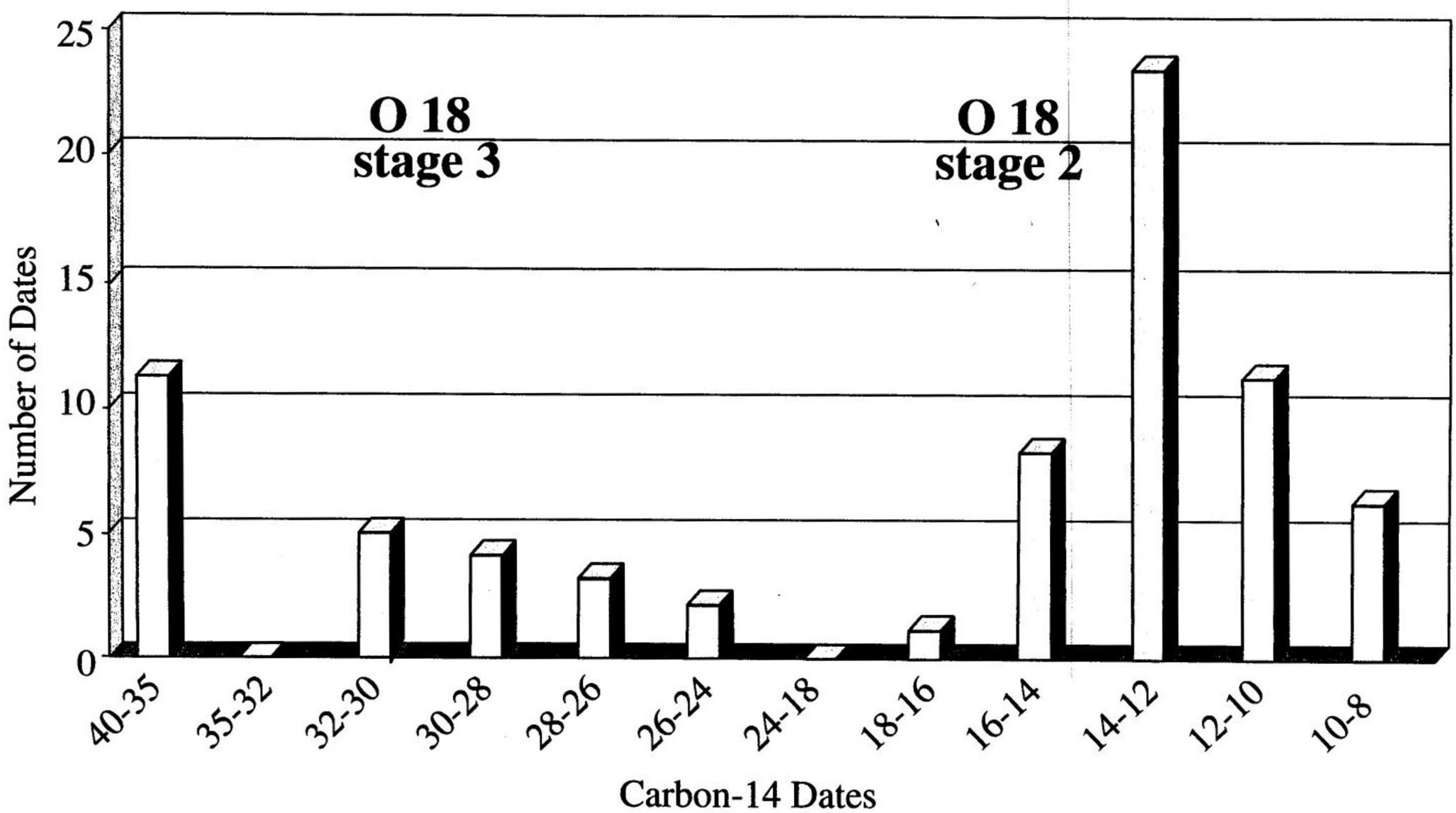

Figure 4. Correlations with Glacial Chronology

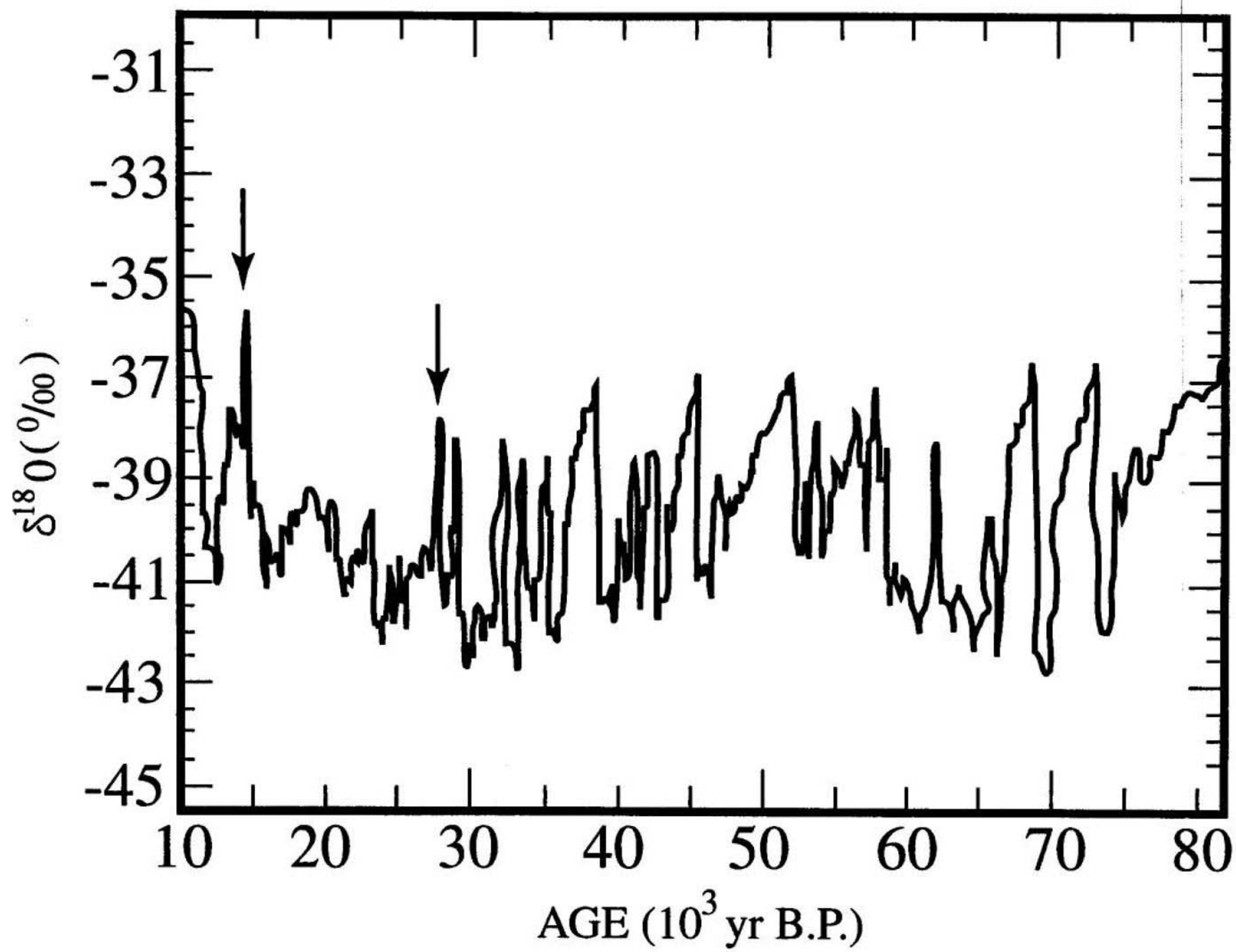

Figure 5. Oxygen Isotope Ratios During The Last 80 KYR

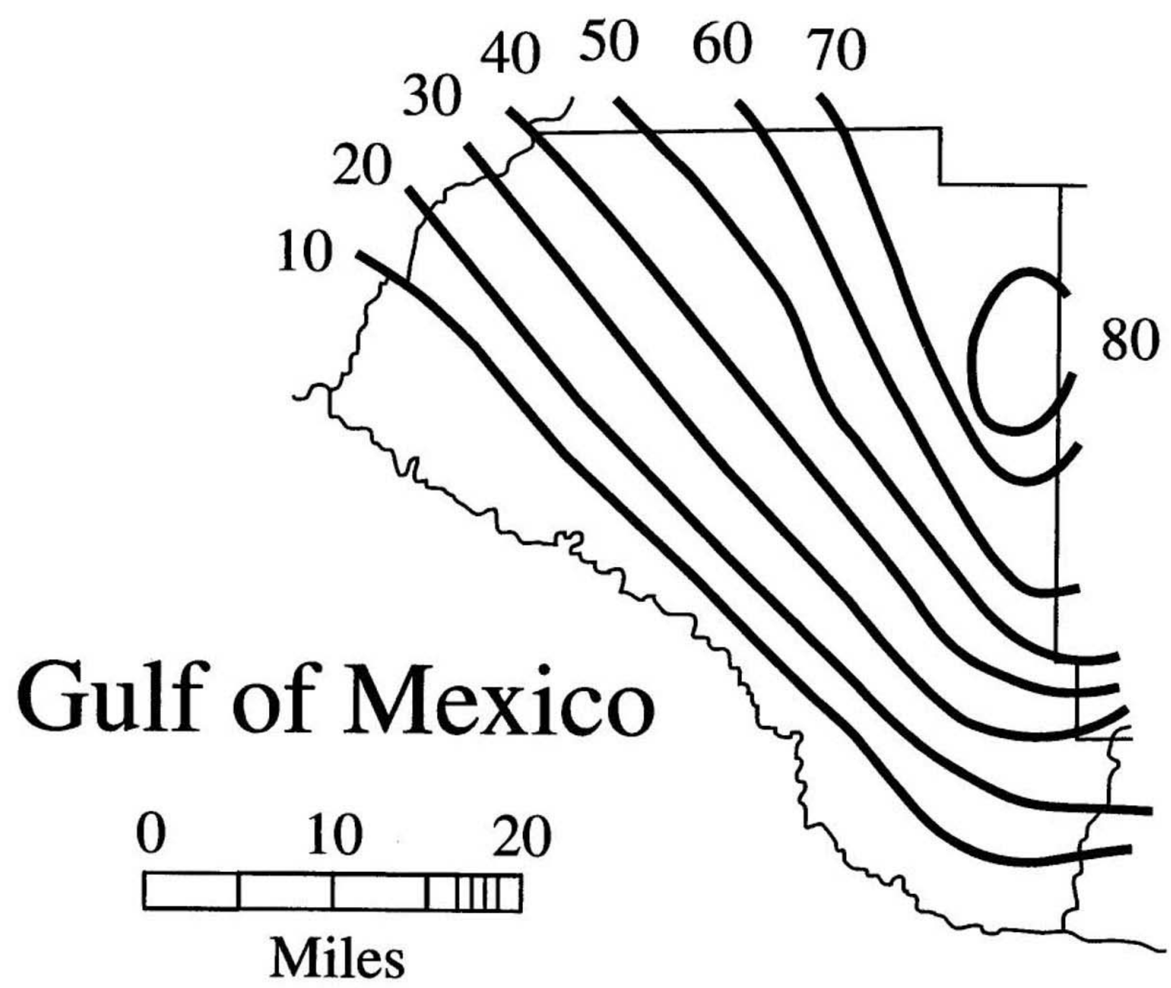

Figure 6. Piezometric Surface Contours in 10' Intervals

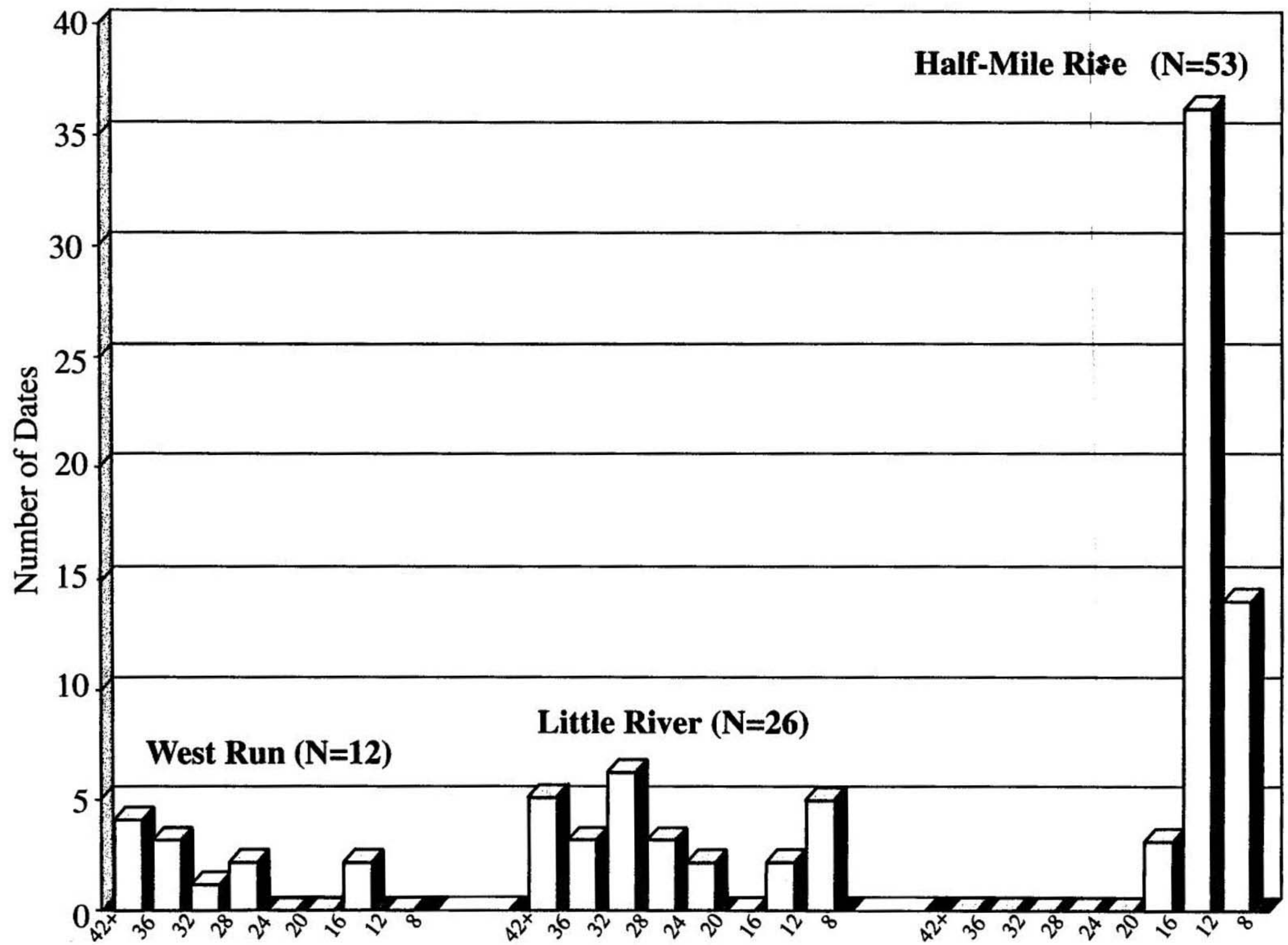

Figure 7. Carbon Date Distribution in three segments of the Aucilla River

ABORIGINAL SETTLEMENT IN THE APALAHCEE REGION OF FLORIDA

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ABSTRACT

This paper discusses types of archaeological and historic sites presently found within the Woodville Karst Plain. Sites there range in age from Paleo-Indian (12,000 to 10,000 B.P.) to mid-20th Century historic sites. They range in type and function from burial mounds to small special use sites. The karst features, such as sinkholes and springs, would have been especially attractive to Native Americans in that they not only provided water during times of lower water tables, but also exposed resources such as chert from which they fashioned many of their tools. In this vein, many sinkholes and springs also attracted animals and could have been used for ambushes and trap falls by aboriginal inhabitants. On the other hand, the sandy soils there were less attractive to Fort Walton Indians, since the red clay hills to the north were much more productive in terms of growing crops such as corns, beans and squash. Another intriguing possibility of shallower portions of springs and sinks in the karst plain, is that many may have served as rock shelters during times of lower water tables. These kinds of sites should provide excellent preservation of organic materials. And unlike the river bottoms in the area, which have been plundered by collectors for many years, the underground streams have remained undisturbed. Thus, many stratified sites with in situ cultural remains are likely to occur within such an environmental setting

Paleo-Indians began trickling into the Apalachee region of Florida, the area between the Ochlockonee and Aucilla rivers, about 12,000 years ago. Sites from this period, which lasted about 2,000 years, are more rare than those of later periods. The state's climate and ecosystems were much different then, with extensive grasslands interspersed with woodland hammocks. Temperatures were more uniform throughout the year, characterized by cooler summers and warmer, non-freezing winters. Mammoths, mastodons, camels, sabercats, dire wolves, giant sloths and short-faced bears roamed the coastal plain in search of food, water and mates before widespread extinction eliminated them sometime before the end of the Pleistocene epoch about 10,000 years ago.

Sea level was lower (from 115 feet 12,000 years ago to 40 feet 8,000 years ago) at this time. This resulted in Florida being close to twice its current size when Paleo-Indians first arrived in the state. Rainfall amounts were much less than now and fresh water was not nearly as readily available because of lower water tables due to less precipitation and reduced sea levels. Paleo-Indians, therefore, would have been more limited on the present land surface as to where they could have subsisted and settled since fresh water was crucial to their survival. Conversely, some areas now underwater provided additional areas for them to live.

Due to the state's acidic soils, few organic materials are preserved in terrestrial archaeological sites. Fortunately, the alkaline waters of springs, sinkholes and karst windows conserve a whole range of organic remains that can be radiocarbon dated and studied to add to our knowledge of prehistory. Without organic material such as bone or wood, sites cannot be radiocarbon dated. On the other hand, prehistoric sites can still be dated using non-perishable artifacts—projectile points or pottery types--that provide us with relative dates. For example, Suwannee and Simpson points, long, lanced-shaped implements worked on both sides that were used to tip spears and knives, are diagnostic of the Paleo-Indian period.

Sites found thus far dating to this period in the Woodville Karst Plain, first defined by Hendry and Sproul (1966) and located in the southeastern portion of the Apalachee region, include a kill in the Wacissa River of an extinct Bison (*Bison antiquus*) with a fragment of projectile point embedded in its skull. Another bone from this animal yielded a radiocarbon date of more than 11,000 years old. Other sites include the Page-Ladson site in the Aucilla River, where remains of Ice Age mammals along with Paleo-Indian and later period artifacts have been found. One of the more notable sites is the Wakulla Springs Lodge site, which represents the first stratified Paleo-Indian/Early Archaic site recorded in northwest Florida. The spring itself also has yielded Suwannee, Simpson and Clovis points, along with 