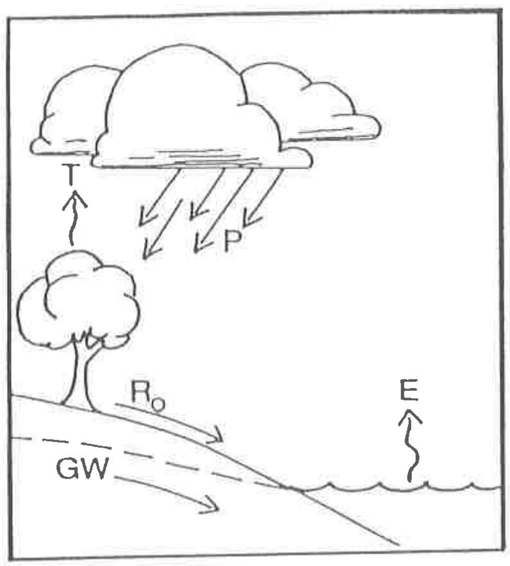
PROCEEDINGS

A CONFERENCE ON THE WATER RESOURCES OF GEORGIA AND ADJACENT AREAS

edited by

RAM ARORA and LEE L. GORDAY



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A Conference on the

Water Resources of Georgia and Adjacent Areas

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Department of Natural Resources
J. Leonard Ledbetter, Commissioner

Environmental Protection Division
Harold F. Reheis, Assistant Director

Georgia Geologic Survey
William H. McLemore, State Geologist

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INTRODUCTION

Ram Arora

The proceedings volume of the conference "The Water Resources of Georgia and Adjacent Areas" sponsored by the Georgia Geologic Survey and the Georgia Institute of Technology presents a collection of papers in the area of ground- and surface-water hydrology, water use, water quality, and water management, as well as precipitation and weather modification. A total of 36 papers were presented at the conference. The text of 17 papers, 19 abstracts, and the conference schedule are included in the proceedings volume. The majority of the papers deal with ground-water resources of the Coastal Plain of Georgia.

The State of Georgia has approximately 20,000 miles of rivers and streams. Traditionally, surface water is the main source of water for municipalities and industries in north Georgia. South Georgia relies heavily on ground water for municipal and industrial use. A major concern is the long-term availability of water for present use and future demand. In the years 1950-1970, water withdrawals in the state increased 104 percent while the population increased 33 percent. The abstract by Pierce and Barber indicates that the total water use in Georgia for 1980 was 6,772 million gallons per day (M gal/d), 4,469 M gal/d of which was used for cooling thermoelectric power plants, 818 M gal/d for industrial use, 773 M gal/d for public supplies, and 578 M gal/d for irrigation use. The most significant growth in water use during the last decade occurred in irrigation (approximately 1200%).

The overall ground-water availability of the Coastal Plain aquifers of Georgia is good. However, there are areas of concern. According to the abstract by McFadden and Perriello, the large ground-water withdrawals from the Clayton Aquifer in southwest Georgia have resulted in significant declines in water levels. This continuous ground-water withdrawal in excess of natural replenishment may lead to aquifer depletion. Meeks and Hayes' abstract indicates that an increase in ground-water withdrawal from the Principal Artesian Aquifer in the Dougherty Plain area will reduce the base flow of streams, increase the possibility of sinkhole development and increase well construction and pumping costs. In the Savannah area of Georgia, water levels in the Principal Artesian Aquifer dropped 40 feet between 1954 and 1961; however, from 1961 to the present the base level has remained essentially constant.

The need for reliable and useful ground-water information in Georgia was accentuated by droughts that occurred in the spring and summer of 1977 and 1978 and by increased withdrawal of ground water by municipal, industrial and agricultural users. In response to these needs, the Department of Natural Resources prepared a six-year (FY 1979-1984) program proposal which permitted the Georgia Geologic Survey to accelerate the collection and analysis of ground-water information. Following the recommendations of Georgia's Governor, George Busbee, the legislature approved funding. The program of work, commonly referred to as the Accelerated Ground-Water Program, was initiated in July, 1978. In cooperation with the U.S. Geological Survey, the Georgia

Geologic Survey has completed hydrologic investigations of the Upper Cretaceous, Clayton, Claiborne, Principal Artesian (Floridan), Jacksonian, Gordon, Dublin, and Midville Aquifers. The results of Upper Cretaceous (Clarke and others), Clayton and Claiborne (McFadden and Perriello), and Principal Artesian (Meeks and Hayes; Maslia) studies were presented at the conference. The abstracts of these presentations are included in this volume. A total of nineteen hydrologic reports have been published as a result of the Accelerated Ground-Water Program. These reports can be purchased from the Georgia Geologic Survey office.

The research in ground-water hydrology in crystalline rock is limited. However, papers presented by Harman and others using geophysical exploration techniques and Perchalski on photohydrologic mapping techniques demonstrate the improved chances of locating ground water in crystalline rocks. Cressler and others (1983, Georgia Geologic Survey Information Circular 63) reported that many wells in the greater Atlanta area provide large supplies of ground water with yields between 40 to more than 200 gal/min, and developed a method to select high-yielding well sites using structural controls and lithostratigraphic units.

Patrick's paper indicates that ground-water contamination is widespread and estimates that about 10 percent of the ground water throughout the United States may be contaminated. The State of Georgia possesses both abundant quantity and high quality water with the exception of high chlorides in southeast Georgia and elevated radionuclide levels (discussed in a paper by Kahn and others in this volume) in sporadic locations in Tift, Montgomery, and Wheeler counties of east-central Georgia. The high chloride and elevated radionuclide levels in the ground water in these cases are due to natural causes. The major concern in the coastal counties is the upward movement of saltwater from zones which are 800-1000 feet deep in Chatham County and between 1800-2000 feet deep in Glynn County. The radioactivity source in Tift, Montgomery, and Wheeler counties appears to be in the phosphate deposits of the overlying Hawthorne Group of Miocene-aged sediments. Municipal ground-water supplies in this area are now being withdrawn from the deeper Ocala Limestone and the quality of ground water is good.

The major concern of the Environmental Protection Agency of the Department of Natural Resources of the State of Georgia is to protect fresh water resources from man's activities. To this end the State of Georgia has several regulations and a management plan to protect the quality and to manage the quantity of its water resources. The Georgia Geologic Survey and the U.S. Geological Survey currently measure water levels in more than 1,400 wells in Coastal Plain aquifers on a regular basis. In addition to these, more than 100 monitoring wells are equipped with continuous water-level recorders. The Georgia Geologic Survey also maintains a file of lithologic and geophysical logs for more than 3,000 wells. Currently, the Georgia Environmental Protection Division has implemented a ground-water management strategy to prevent pollution, to protect aquifers, and to coordinate the functions within the Georgia Environmental Protection Division.

THE WATER RESOURCES OF GEORGIA AND ADJACENT AREAS

October 13 and 14, 1983

CONFERENCE SCHEDULE

Thursday, October 13

8:00 **Registration**

9:00 **Introduction and Overview** — **Bernd Kahn, Moderator**

Welcome — Joseph W. Pettit, President, Georgia Institute of Technology

History of the Accelerated Ground-Water Program — J. Leonard Ledbetter, Director, Environmental Protection Division

Accomplishments of the Accelerated Ground-Water Program — William H. McLemore, State Geologist

An Overview of Georgia's Water Resources — James E. Kundell, Institute of Government, University of Georgia

The Multistate Tertiary Limestone Aquifer System — Richard H. Johnston, U.S. Geological Survey

10:05 **Break**

Water Use (Poster Session) — **Posters on Display Until 1:40 pm, October 14**

Water Use in Alabama, 1981 — Robert M. Baker and James D. Moore, Geological Survey of Alabama

South Carolina 1980 Water Use Estimates — Joseph A. Harrigan, South Carolina Water Resources Commission

Water Use in Georgia — Robert R. Pierce, U.S. Geological Survey and Nancy L. Barber, Georgia Geologic Survey

10:30 **Ground Water I** — **Ram Arora, Moderator**

Photohydrologic Map Supplements for Ground-Water Investigations — Frank R. Perchalski, Tennessee Valley Authority

Developing Ground-Water Supplies in the Georgia Piedmont: Applied Technology Versus the "Dry-Hole" Syndrome — H. Dan Harman, Jr., Engineering Science, Inc., Don A. Watson, Ground Water and Soil Services, and Tom Duffey, NUS Corporation

Hydrologic Framework for Coastal Plain Aquifer Systems of Georgia — Ram Arora, Georgia Geologic Survey

Hydrogeology of the Providence Aquifer of Southwest Georgia — John S. Clarke, Robert E. Faye, and Rebekah Brooks, U.S. Geological Survey