600 bone pins, mastodon, deer, charred wood, tapir, giant armadillo, camel, horse and bison remains mixed with recent objects. Wakulla was probably nothing more than a sinkhole—as opposed to the major artesian spring that it is today--at this time, since water tables were much lower when these megafauna co-existed with humans in the region. (For example, an extinct land tortoise [*Geochelone crassicutata*] was found on a dry ledge about 85 feet below the current water level at Little Salt Spring in Sarasota County, with a wooden stake stuck in its shell. The stake yielded a radiocarbon date of more than 12,000 years.) Although it intrigues the public, the possibility that people inhabited or used caves such as Wakulla and other nearby deep tunnels is most unlikely since the conduits feeding the spring are from 200 to 300 feet deep and have been filled with water for the whole of human history.

Archaic cultures (10,000-2,500 B.P.) are normally divided into Early, Middle and Late periods in southeastern North America. During this time, the climate gradually become more humid. Sea level began rising, rapidly at first and then more slowly as glaciers melted. By approximately 5,000 years ago, water tables and ecological communities were becoming similar to those of today. Increasing populations of native Floridians become more sedentary as they began exploiting smaller territories. The diagnostic tools at this time were various forms of triangular-shaped projectile point/knives that manifested notched (such as Bolens), and later stemmed (such as Newnans) bases, for attaching these stone implements to shafts. At the beginning of the Early Archaic, it is believed that Indians switched from hand held spears to atl-atls or spear throwers to more effectively bring down game, which for the most part, were the same species as contemporary animals. The cumulative effects of these changes led to increased regionalization as native peoples began adapting to specific local resources.

Fiber-tempered pottery, which was tempered with Spanish moss or strands of fiber from palmetto, was invented near the end of the Archaic and thus ceramics became another way to identify cultures. In the Apalachee region, the people that made the first pots are known by archaeologists as the Norwood culture. They decorated their pottery by making stick impressions on its outer surface before it was fired. Many large coastal shell middens date to this time, although some sites have been inundated by rising sea level and others have been destroyed by modern borrowing activities and development.

The Woodland period (500 B.C.—A.D. 1,000) followed the Archaic. As this period progressed, certain styles of decoration and kinds of tempering agents of pottery vessels became more and more distinct for given regions inhabited by discrete peoples. Native Americans began burying their dead in mounds at this time, often accompanied by elaborate grave goods, some from faraway places. By about 2,500 years ago, Florida's coastal areas, including those in the Big Bend, had become optimal habitat for oysters and other shellfish. Aboriginal inhabitants were obviously attracted to these bountiful resources common in estuaries along Apalachee Bay.

The Deptford culture (500 B.C.—A.D. 200) was the first expression of the Woodland tradition in Florida. It was mainly a coastal occupation, although some Deptford sites are located inland in the interior valleys and other locales. The latter sites were small and found underlying more recent ones. Much of their ceramics were decorated by stamping vessel surfaces with carved wooden paddles before the pieces were fired, leaving a distinctive groove- or checked-stamped impressions on the pottery. Also at this time, pottery was no longer tempered with fibers, but instead with pastes such as quartz sands that were mixed with the clays. Deptford economy centered on marine resources, especially fish and shellfish. They primarily lived in the coastal hammocks, but would make forays inland to harvest nuts and berries where fruit-bearing plants were more plentiful.

These people were followed by the Swift Creek culture (A.D. 200-400). It was during this time that villages were first established in significant numbers in the interior forest and river valleys of the eastern Panhandle, although Swift Creek sites can also be found along the coast. Their ceramics were characterized by complicated stamped pottery and are commonly found in the Tallahassee (red clay) Hills, as delineated by Cooke. These sites are especially prevalent in the river valley forest and other fertile locales. This suggests that gardening may have played a role in the Swift Creek economic system, although evidence supporting cultivation remains sparse. Bone and stone tools appear in greater numbers in their tool kits than during the previous Deptford period.