11:50 **Lunch**

1:00 **Water Quality** — **Frederic G. Pohland, Moderator**

Groundwater Quality — Ruth Patrick, Academy of Natural Sciences of Philadelphia

Geochemical Patterns as Indicators of the Origin and Source of Waters in a Multi-Level Aquifer System — James M. Frazee, Jr., St. Johns River Water Management District

Radioactivity Levels in Georgia Water Supplies — Bernd Kahn, Marcia Wilson, and John Gasper, School of Nuclear Engineering and Health Physics, Georgia Institute of Technology, and Susan Adamovitz, Environmental Protection Division

Assimilative Capacity Improvement Due to Reservoir Release Aeration — B. R. Kim, Georgia Institute of Technology, J. M. Higgins and C. E. Bohac, Tennessee Valley Authority

Forest Cutting and Water Quality in the Georgia Piedmont — J. D. Hewlett, School of Forest Resources, University of Georgia

Velocity Equation for Water Quality Modeling in Georgia — Roy G. Burke, Environmental Protection Division

Water Quality of Releases From Corps Lakes in Georgia — George M. Strain, U.S. Army Corps of Engineers

3:20 **Break**

3:40 **Ground Water II** — **Larry R. Hayes, Moderator**

The Water Resources of the Central Savannah River Area — Reevaluated — George E. Siple, South Carolina Water Resources Commission

The Hydrogeology of Richmond County, Georgia — Lee L. Gorday, Georgia Geologic Survey

Ground-Water Conditions in the Black Creek Aquifer System of Northeastern Coastal South Carolina — A. Michael Pelletier, South Carolina Water Resources Commission

Effects of Increased Pumpage on the Tertiary Limestone Aquifer: Dougherty Plain, Georgia and Ft. Walton Beach, Florida — Morris L. Maslia, U.S. Geological Survey

5:00 **Adjourn**

Reception at Alumni House

To be hosted by Thomas Stelson, Vice President for Research, Georgia Institute of Technology, immediately following the day's last session

Friday, October 14

8:00 **Surface Water** — **Jeffrey T. Armbruster, Moderator**

Characteristics of the "Seven-Day, Ten-Year Minimum Streamflow" Statistic — Kathryn J. Hatcher, Institute of Natural Resources, University of Georgia

Effects of the Drought of 1980-81 on Streamflow and on Ground-Water Levels in Georgia — Robert F. Carter, U. S. Geological Survey

Macro and Micro Hydrology of the Okefenokee Swamp — Elizabeth R. Blood, Baruch Institute, University of South Carolina

Sediment Sources and Transport in King's Bay and Vicinity, Georgia and Florida — Dean B. Radtke, U.S. Geological Survey

9:20 **Break**

9:50 **Precipitation and Weather Modification** — **C. Gerald Justus, Moderator**

Precipitation Measurement from Space — Thomas T. Wilheit, Goddard Laboratory for Atmospheric Sciences, National Aeronautics and Space Administration

Precipitation Estimates From Visible and Infrared Satellite Data — Roderick Scofield, Satellite Applications Laboratory, National Oceanographic and Atmospheric Administration

Precipitation Results of Cloud Seeding Research in Florida — William Woodley, Environmental Research Laboratories

Comparative Study of the Causes and Effects of Recent Southeastern Droughts — C. G. Justus and M. V. Paris, School of Geophysical Sciences, Georgia Institute of Technology

11:10 **Lunch**

12:20 **Ground Water III** — **Stephen S. McFadden, Moderator**

The Hydrologic and Stratigraphic Relationships of Tertiary and Younger Sediments of Northwestern Allendale County, South Carolina — Raymond L. Knox, South Carolina Department of Health and Environmental Control, John V. Kinsella, Golder Associates, and Gary G. Padgett, South Carolina Department of Health and Environmental Control

Hydrogeology of the Clayton and Claiborne Aquifers, Southwestern Georgia — Stephen S. McFadden and P. Dennis Perriello, Georgia Geologic Survey

Parameter Estimation of the Clayton Aquifer Near Albany, Georgia — E. L. Kuniansky, U.S. Geological Survey and M. M. Aral, School of Civil Engineering, Georgia Institute of Technology

Recharge and Water Budget in the Principal Artesian Aquifer in Southwest Georgia — Wanda C. Meeks and Larry R. Hayes, U.S. Geological Survey