The distribution of later Weeden Island (A.D. 400-1,000) sites in northwest Florida closely shadows Swift Creek sites, although Weeden Island sites are much more prevalent. These sites were concentrated around lakes Miccosukee and Iamonia. Pottery during the earlier phase of this culture was characterized by Swift Creek Complicated Stamped and Weeden Island plain wares. In the late Weeden Island period, Wakulla check-stamped pottery became the most prevalent decorated ceramic in non-mound settings. It developed about A.D. 750 and reflects the adoption of maize agriculture into the Weeden Island economic system. Such a change in subsistence had far reaching implications for native societies of the Panhandle, leading to changes that eventually evolved into the Fort Walton culture about A.D. 1000.

Fort Walton represented the final major prehistoric period in southeastern North America known as the Mississippian (1000-1600). The Fort Walton Culture was not only the most politically complex, but also supported the densest population of people in the state. They practiced mound building, intensive agriculture and made pottery in a variety of vessel shapes with many decorative motifs, with some of the same styles found at other Mississippian sites in the Southeast. Most of the incised pottery featured curvilinear and rectilinear motifs, some of which bore animal-head effigies. Fort Walton people cultivated maize, beans, sunflower and squash and used wild plants such as hickory nuts, acorns, persimmons, maypops, wild cherry, saw palmetto berries, cabbage palm and chinquapin. Their sites are located more inland than sites from previous periods since their primary subsistence had shifted almost totally from collected to cultivated plant foods, which thrived in the rich clay soils.

At the time of Ponce de Leon’s arrival in Florida in 1513, there were about 50,000 Indians living in the Apalachee region surrounding Tallahassee. By the time the first Spanish Mission was established here, the Fort Walton complex had been replaced by Leon-Jefferson (1600-1700) ceramics, reflecting the rapid social change which resulted from contact with the Spanish. In addition to cultivating maize, beans and squash, these people, called Apalachees by the Spanish, fished, hunted and collected wild foods. They were eventually ravaged by European diseases and displaced by Creek Indians (1700-1840), who came down from Georgia. The Creeks that migrated into north Florida later became known as Seminoles.

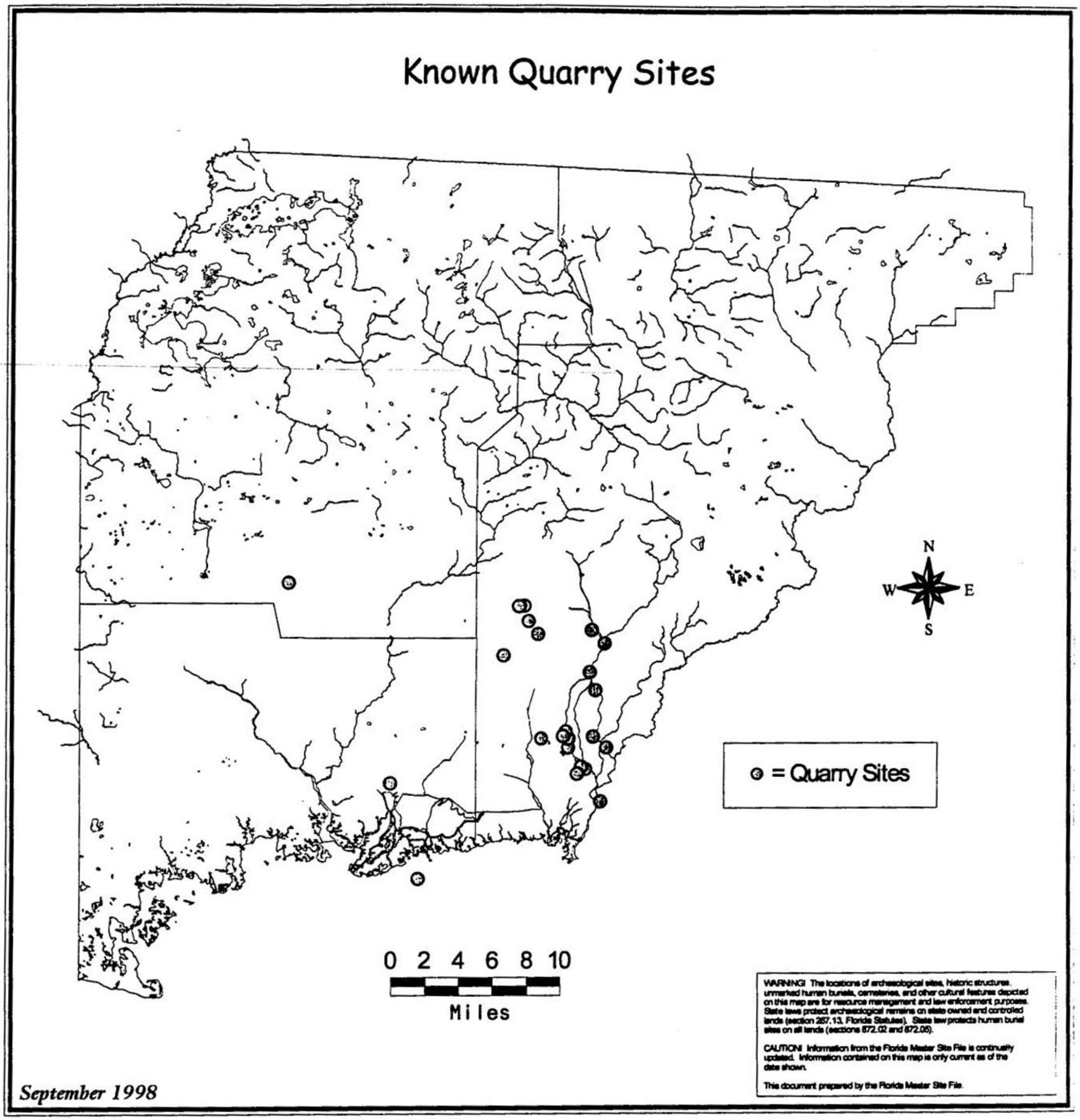
Water was probably the most significant variable in determining where prehistoric peoples settled in the region. Most water that falls on the Woodville Karst Plain or enters as streams from outside the area immediately disappears into subsurface conduits, which results in very few surface streams. The higher water levels in the Apalachee region occur in perched aquifers in northern Leon and Jefferson counties, and the lower in southern Leon and Jefferson and in Wakulla counties in the karst plain, where the water table is essentially the same as the potientometric surface. Water level fluctuation in response to rainfall is much less in the karst plain than in the Tallahassee Hills, thus providing Native Americans with much more reliable, although in fewer locations, water sources prior to 5,000 years ago.

Another important resource found in the karst plain is chert—a mineral resembling flint—that Indians used to make tools. A relatively thin zone of chert, where limestone has been replaced by silica, appears at the top of the Suwannee limestone in the Woodville Karst Plain. The silica that formed the chert most likely came from groundwater passing through and dissolving quartz and clays then precipitating and replacing portions of the limestone. Whereas Suwannee limestone lies 100 feet or more beneath clastics in the west, it reaches the surface in eastern portions of the karst plain (Figure 1). From just below Lamont to about Nutall Rise, limestone is almost continuously exposed along the banks and in rapids as silicified limestone (chert) boulders in the Aucilla River. It also outcrops in the Wacissa River from just below its headwaters to its confluence with the Aucilla and sporadically along the Gulf coast in southeast Wakulla and southern Jefferson counties.

Soil types are yet another significant variable in site selection and reflect past biologic and geologic processes. Those soils present north of the Cody Scarp (an outfacing escarpment representing the most persistent topographic break in Florida), in the Tallahassee Hills have been described as red, sandy-clay hills. These loamy soils support lush natural vegetation. Their relative impermeability have led to the development of many wet weather ponds and lakes in the area. On the other hand, the soils of the Woodville Karst Plain, located south of the Cody Scarp, are described as loose, quartz sands that form a thin cover over a limestone substrate, characterized by karst depressions and sand dunes. Soil surveys of Leon, Jefferson and Wakulla counties depict the soils in the karst plain as either subject to drought and of low fertility or poorly-drained with a tendency to remain wet in areas bearing organic hardpans. Neither soil condition is conducive for growing crops. On the other hand, the soil surveys reveal that the mostly well-drained loamy soils in the Tallahassee Hills are moderately well-suited for producing a variety of crops. Although soil surveys were done for modern farmers, the results are revealing when looking at Figure 2, which shows that prehistoric people from the middle Woodland (Swift Creek) onward preferred the richer soils in the clay hills to locations in sandy karst plain. This graphic would be even more striking except that the percent of land surveyed for archaeological sites in Leon County 696/73.60 square miles is twice that of Jefferson County 699/31.33 and five times greater than that in Wakulla County (635/14.66).

Sites in the Apalachee region range in age from Paleo-Indian to mid-20th Century historic sites. They range in type and function from large ceremonial complexes with temple mounds to small special use sites. Features in the Woodville Karst Plain, such as sinkholes and springs, would have been especially attractive to early Native Americans in that they not only provided water during times of lower tables, but also exposed resources such as chert from which the Indians fashioned many tools. Moreover, seven of the state’s 27 first magnitude “springs” (Only three of which—Wakulla, Spring Creek Springs and Wacissa Springs group—are true springs, the other four--Natural Bridge Spring, St. Marks River Spring, Kini Spring and River Sink Spring--are either lost rivers or karst windows) lie within the Woodville Karst Plain. These and scores of other water-filled springs and sinkholes obviously attracted animals and could have been used for ambushes and trap falls by aboriginal inhabitants. On the other hand, the sandy soils in the area were less attractive to agriculturists such as the Fort Walton people, since the red clay hills to the north were much better suited for growing their crops.

Another intriguing possibility in the karst plain, is that many shallower portions of caves, such as the siphon tunnel of Little Dismal, portions of the Leon Sinks Cave System, Chip’s Hole and McBride Slough Spring cave, may have served as rock shelters during times of lower water tables. These shallow aquatic caves also should provide excellent preservation of organic materials. And unlike most river bottoms in the area, which have been scavenged by rabid artifact and fossil collectors for more than four decades, the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WARNING! The locations of archeological sites, historic structures, unmarked human burials, cemeteries, and other cultural features depicted on this map are for resource management and law enforcement purposes. State laws protect archeological remains on state owned and controlled lands (section 267.13, Florida Statutes). State law protects human burial sites on all lands (sections 872.02 and 872.05).
CAUTION! Information from the Florida Master Site File is continually updated. Information contained on this map is only current as of the date shown.
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Figure 1

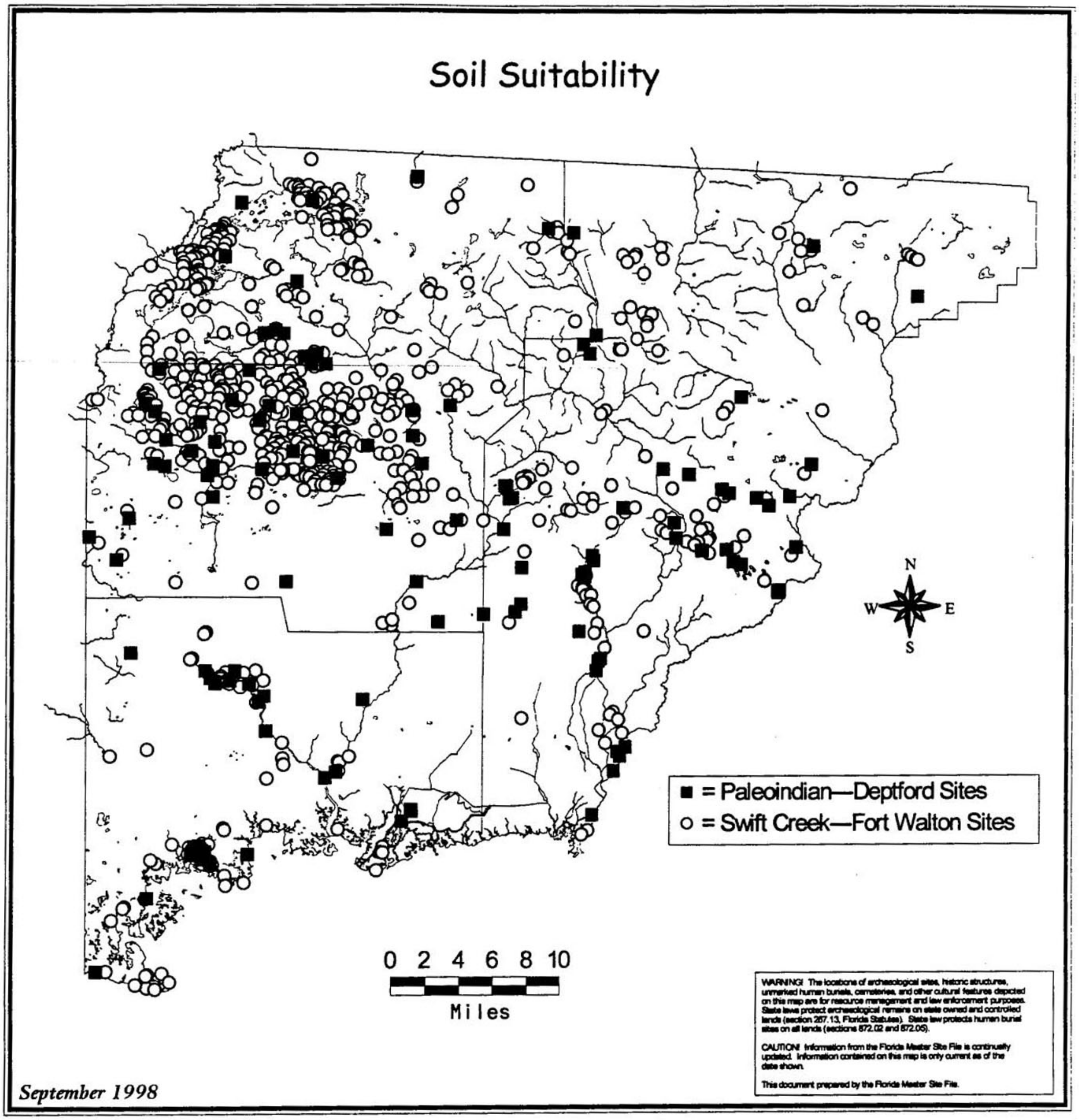
Soil Suitability
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Figure 2

underground streams remain virtually free of human plundering. Thus, unmolested stratified cultural remains await discovery within these dark reaches.

In closing, many opportunities abound for archaeologists trained to cave dive to conduct research stemming from the ongoing exploration of openings into the Woodville Karst Plain. Shallower portions (i.e., 70 feet or less) of water-filled sinks in the karst plain may have served as rock shelters for Paleo-Indian and Early Archaic peoples during times of lower tables. These sites have long been hidden by the silts of time. Perhaps these submerged caves may one day be surveyed for archaeological sites, since they could help solve a plethora of mysteries about what human life was like long before the arrival of Europeans in the Apalachee region of Florida.

ACKNOWLEDGMENTS

I would like to thank Susan Harp, Melissa Memory, Frank Rupert, Louis Tesar, Vince “Chip” Birdsong, Dee McDonald, Mary Glowacki, Roy Lett, Pam Vojnovski and Marion Smith for their help on various aspects of this paper and for preparing for the presentation at the symposium. Any errors in form, facts or interpretation that may have been introduced here, however, are the sole responsibility of the author.

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WATER VISIBILITY AND RAINFALL AT WAKULLA SPRINGS - A SHORT HISTORY

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ABSTRACT

There are recorded references concerning water visibility at Wakulla Springs dating back to 1894. These references concern dark water and its impact on revenue production. Since 1985, the days that glassbottom boats took tours over the springs have been recorded. This data has been compiled and graphed. Daily rainfall amounts have been recorded at the Tallahassee Airport for 1985 through 1992. Since 1993 daily rainfall has been recorded at Wakulla Springs State Park. The rainfall data has been compiled and graphed. Since September of 1994, the water visibility of the springs has been measured and recorded. This visibility data has been compiled and graphed.

This is a presentation and comparison of the collected rainfall and spring visibility data. The possible correlations that exist between the data will also be discussed.

Wakulla Springs State Park is a 2,880-acre tract located about 12 miles south of Tallahassee, Florida. The main natural feature of the park is Wakulla Spring, a first magnitude spring considered to be one of the world's largest and deepest freshwater spring. Wakulla Spring has a depth of approximately 185 feet, a spring bowl of almost 4 acres, and an estimated water flow of 120,000 – 600,000 gallons per minute. The park has approximately 700 acres of wetlands most of which are associated with the Wakulla River. The rest of the 2,100 acres are surrounding managed uplands. At the park are a lodge and a full service restaurant. Several feature movies have been filmed at the park showcasing its crystal clear water. Wakulla Springs has been a state park since 1986.

Wakulla Spring is the source of the Wakulla River. The Wakulla River is nine miles in length. The river flows into the St. Marks River and then into the Gulf of Mexico. The first three miles of the river are contained within the boundary of Wakulla Springs State Park. The park runs tour boats on the upper mile of the river and over the spring. The park's portion of the river is a haven for wildlife. Visitors from all over the world come to ride the boats and view the wildlife. The park has 14 listed animal species.

The park runs glassbottom boat tours over the spring. Glassbottom boat tours have been running at Wakulla since the 1930's. On these tours the visitor is able to view the features of the spring and see the underwater wildlife that lives there. The maximum depth that can be viewed is to the bottom, 125 feet down. In the last ten to 12 years, glassbottom boats have been unable to run the majority of time due to poor water visibility of the spring.

In talking with old time employees (veterans of 30+ years) at the park, it is their impression that in the past Wakulla Spring did not turn dark often or stay dark for long periods of time. Water turning dark at Wakulla Spring is a park term for water visibility of less than 75 feet, which does not allow for the running of the glassbottom boats. In conducting a literature search of park files, several references to dark water have been discovered. These historical references include the following:

> Wally Jenkins in a conversation with biologist Jon Dodrill, said the spring was "Gin clear" when they dove the spring in 1955 – 1957. But in May of 1957 the spring suddenly began to darken and became almost wine dark. Jenkins also said the spring was clear during the summer of 1976 when *Airport 77* was filmed but turned dark in January 1977.
>
> **April 12, 1962** – A note to Ed Ball, the owner at that time, stated, "The spring has been high and black for the past couple of weeks."
>
> **June 13, 1958** – A letter to H. McQuirter stated, "That when the water is dark, or business is slack the boat drivers should do other work."
>
> **January 17, 1946** – A note to R.L. Main from Newton Perry stated, "Our spring has been black for quite sometime and, consequently, our revenue has not been such that we feel that we can spare the money to meet the pay roll the period."
>
> **March 18, 1946** – A note to Ed Ball stated, "Business has been very good. However, we had a very heavy rain all day Saturday, Saturday night and Sunday. The water is high and the spring is beginning to darken."

September 13, 1945 – A letter to Ed Ball from Newton Perry stated "The water at the spring has once again cleared up, and I am hoping that it will stay clear for a while. We have lost so much money by the spring going black this summer."

March 31, 1894 – Henry L. Beadel's personal diary states "The water has been stirred up by the heavy rains, and we could only see down 80 feet."

Based on these references, it can be concluded that dark water days have been occurring at Wakulla Spring since 1900. What is not conclusive is the frequency or duration of these dark water days.

Since 1987 the park has been tracking financial returns from glassbottom boat tours. From this information it is possible to determine what days glassbottom boats where operational. There are several different glassbottom boats that run at the park. The only reason no boats would have run during a day is that the spring was too dark, water visibility of less than 75 feet. So from this information we are able to determine when the spring was clear, visibility of more than 75 feet, and when the spring was dark, visibility of less than 75 feet. Graph 1 is a graph of the number of days that the glassbottom boats did not run from 1987 to September of 1998. Graph 2 is the percentage of "down days" per year since 1987. This data shows that since 1987 the visibility of the water at Wakulla Spring has been too poor to run the glassbottom boats 58% of the time. More than half the time! Since 1994 the park has been recording water visibility through the use of a secchi disk. This data is represented in Graph 3. The periods of dark "down days" and clear "up days" appear quite streaky, occurring for long durations. Table 1 shows periods of Glassbottom boat "down days" of over 100 consecutive days. Table 2 shows periods of Glassbottom boat "up days" of over 100 consecutive days. These "down day" streaks and "up day" streaks are often back to back. For example, the spring was dark from June 11, 1989 to April 27, 1990, clear from April 28, 1990 to January 21, 1991, dark again from January 22, 1991 to September 20, 1991, then clear again from September 21, 1991 to February 9, 1992. This period of extended times for dark water and clear water covers a time span of 980 days, greater than 2 ½ years. In order for the spring to start a long period of dark water, it appears that a major rain event must occur, i.e. greater than 10 inches of rain in one month. The same can be said to start a long period of clear water, very little rainfall during a month, i.e. less than 2 inches of rain during a month.

The park has been recording daily rainfall at the park since 1994. The rainfall is recorded to track a drought index for prescribed burning. The NOAA weather station at the Tallahassee Airport has rainfall information for that area dating back to before 1987. With this information, we are able to estimate the monthly rainfall for the Wakulla Spring area from 1987 through 1998. Graph 4 shows this information.

Park staff has observed that there appears to be a relationship between rainfall and water visibility of the spring. When heavy rains occur, it is common for the spring's water to darken soon after the rain event. Graph 5 shows the data comparing these two variables. Based on this data a relationship does appear. Spring water visibility is impacted by certain rainfall events. The impact of rainfall events varies based on time of year, amount of rain, and previous condition of the spring water.

To explain the fact that it is now more common for Wakulla Spring to be dark than clear, park staff wondered if these last ten to 12 years had been extremely wet years. The rainfall data from this 12-year period was compared to rainfall data dating back to 1961. The overall yearly average rainfall per year from 1961 to 1986 is 65.7 inches. This compares to an average of 62.1 inches for 1987-1998. So actually, on average the last 12 years have been drier than 1961 to 1986. How about major rain events, are more occurring now (1987-1998) then in earlier years (1961-1986)? The data shows that 1994 was the second wettest year since 1961. The data also shows that 1988 was the driest year, 1993 the second driest year, and 1990 the fourth driest year since 1961. Overall the data shows that for the last 12 years rainfall has been below average and that there has been no dramatic increase in yearly rainfall.

Another concern of park staff in regards to water visibility at Wakulla Spring, was to see if there was a seasonal effect of rainfall that had an effect on water clarity. Graph 6 shows the total monthly rainfall since 1987. This data shows that there is a definite rainy season from June through August. It also shows that the winter months of January, February and March are wet times. The dry season occurs in the spring, April and May, and then again in the fall and early winter. Graph 7 shows the monthly average of "down days" since 1987. This data shows the spring is most likely to be dark during February and March with eight other months having a greater than 50% chance of the spring being dark. The best time to visit Wakulla Springs State Park and expect the spring to be clear is in May and June.