Ground-Water Conditions in the Tertiary Aquifer Systems Near Charleston, South Carolina — A. Drenan Park, South Carolina Water Resources Commission

1:40 **Break**

2:10 **Water Management** **Chris White, Moderator**

Wetlands as Vital Components of the Nation's Water Resources — Eugene P. Odum, Institute of Ecology, University of Georgia

Regulation of Water Withdrawals in Georgia — Robert Pierce and Thomas C. Burdette, Jr., Georgia Environmental Protection Division

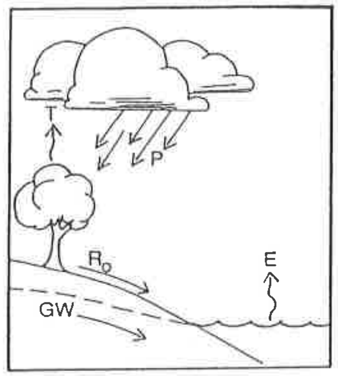
Irrigation Management in Georgia — E. Dale Threadgill, J. R. Stansell, and J. E. Cook, Coastal Plain Experiment Station, University of Georgia

The Changing Infrastructure for Water Resources Financing — Ronald M. North, Institute of Natural Resources, University of Georgia

3:30 **Open Forum, Questions, Answers and Discussion** **William H. McLemore, Moderator**

4:00 **Adjourn**

ABSTRACTS



HYDROGEOLOGIC FRAMEWORK FOR COASTAL PLAIN AQUIFER SYSTEMS OF GEORGIA

ARORA, Ram, Georgia Geologic Survey, 19 M.L. King, Jr., Dr., SW., Atlanta, GA 30334

The Principal Artesian, Claiborne, Clayton, Cretaceous (including Providence), and Shallow Aquifers in the Coastal Plain of Georgia provide ground water for irrigation, industrial, domestic, and municipal supplies. The nature and distribution of the aquifers are controlled by lithologic, stratigraphic, and structural features. The geologic characteristics including stratigraphy, structural controls, areal and subsurface distribution are illustrated on isopach (thickness) maps, structural contour maps for both the top and bottom, and geologic cross-sections. Hydrogeologic data from the ground-water monitoring well program, consisting of drill cores and cuttings, geophysical logs, and aquifer tests, provide an understanding of hydrogeology. Maps showing transmissivity, total dissolved solids, chlorides, natural radioactivity, and water levels define ground-water availability and quality. The Coastal Plain Aquifer systems of Georgia generally have abundant high-quality water for present use and future development.

VELOCITY EQUATION FOR WATER QUALITY MODELING IN GEORGIA

BURKE, Roy, III, Environmintal Protection Division, 148 International Boulevard, Suite 800, Atlanta, Georgia 30303

Tabletop water quality modeling still plays an important role in the water pollution control activities of the Georgia Environmental Protection Division. Tabletop models are those developed without the aid of extensive field data. One important component of GEORGIA DOSAG, our basic water quality model, is the equation used to predict flow through velocity. However, Georgia is characterized by wide physiographic diversity which reduces the effectiveness of uncalibrated velocity equations. Using 15 years of accumulated time-of-travel studies, a series of empirical velocity equations were developed and calibrated to various physiographic conditions in Georgia. Equations are available for each major soil province - $Q<100$ cfs, $100<Q<1000$ cfs, and $Q<1000$cfs. Now in the absence of extensive field data, we have data based velocity equations which can be tailored to each site under study.

EFFECTS OF THE DROUGHT OF 1980-81 ON STREAMFLOW AND ON GROUND-WATER LEVELS IN GEORGIA

CARTER, Robert F., U.S. Geological Survey, 6481-B Peachtree Industrial Blvd., Doraville, GA 30360

The 1980-81 drought resulted in the lowest rates of streamflow since 1954 in most areas of Georgia, and the lowest since 1925 in some areas. Over most of the State, minimum average streamflows for periods of 1, 7, 30, 60, 90, and 183 consecutive days receded to low levels estimated to be reached at average intervals of 10 to 25 years. Flows in the Flint River from central to southwest Georgia receded to levels estimated to be reached at average intervals of 70 years. Pool levels at 4 major reservoirs receded to the lowest levels since the reservoirs were first filled.

Ground-water levels declined below the lowest levels previously observed in many observation wells. Nearly continuous declines were recorded in some wells for as much as 20 consecutive months, and levels remained below the previous minimum level of record for as much as 9 consecutive months.