In conclusion, Wakulla Spring has had poor water visibility 58% of the time over the last 12 years. There is historical evidence that dark water has occurred at Wakulla Spring since 1900. There appears to be a relationship between local rainfall events and spring water visibility. The last 12 years have been drier than average. The wet season at Wakulla occurs June through August with the winter months of January, February, and March being the next wettest. The dry season is April and May with the fall and early winter also being dry. The best chance to see the crystal clear waters of Wakulla Spring is during May and June. The park staff of Wakulla Springs State Park will continue to monitor the rainfall and the spring water visibility so as to gather a larger database to draw conclusions from.

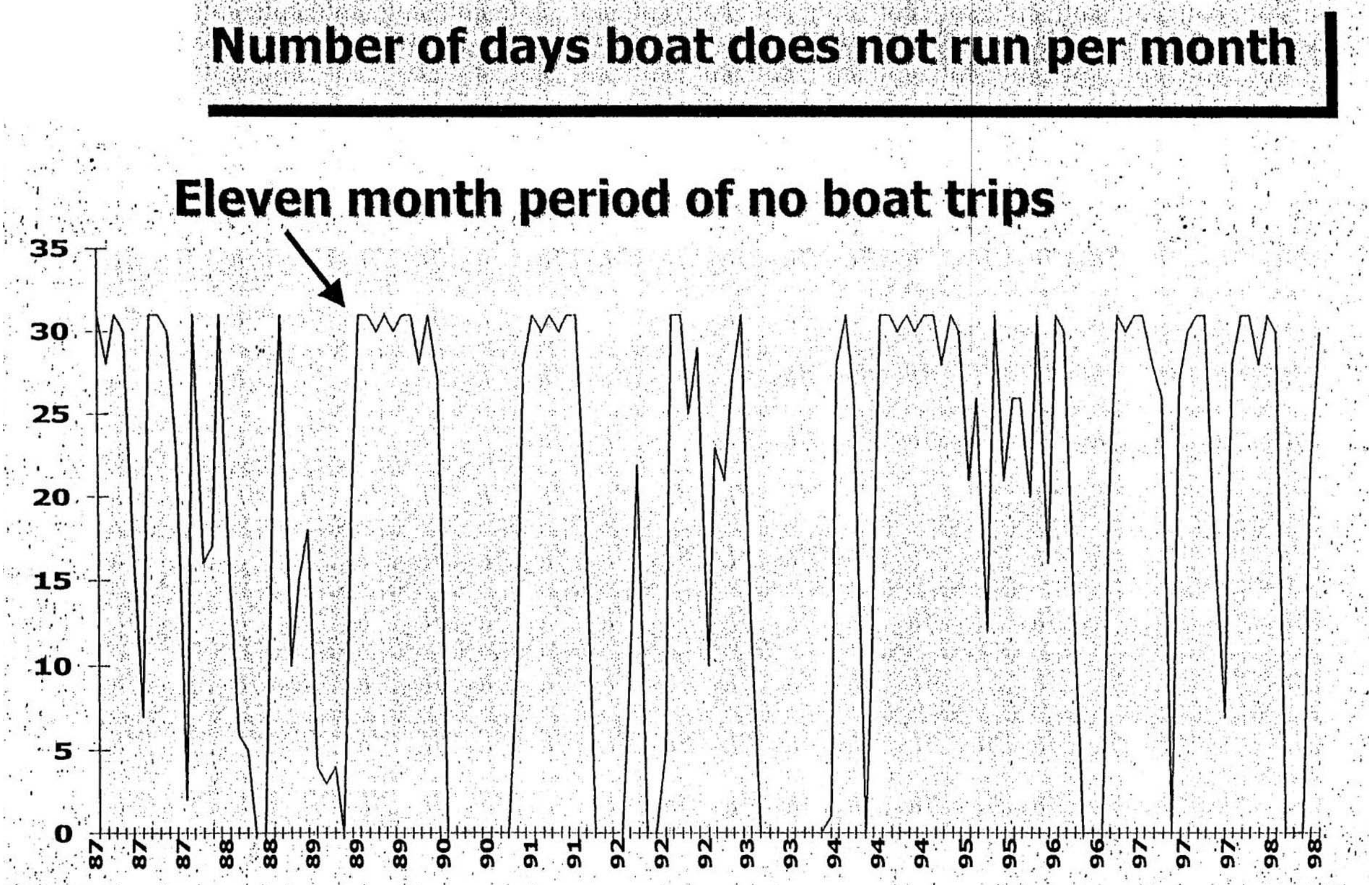

Figure 1. Number of days that the Wakulla Springs State Park glassbottom boats did not run from 1987 to September 1998

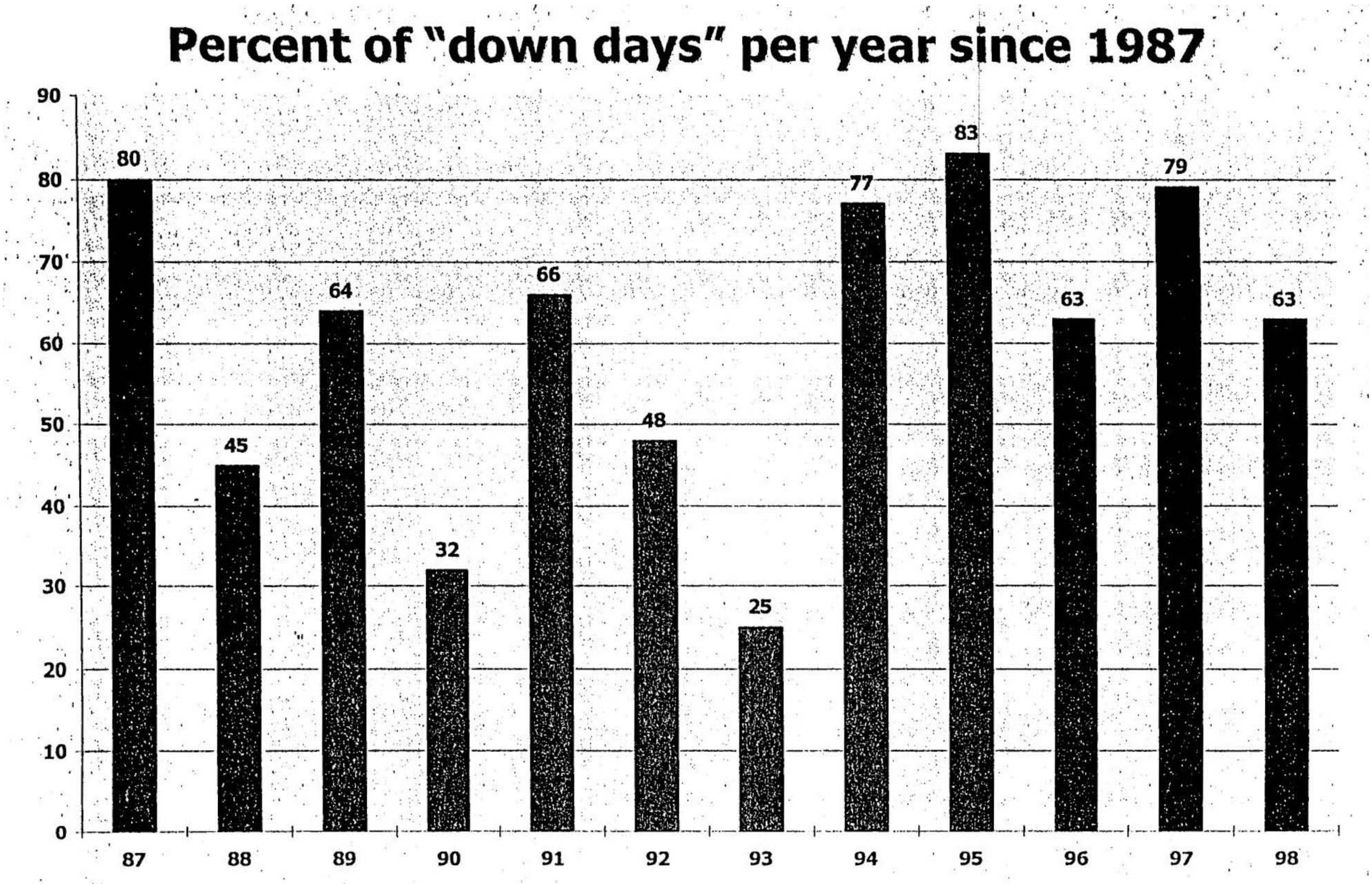

Figure 2. Percent of "down days" per year at Wakulla Springs State Park since 1987

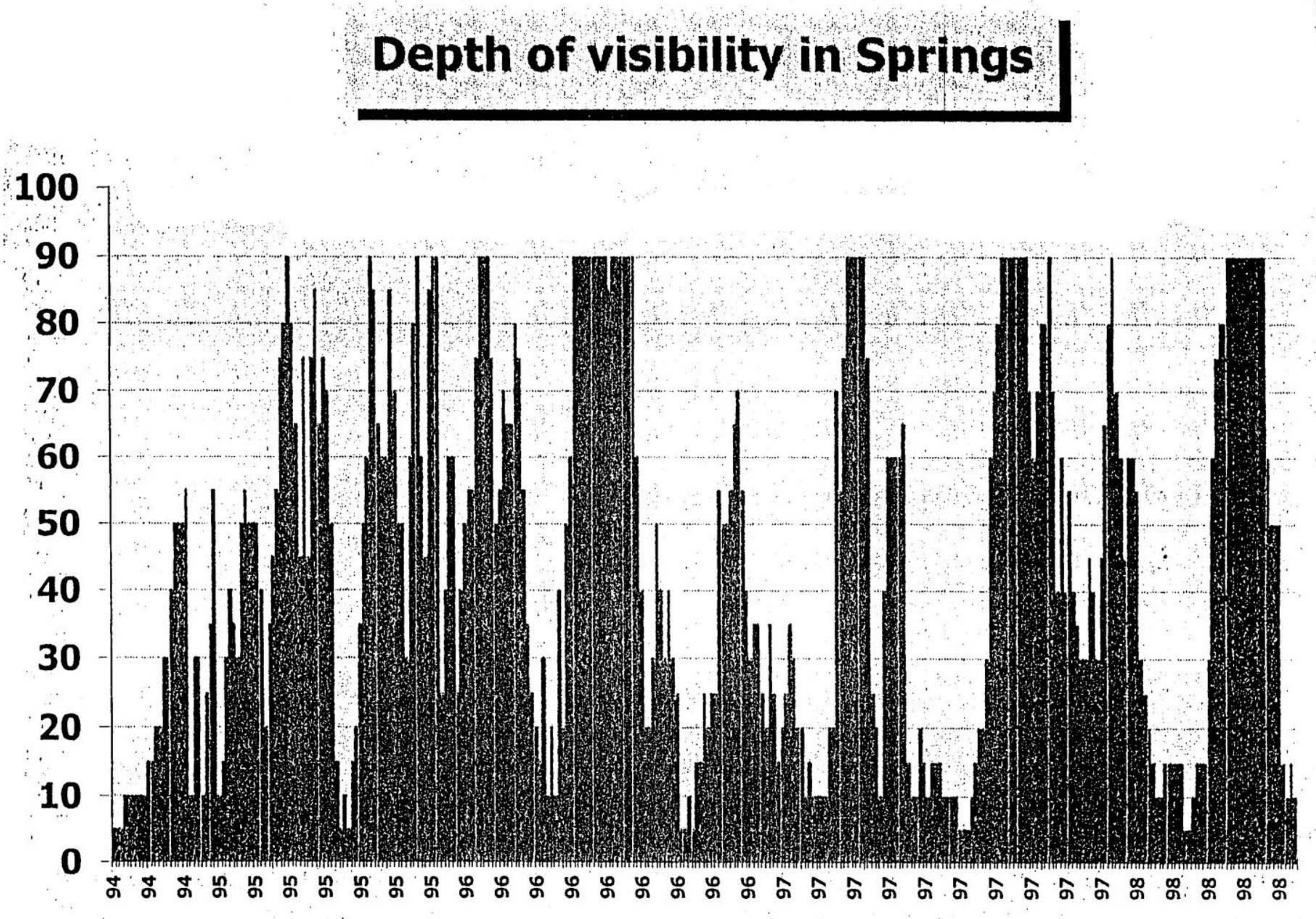

Figure 3. Water visibility recorded at Wakulla Springs State Park from 1994 to 1998