HYDROGEOLOGY OF THE PROVIDENCE AQUIFER OF SOUTHWEST GEORGIA

CLARKE, John S., FAYE, Robert E., BROOKS, Rebekah, U.S. Geological Survey, 6481-B Peachtree Industrial Blvd., Doraville, GA 30360

The Providence aquifer consists of sand of Upper Cretaceous age and lies within the Coastal Plain physiographic province of southwest Georgia. The aquifer ranges in thickness from 40 to 340 feet and has transmissivities that range from 760 to 4,600 feet squared per day.

During 1980, an estimated 9 million gallons per day were pumped from the Providence aquifer. From 1950-80, ground-water use increased 230 percent in Americus and 240 percent in Albany, causing water-levels in the aquifer to decline more than 100 feet.

Recharge water enters the aquifer in the northeastward-trending outcrop belt and flows southward, bounded by the Ocmulgee River on the east and the Chattahoochee River on the west. Additional recharge is received through leakage from underlying units. Discharge from the aquifer to streams occurs both in the outcrop area and downdip through overlying units. Idle multi-aquifer wells in Albany and Dawson provide conduits for upward discharge of water from the Providence aquifer.

Water from the Providence aquifer is a soft, sodium bicarbonate type which generally has no constituent concentrations that exceed the Georgia Environmental Protection Division and the U.S. Environmental Protection Agency standards for safe drinking water.

GEOCHEMICAL PATTERNS AS INDICATORS OF THE ORIGIN AND SOURCE OF WATERS IN A MULTI-LEVEL AQUIFER EVALUATION

FRAZEE, James M., Jr., St. Johns River Water Management District, P. O. Box 1429, Palatka, FL 32078-1429

Geochemical Pattern Analysis using the Piper trilinear diagram and a modified Durov doubled tetrahedral diagram provides a rapid predictive tool to study hydrologic systems. It is a first-line predictive method serving as a basis for more detailed and costly evaluations. The Piper method allows an excellent separation of base level source waters and more saline waters of varying age. The Durov diagram separates the source waters and particularly the upland source, direct conduit recharge waters. This second step is necessary in some source areas due to low TDS concentrations and transitional acidic pH storage.

The technique is used to areally map changes in ground waters of both the Floridan aquifer and shallower surficial aquifers. In areas of inter-aquifer movement, trend diagrams are developed to describe changes with depth or with surface infiltration of waters from characteristically different source aquifers. A flow diagram relates water groups and types showing progressive changes in geochemistry. Examples illustrate the regional Floridan aquifer system and localized surficial aquifers in Georgia and Florida.

THE HYDROGEOLOGY OF RICHMOND COUNTY, GEORGIA

GORDAY, Lee L., Georgia Geologic Survey, 19 M.L. King, Jr., Dr., SW, Atlanta, Georgia 30334.

The Cretaceous Sand Aquifers supply ground water to industrial and municipal users in Richmond County. Ground-water use in Richmond County averaged 14.5 million gallons per day, with expectations of even greater use in the future as the population grows and industries expand. The aquifers are composed of upper Cretaceous sands and gravels that crop out in the northern portion of Richmond County and dip to the south-southeast. Sands and gravels near the base of the upper Cretaceous sediments form the aquifer that supplies the majority of the ground water used. A second upper Cretaceous aquifer is located higher in the unit, but its use is generally limited to down dip areas. A clay bed that is inferred to be a weathering profile separates the two aquifers. The effectiveness of the clay bed in hydraulically separating the aquifers is not well documented. Analysis of one pump test indicates that leakage from the clay bed is significant. Analysis of the available pump test data for the lower aquifer indicates an average transmissivity of 0.087 ft^2/s. Transmissivity estimates for the upper aquifer are not available. Ground-water flow in the lower aquifer is generally from west to east.

DEVELOPING GROUND-WATER SUPPLIES IN THE GEORGIA PIEDMONT: APPLIED TECHNOLOGY VERSUS THE "DRY HOLE" SYNDROME

HARMAN, H. Dan, Jr., Engineering Science, Inc., 57 Executive Park, Atlanta, GA 30329; WATSON, Don A., Ground Water and Soil Services, Rt. 2, Whitesville Rd., LaGrange, GA 30240; DUFFEY, Tom, NUS Corporation, 1726 Montreal Circle, Suite 20, Tucker, GA 30084

The abundance of igneous and metamorphic rocks in Georgia's Piedmont Province is readily apparent to engineers, geologists, and the local populace of this northern region of Georgia, but the abundance of ground water is not so readily apparent. In fact, some professionals and the local populace are very skeptical and pessimistic about the potentials for developing ground water in the Piedmont. Their method of developing ground-water supplies may be a "hit-or-miss" or "let's try another hole over there" approach. This method is, of course, time consuming not to mention expensive. It is based on an old yet ever present attitude that ground water in the Piedmont is limited to domestic supplies and encountering water bearing fractures is just a case of good fortune. Projects to develop public water supplies from ground-water sources are major investments, but seldom are projects conducted using methods such as exploration geophysics.