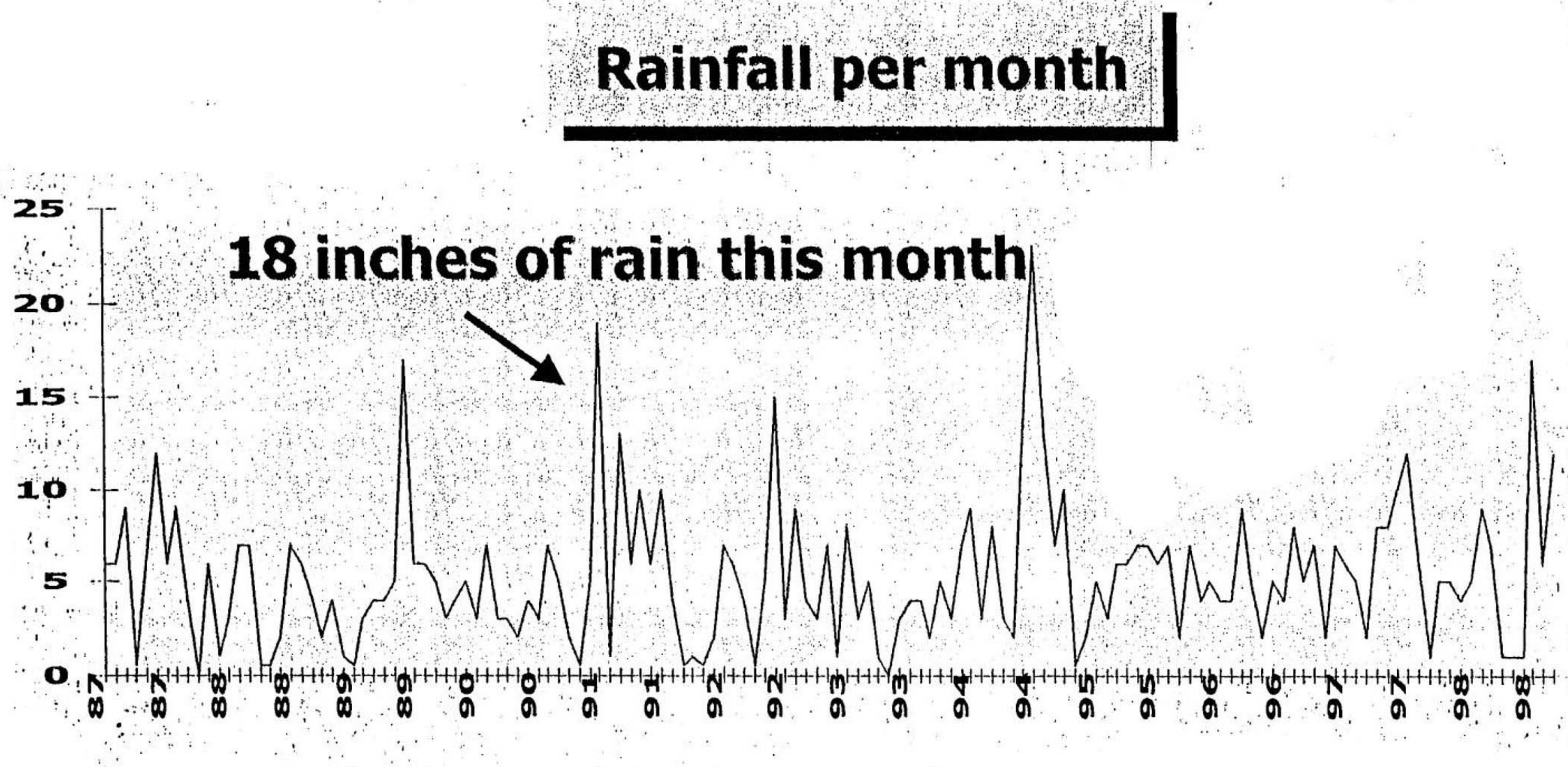

Figure 4. Rainfall at Wakulla Springs State Park from 1987 to 1998. The data for 1987 to 1994 are estimated from Rainfall recorded at the NOAA Weather Station at the Tallahassee Airport. The data for 1994 to 1998 are from Park records