In a recently conducted independent survey the status of Piedmont ground-water development was assessed. Ground water in the Georgia Piedmont was considered a dependable public water source by only forty percent of the water supply firms responding to the survey. Another forty percent considered using Piedmont ground water on a case-by-case basis. Twenty percent did not consider Piedmont ground water a dependable source and would rather use surface water. The main sources of ground-water data (location, depth, quality, etc) were water well drillers, federal and state geological departments and the respondent's own experience. Yet, eighty percent of the respondents stated knowledge of "dry holes" varying from a low range of 1 to 10 to a high range of 50 to 100 occurrences. Seventy percent stated knowledge of occassions to "try another hole" from a low range of 1 to 10 to a high range of 10 to 50. Yet, the percentage of respondents who were aware of exploration geophysics was sixty percent. The available technology useful in the development of ground-water supplies in the Piedmont is not being fully applied.

This paper discusses the complexity of ground-water development in the Georgia Piedmont and some past and present attitudes about its occurrences. The present public water supply use of ground water in the Georgia Piedmont is also discussed as well as how the use of exploration geophysical techniques, specifically electrical resistivity, can be applied to ground-water development. Through applied technology the "dry hole" syndrome can be overcome in most cases and the development of ground-water supplies in the Georgia Piedmont can be improved.

SOUTH CAROLINA 1980 WATER USE ESTIMATES

HARRIGAN, Joseph A., S. C. Water Resources Commission, Columbia, S. C. 29250
Withdrawal water use in South Carolina for 1980 averaged 5800 mgd (million gallons per day), nearly all from fresh water sources. This representa a 72% increase since 1970, due mainly to the start-up of a few very large water users. Average per capita withdrawal water use averaged 1812 gallons per day, an increase of 39% over 1970 per capita use.

Withdrawal water use includes: public supply, self-supplied industry, agricultural irrigation and livestock, self-supplied domestic, and thermo-power. Thermo-power water use represents 76% of the total withdrawal water use, followed distantly by self-supplied industry (16%) and public supply (17%). All types of water use grew during the past decade ranging from a doubling of thermo-power water-use to only a minor increase in livestock water use.

Even though the volume of ground water use is only 3% of the total withdrawal use, 15% with thermo-power water use excluded, it is still a vital water supply. Nearly two-thirds of all self-supplied industries and public suppliers utilize ground water as well as all self-supplied domestic users.

Agricultural irrigation water-use should show the greatest increase during the next few decades primarily because mechanized irrigation practices are now just catching hold in South Carolina. Public supply water-use growth should continue to grow at its present rate due to population and industrial migration here to the Sun-Belt region. However, industrial as well as thermo-power water use will grow at a lesser rate due to implementation of water reuse and recycling technologies.

Hydroelectric power generation, water use, an instream use, grew nearly 30%, due largely to the addition of two large pump-storage facilities since 1970.

THE MULTISTATE TERTIARY LIMESTONE AQUIFER SYSTEM

JOHNSTON, Richard H., U.S. Geological Survey, 75 Spring St., Atlanta, GA 30303
The "principal artesian aquifer" of coastal and south Georgia is part of the multistate Tertiary limestone aquifer system underlying all of Florida and parts of adjoining Alabama, Georgia, and South Carolina. Present pumpage is about 3 billion gallons per day with Georgia accounting for about 600 million gallons per day.

The aquifer system is a sequence of limestone and dolomite that is hydraulically connected in varying degrees. Thickness of the carbonate rocks varies from a featheredge at the outcrop to more than 1,500 feet downdip. Hydraulic properties of the aquifer system are highly variable; transmissivity ranges from less than 1,000 feet squared per day in panhandle Florida to more than 1,000,000 feet squared per day in the central Florida springs area. A sharp contrast in flow activity exists among different areas of the aquifer system. High recharge and high discharge rates coupled with high transmissivity characterize the unconfined and thinly confined parts of the system. Extremely sluggish flow, virtually no recharge, and minimal discharge characterize the deeply buried parts of the system.