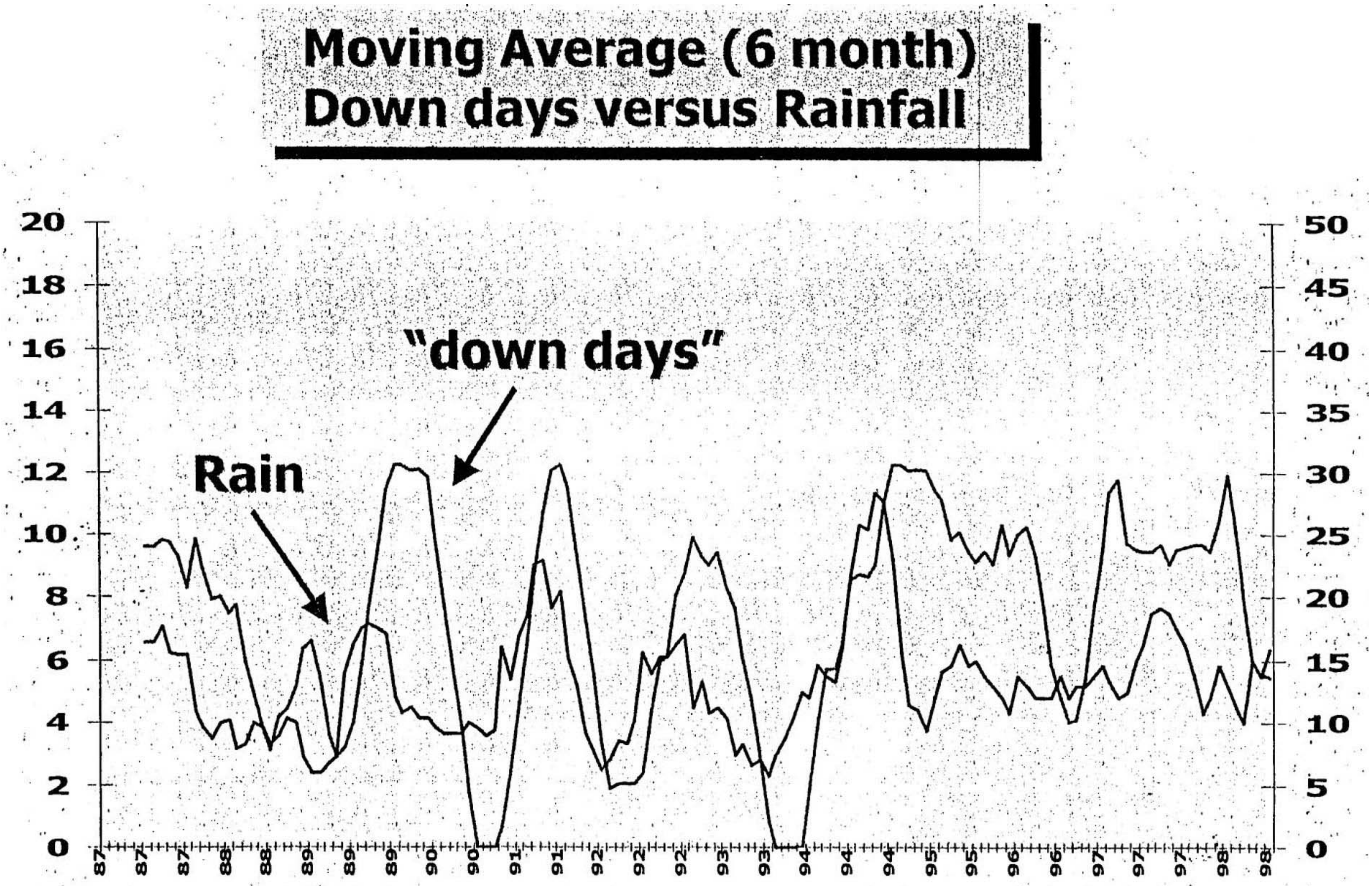

Figure 5. Comparison of "down days" and rainfall

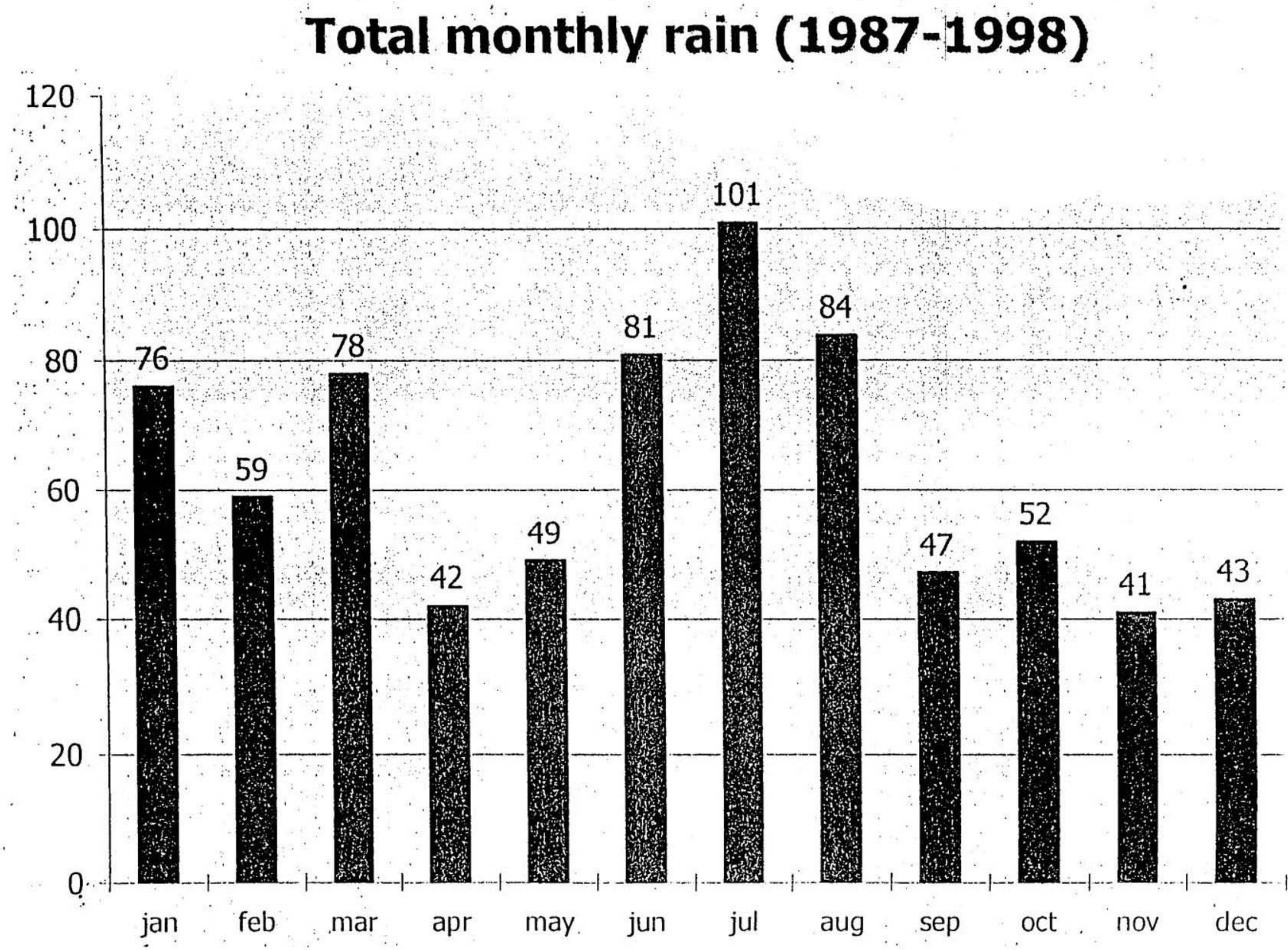

Figure 6. Total monthly rainfall at Wakulla Springs State Park for 1987-1998

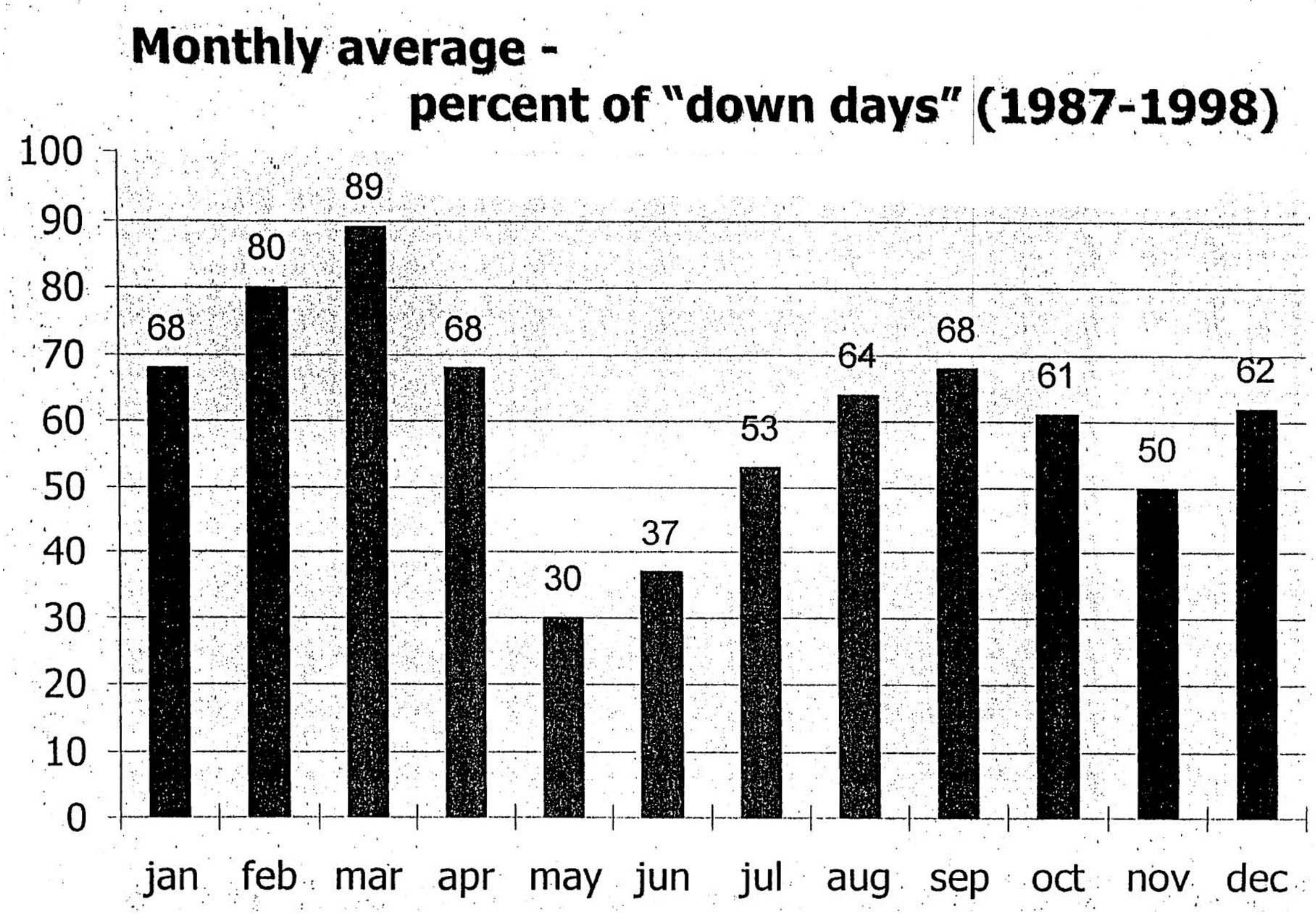

Figure 7. Monthly average of "down days" at Wakulla Springs State Park for 1987-1998

Long periods of Glassbottom Boat "down days"

		Rainfall		
# Days	Dates	Start	End	Avg
165	12/1/86 - 5/17/87	8	0	6
122	6/8/87 - 10/23/87	12	0	11
320	6/11/89 - 4/27/90	17	3	6
242	1/22/91 - 9/20/91	19	1	8
337	6/18/94 - 5/10/95	13	6	8
197	9/21/96 - 3/26/97	5	2	5
136	5/5/97 - 9/17/97	8	1	7
179	11/3/97 - 4/30/98	6	1	5
	Mean	**11**	**2**	**7**

Table 1. Periods of Wakulla Springs State Park glassbottom boat "down days" of over 100 consecutive days

Long periods of Glassbottom Boat "up days"

		Rainfall		
# Days	Dates	Start	End	Avg
266	4/28/90 - 1/21/91	2	19	3
152	9/21/91 - 2/9/92	1	6	2
292	4/14/93 - 1/30/94	1	8	3
122	5/12/96 - 9/10/96	2	5	3
	Mean	**1**	**10**	**3**

Table 2. Periods of Wakulla Springs State Park glassbottom boat "up days" of over 100 consecutive days

NON MARKET VALUES OF NATURAL RESOURCE USE

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ABSTRACT

Natural resources such as fisheries; wetlands and manatees are rarely traded in an open market as most other goods and services are traded in the rest of the economic system. Thus, such resource use is not included in the U.S. Gross Domestic Product even though vital economic services are rendered to many individuals from such resources. The problem is rooted in a difficulty in assigning property rights to those that derive economic value from the natural resources.

Despite the property right problem, economists have formulated economic models to estimate the asset value of such common property resources as fisheries; wetlands and even endangered species in Florida. The presentation will look at the methodogy and how it is appplied to three natural resources in Florida: (l) recreational fisheries; (2) saltwater beaches and (3) wetlands with numerical examples.

Additionally, the talk will include NOAA/Sea Grant efforts to develop a workbook of natural resources values to be used by non-economists in areas from litigation to preparation of government reports on the economic status of various natural resources.

THE APALACHICOLA NATIONAL FOREST
STAYING ONE STEP AHEAD OF THE THREAT

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ABSTRACT

The Apalachicola National Forests hosts several major sinkholes which open to the Woodville Karst system. Beginning with the 1985 Forest Plan and continuing, with significant improvements, into the 1998 Forest Plan, land use standards and guidelines have been designed to fully protect this valuable resource. The most significant sinkholes such as Big Dismal Sink and Gopher Hole are well protected. But less well known depression ponds remain threatened by uncontrolled, illegal activities such as mud bogging and trash dumping. Since depression ponds contain several potentially endangered species, future protection measures will be focused on stopping illegal activities which impact these areas.

The Apalachicola National Forest hosts several major sinkholes, which open to the Woodville Karst system. Among the more prominent sinkholes are Big Dismal sink, Gopher Hole sink and Sullivan sink within the Leon Sinks Geological Area, and Promise sink and Go Between sink in the River Sinks Special Emphasis Area. Less prominent, although no less important ecologically, are hundreds of small ephemeral depression ponds and dry depressions throughout the eastern portion of the forest.

The importance of the major sinkholes is obvious. Since these sinks open directly into the underground river system, which eventually surfaces at Wakulla Springs, water quality issues are paramount. However, these larger sinks also support a unique collection of plants and animals, as well as a valuable collection of cultural artifacts, making their value even greater.

In contrast, the small ephemeral depression ponds and dry depressions are less obvious but no less important. Ephemeral depression ponds support a wide variety of plants and animals, which depend on the seasonal fluctuations in water level for their existence. Several species of endangered and very rare amphibians are found nowhere else but in these ponds.

Protection of this unique resource, both large and small, is a major objective of National Forest Management. A framework of laws and regulations, which come to focus in the Land and Resource Management Plan for the National Forests in Florida (the Forest Plan), provides the legal basis for protection. Beginning with the 1885 Forest Plan and continuing with the latest revision due to be approved this winter, the Forest Plan employs a tiered approach to resource management and protection.

First, the Forest Plan provides the overall management direction. The current revision emphasizes uneven-aged management techniques which will maintain a continuous canopy of trees throughout time. Practices which can threaten water quality such as clearcutting, intensive site prep and herbicide use are dramatically reduced.

Second, the Forest Plan makes land allocation decisions and places land into categories which emphasize unique resource values. Examples are the Leon Sinks Geological Area, the River Sinks Special Emphasis Area, and the urban interface zone near Tallahassee where special access restrictions apply.

Third, the Forest Plan prescribes management practices, which limit the range of resource management techniques, which can be employed. Practices such as double roller drum chopping are prohibited in favor or less impacting techniques like prescribed burning.

Fourth, standards and guidelines designed to mitigate adverse effects resulting from management practices are defined. Standards and guidelines are specific, measurable restrictions that must be implemented. For example, where herbicides are determined to be needed, they may not be applied closer than 200 feet from water.

Even with the multi-layered measures contained in the Forest Plan to protect the unique resources of the Woodville Karst Plain, several threats remain. The population growth of the region is clearly the most serious threat. With increasing population comes increasing pressure on limited resources, such as land for housing, shopping and schools, demands for recreation facilities, roads, airports and infrastructure.

The Apalachicola National Forest hosts much of the outdoor recreation experiences for the ever-growing population of the region. Legal recreation activities such as hunting, fishing, swimming, camping and sightseeing mean more people in concentrated areas. Although these activities can threaten the resource values of the sinkholes and ponds, they are relatively easy to regulate and control.

A far more serious threat comes from illegal activities such as mudbogging, an activity where 4X4 trucks with large tires are intentionally driven into swampy areas to test the ability of the truck and driver to negotiate ever more difficult situations. Illegal trash dumping, often associated with mudbogging, is also a major threat to sinks and dry depressions.

Mudbogging produces several serious impacts. First, the repeated passage of heavy trucks eventually eliminates the vegetation from around the semi-wet fringe of ephemeral depression ponds. Second, ruts created by the tires channel water away from the ponds and disrupts the subsurface hydrology. Third, trucks wallowing in the shallow water of the ponds cause excessive siltation and reduced water quality. Finally, the activity physically destroys wildlife such as amphibian eggs.

Taken together, these impacts pose a serious threat to the unique collection of animals and plants which occupy these shallow ponds. Since some of the species, which occupy these ponds, occur nowhere else, the activity of mudbogging has the very real potential to drive several species to extinction. It is hard to believe that a few thoughtless and uninformed individuals who own large 4X4 trucks could, in the span of a few years, eliminate from the face of the Earth species which have taken millions of years to evolve into their present form.

Aside form the serious legal implications involved, the economic impacts from this shortsighted activity could be tremendous. If any of these species are driven to near-extinction on the portion of their ranges open to public use, the pressure to preserve these species will shift to private lands where mudbogging is not as common. Land use restrictions could cost private landowners huge sums in the future.

Another illegal activity which poses a severe threat to sinkholes and depression ponds is trash dumping. From industrial to commercial to household, a wide variety of waste is dumped on the National Forest. Industrial waste includes toxic and hazardous chemicals, agricultural waste such as dead animal carcasses, pesticides and fertilizers. Commercial waste includes construction materials, demolition waste and used tires. Household waste includes lawn trash, old carpet and used appliances.

All these things end up in depression ponds and sinkholes. Since most major sinks are in restricted access special areas, they are relatively well protected from illegal dumping. But most of the small sinks and the depression ponds are vulnerable and receive a constant influx of trash and waste.

This poses a serious threat to the water quality of the Woodville Karst system since many of these sinks connect to the underground flow directly. Many sinks have sand plugs which prevent human access into the caverns, but which allow the relatively free passage of water. An abandoned car, for example, could deposit several gallons of gasoline and several quarts of oil directly into the waters which eventually feed Wakulla Springs.

In addition to the threats to water quality, illegal dumping degrades the pristine view most visitors to the National Forest expect. The unsightly appearance of randomly dumped trash detracts from the very qualities that people cherish in their wild lands. Ironically, it costs far more to clean up illegally dumped waste than it would have cost to dispose of it legally. Essentially, the illegal dumpers are, in effect, transferring their costs to the population at large.

Although increased law enforcement will help alleviate these illegal activities, it is unrealistic to think that enough officers could stem all the mudbogging and trash dumping over these vast areas. Instead, public education must also be employed. People may be less likely to dump trash into a depression pond if they knew they might be swimming in their own waste at Wakulla Springs weeks or months later. Mudboggers might be less willing to engage in wanton destruction of ponds if they knew that their activities might drive an entire species to extinction.

For those who can not be educated to the negative effects of their practices, stiff fines and even jail time can be employed. These are harsh remedies, yet harsh remedies may be required to change attitudes toward natural resources which may have evolved over generations.

The bottom line is that the sinkholes and depression ponds of the Woodville Karst must be protected. Once this resource is destroyed, no technology and no amount of money may be able to repair the damage.

SOILS OF THE KARST PLAIN AND THEIR ECOLOGICAL COMMUNITIES: CORRELATIONS AND CONSTRAINTS FOR SUSTAINABLE USE

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ABSTRACT

Soils occurring in the Wakulla Springs Karst Plain can be generally grouped into five categories: (1) soils on the sand ridges; (2) soils on the low uplands; (3) soils in the coastal marshes; (4) soils in the depressions and drainageways; and (5) soils on the flatwoods. Soil and vegetation can vary either coincidentally or independently. Abrupt changes in vegetation can occur across major soil boundaries, such as a boundary between sand ridge soils and drainageway soils. Abrupt vegetation changes usually are due to a difference in water or nutrient supply regime across the soil boundary. In general -- and barring recent disturbance, soils on the sand ridges support an ecological community known as Longleaf Pine - Turkey Oak Hills. Soils on the low uplands support this community as well, but also Mixed Hardwoods and Pine. Soils in the coastal marshes support Salt Marsh. Soils in depressions and drainageways support Wetland Hardwood Hammock, Swamp Hardwoods and Cypress Swamp. Soils on the flatwoods support the ecological community known as North Florida Flatwoods, interspersed with wetter Shrub Bog -Bay Swamp communities.

Reasons for non-coincidence of present-day vegetation and soil boundaries are numerous. Soil factors critical to the establishment and dominance of some major plant species -- such as water and nutrient availability in a porous soil at a rooting depth greater than the 2 m surveyed -- may not be among the factors used to classify and map soils. Furthermore, past events, both natural and human-caused, have written an ecological history for every site that may well vary in important ways from the history of every other site with similar soils. Hurricanes, tornadoes, floods, droughts and fires have been joined by logging, turpentining, grazing and sometimes clearing for cultivation or pasture to create a suite of potential disturbance events that have not fallen uniformly on the landscape. These non-soil factors always share responsibility for -- and often dominate -- the course that vegetative succession takes; but over time, given similarity in critical soil factors, similar vegetative assemblages will be produced, although their pathways of succession may vary.

Considering soil as habitat and examining soil-vegetation correlations thus involves two steps. First, the major soil features and process variables that affect plant growth and health must be understood. These include water table, seasonal water availability, aeration, penetrability, acidity and base content, nutrient supplies, salinity, and root pathogens -- as well as disturbance history. Second, we must know something about how plants, animals and ecosystems respond to the intensities and interactions of these variables. Because many of these features and variables are incorporated in the soil classification, soil classes at one level or another often do delimit major vegetative assemblages.

Land development in Florida has a history of altering many of these soil features and variables that are integral to a soil's fitness for support of a particular vegetative assemblage. Cut-and-fill grading, site drainage, and elevation of the land surface by fill -- often using marl or shell material with a high pH -- all alter the soil features and variables in a way that changes the plant successional assemblages likely to occur, sometimes drastically. Many highly-disturbed soils are so ill-suited to supporting native vegetative assemblages that they are readily colonized by aggressive nuisance exotic plants, and become springboards for exotic plant invasion of native habitat.

As the Wakulla Springs Karst Plain undergoes intensifying semi-rural and suburban development, sustaining this unique region's native plant associations and wildlife will require that we practice site-by-site conservation of all attributes of our soil resources. These attributes include seasonal wetness, which usually makes a soil unsuitable for a variety of human uses connected with housing development. Land and subdivision platting needs to be undertaken with the goal of including within each parcel a mix of soils matched to the mix of uses envisioned. The prevailing approach to platting is often blind to soil suitability, and sets up a cascade of site-by-site alteration of soil to make unsuited sites meet landowner goals. This practice eventually will result in a cumulative loss of the region's potential to support the flora and fauna that

constitute its people's natural heritage. And in this region, still rich in outdoor recreation traditions, the natural heritage still undergirds a sustainable cultural heritage that is being squeezed into smaller and smaller pockets within the matrix of modern Florida. So, there is much at stake when we plat, and when we individually decide how to manage our soil, for the soil really is the basis for the culture.

FLORIDA YARDS AND NEIGHBORHOODS (FYN) PROGRAM IN THE ST. MARKS/WAKULLA RIVER WATERSHED

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ABSTRACT

Nature of Problem: *The groundwater resources of the Wakulla Springs Karst Plain are recharged within and beyond the boundary of this geologic region. Impervious surface in much of the Tallahassee urban and suburban area generates storm water run-off into Karst Plain. This storm water carries nonpoint source pollutants. Homesite practices, too, within the Karst Plain can negatively affect ground water quality. These practices include: landscape design and maintenance, septic systems, livestock and pet waste, sediment erosion, solid waste, hazardous chemicals, automotive and boat maintenance, and drinking-water well maintenance.*

Program Description: *Working in partnership with homeowners or neighborhood associations, and with other citizen organizations, the Florida Yards and Neighborhoods (FYN) Program will be used to teach the residents of Leon and Wakulla counties how to reduce their impact on surface and ground water quality. The program delivery strategy will include working closely with each partner organization to design seminars, indoor and "backyard" workshops, and consultations that address the water quality issues of greatest concern to each neighborhood or group. Follow-up assistance using trained volunteers will be a critical part of the strategy to achieve adoption of Best Management Practices (BMPs). Residents will be taught BMPs to maintain or improve water quality in their specific lake, stream, river, spring, or sink. Practices to be addressed include stormwater runoff management, animal waste management, sediment erosion control, pond management, alternative shoreline treatments, litter control, boat maintenance, hazardous waste management, wildlife habitat improvement, etc.*

Projected Impact and Benefits: *Urban and suburban impacts on water quality and natural ecosystems of the Wakulla Springs Karst Plain will be reduced as Leon and Wakulla residents adopt Best Management Practices that decrease stormwater run-off, reduce water consumption, increase the onsite re-use of organic waste materials, minimize the use of fertilizers and pesticides, reduce the discharge of nonpoint source pollutants, and use plants that more closely harmonize with Leon and Wakulla's natural areas and wildlife. This will require continuing education of new residents in order to preserve the Karst Plain's natural resources so critical to our quality of life. The collaborative delivery of the Florida Yards and Neighborhoods (FYN) Program will enhance our ability to stimulate change on the order of magnitude necessary to protect the Wakulla Springs Karst Plain water resources and unique ecosystems for generations to come.*

WILDLIFE HABITAT MANAGEMENT ON ST. MARKS NATIONAL WILDLIFE REFUGE

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ABSTRACT

St. Marks National Wildlife Refuge includes about 66,000 acres of wildlife habitat strecthed along 40 miles of coastline in the Big Bend area of the Florida Panhandle. The refuge supports a wide variety of plant communities, from seagrass beds in Apalachee Bay to tidal saltmarsh, freshwater marshes, spring-fed and blackwater rivers, swamps, hardwood hammocks, pine flatwoods, and longleaf pine-turkey oak sandhills. In addition, there are 2,000 acres of impoundments constructed by the Civilian Conservation Corps in the 1930's and early 1940's.

The goal of refuge management is to provide high quality wildlife habitat and enhance wildlife populations, especially endangered and threatened species, and migratory birds. Management activities range from passive protection of wooded wetlands, hardwood hammocks, and much of the federally designated St. Marks Wilderness, to selective logging in many pine habitats, water level and salinity manipulation in the managed impoundments, and actively prescribed burning in many habitats.

Obstacles to providing these high quality habitats for wildlife often occur outside the refuge boundary. Air quality, water quality, and water quantity are all greatly impacted by activities off refuge. Adjacent land use changes such as residential or commercial development can complicate or even suspend the prescribed burning activities which are so vital to maintaining quality pine habitats and reducing the risk of catastrophic wildfires.

ARE ONE TO FIVE ACRE LOTS THE ANSWER?

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ABSTRACT

Over and over controversial development proposals are given the same solution. From adjacent neighbors, it's reduce the density and we won't oppose it. From government, it's reduce the density and we'll approve it. So densities have been reduced. Both directly through zoning categories which set minimum acreage and maximum square footage requirements and indirectly through setback requirements, height restrictions, and minimum parking requirements. Development causes real problems: stormwater and wastewater pollution, traffic congestion, impacts to wildlife, and increased demand for government services. But has the solution solved the problems, or made them worse? The discussion will present a regional perspective of the impacts of low density development, and where it's taking us.

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