Computer simulation of flow in the aquifer system provided estimated rates of recharge and discharge and indicated how these rates are affected by pumping. Simulation showed that before ground-water development began, the discharge from the aquifer system was about 21,000 cubic feet per second of which about 90 percent occurred as spring flow or discharge to rivers, as compared to about 10 percent areal seepage in coastal areas. Today spring flow and discharge to rivers account for about 75 percent of the aquifer's total discharge, areal seepage represents about 7 percent of present-day discharge, and pumpage accounts for about 18 percent.

From a regional perspective, the major change in the aquifer system has been the development of three areas of regional water-level declines around pumping centers. Within two of these areas, deep cones of depression occur around Savannah, Ga., and Fernandina Beach and Ft. Walton Beach, Fla.

ASSIMILATIVE CAPACITY IMPROVEMENT DUE TO RESERVOIR RELEASE AERATION

KIM, B. R., Georgia Institute of Technology, Atlanta, Georgia 30332; HIGGINS, J. M., Tennessee Valley Authority, 248 401 Building, Chattanooga, Tennessee 37401; and BOHAC, C. E., Tennessee Valley Authority, 248 401 Building, Chattanooga, Tennessee 37401

Many reservoirs in the southeastern United States have dissolved oxygen concentrations in their releases which are lower than desirable during portions of the year. Therefore, aeration of releases from upstream reservoirs was investigated as a means of increasing minimum dissolved oxygen concentrations. This paper examines the potential for reservoir release aeration to increase the assimilative capacity of streams using the South Fork of the Holston River as a case study.

THE HYDROLOGIC AND STRATIGRAPHIC RELATIONSHIPS OF TERTIARY AND YOUNGER SEDIMENTS OF NORTHWESTERN ALLENDALE COUNTY, S.C.

KNOX, Raymond L., SCDHEC, 2600 Bull St., Columbia, S.C. 29201; KINSELLA, John V., Golder Associates, 5125 Peachtree Road, Atlanta, Ga. 30341; PADGETT, Gary G., SCDHEC, 2600 Bull St., Columbia, S.C. 29201

The relationships between ground-water hydrology and post-mid-Eocene sediment stratigraphy were investigated in an area south of Martin, S.C., bordering the Savannah River. Detailed drilling, sampling, and water-level measurement programs in conjunction with borehole geophysical logging were used in this investigation.

Borings have identified the presence of the Tobacco Road Sand formation of Huddleston and Hetrick (1978). The distinctive basal carbonate facies (silicified limestone and chert layer) of this formation was encountered in numerous borings and traced in outcrops in the area of investigation. Typical sands of Dry Branch formation lithology with a top clay layer were found immediately beneath the Tobacco Road deposits. Preliminary paleontological evidence establishes the lithological correlation.

Potentiometric head-level declines with depth and absence of aquitards over the upland portion of the study area provide evidence for localized recharge to both formations. The underlying Tertiary limestone aquifer may also be receiving localized recharge in addition to that from updip subcrop areas. The sands are, for the most part, discharging to the Savannah River. The Tertiary limestone aquifer may also be leaking to the river.

EFFECTS OF INCREASED PUMPAGE ON THE TERTIARY LIMESTONE AQUIFER: DOUGHERTY PLAIN, GEORGIA AND FT. WALTON BEACH, FLORIDA

MASLIA, Morris L., U.S. Geological Survey, 6481-B Peachtree Industrial Blvd., Doraville, GA 30360

Increased ground-water withdrawals in the Dougherty Plain, Georgia, and Ft. Walton Beach, Florida, areas were simulated using finite difference ground-water flow models. Aquifer transmissivity in the Dougherty Plain ranged from 3,000 to 300,000 feet squared per day and in the Ft. Walton Beach area ranged from 250 to 25,000 feet squared per day. Leakance of the overlying confining bed ranged from 0.0002 to 0.0075 foot per day per foot in the Dougherty Plain and from 0.0000003 to 0.00002 foot per day per foot in the Ft. Walton Beach area. Storage coefficients ranged from $2x10^{-4}$ to $3x10^{-2}$ in the Dougherty Plain and from $5x10^{-4}$ to $1x10^{-3}$ in the Ft. Walton Beach area.

During a simulated 3-year hydrologic drought in the Dougherty Plain, mean ground-water levels declined 26 feet with existing pumpage of 113 billion gallons per year and declined 33 feet with projected pumpage of 408 billion gallons per year. Under normal hydrologic conditions and projected pumpage of 287 billion gallons per year, mean ground-water levels declined by 4 feet at the end of a 10-year simulation. Aquifer discharge to streams was reduced about 30 percent.

In the Ft. Walton Beach area, increases from 1978 pumpage of 15.5 million gallons per day to year 2000 projected pumpage of 20.5 million gallons per day resulted in simulated water-level declines of 20 to 60 feet in the Ft. Walton Beach area. By moving simulated pumpage to high transmissivity areas, water levels declined only 10 to 20 feet.

HYDROGEOLOGY OF THE CLAYTON AND CLAIBORNE AQUIFERS, SOUTHWESTERN GEORGIA

MCFADDEN, Stephen S. and PERRIELLO, P. Dennis, Georgia Geologic Survey, 19 M. L. King, Jr., Dr., SW, Atlanta, GA 30334

The Clayton and Claiborne aquifers of southwestern Georgia are locally important sources of ground water in a fifteen-county study area. Comparison of historic and recent water-level measurements indicates declines of hydraulic head in both of these aquifers.

Potentiometric maps of the Clayton aquifer show that a cone of depression is centered at Albany and extends into neighboring counties. In Albany, the hydraulic head has declined approximately 170 feet from 1885 to 1981. Records from throughout the area show that the declines in hydraulic head are widespread. Reasons for the declines are increased municipal, industrial, and agricultural withdrawals; limited recharge; and the hydraulic properties of the aquifer. Total water use from the Clayton aquifer is estimated to be 26 Mgal/d while recharge from rainfall infiltration averages about 14.7 Mgal/d. The area over which the hydraulic properties are conducive to the construction of high-yielding wells is relatively small. Because of these factors, the declining potentiometric levels in the Clayton aquifer can be expected to continue.

More localized declines in hydraulic head have occurred in the Claiborne aquifer. A cone of depression is present around the city of Albany, where the hydraulic head has declined 70 feet from the 1950's to 1981. Declines in this aquifer are due to local municipal, industrial, and agricultural withdrawals, coupled with the hydraulic properties of the aquifer. Total water use from the Claiborne aquifer is estimated to be 36 Mgal/d while recharge from rainfall infiltration is estimated to average 100-133 Mgal/d. Hydraulic properties are such that large withdrawals concentrated in relatively small areas can cause large potentiometric declines.

RECHARGE AND WATER BUDGET OF THE PRINCIPAL ARTESIAN AQUIFER, SOUTHWEST GEORGIA

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The surficial material of the 4,400-square-mile Dougherty Plain area consists of about 25 to 125 feet of sandy clay residuum derived from solution weathering of the Ocala Limestone. The underlying limestone aquifer is referred to as the Principal Artesian aquifer in Georgia and is the primary source of water in southwest Georgia.

Rainfall that is not evaporated, transpired, retained in the unsaturated zone as soil moisture, or discharged to streams, moves downward through the residuum to recharge the Principal Artesian aquifer.

Recharge to the aquifer varies considerably with location because of the highly variable leakance of the residuum and difference in water levels between the residuum and aquifer. Digital modeling indicates that annual mean recharge varies from about 0.1 to 2 million gallons per day per square mile; the latter occurring in highly developed karst areas where stream losses to the aquifer are high. Annual mean recharge is about 2,000 million gallons per day whereas late-summer mean recharge is only 1,400 million gallons per day.

Hydrograph separation indicates that annual mean ground-water discharge to streams from the residuum and the Principal Artesian aquifer is about 2,600 million gallons per day, and late-summer mean discharge is about 1,500 million gallons per day. Additionally, annual mean pumpage from wells in the Principal Artesian aquifer is about 225 million gallons per day (210 million gallons per day for irrigation and 15 million gallons per day for all other uses). As with recharge, both pumpage and natural discharge in the Dougherty Plain vary considerably with areal location and time of year.

PHOTOHYDROLOGIC MAP SUPPLEMENTS FOR GROUND-WATER INVESTIGATIONS

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In the search for new ground-water resources and the protection of known ground-water reserves, the most satisfactory plans result when the best, most complete hydrogeologic model is employed. This can often be accomplished through the use of innovative mapping and data collection strategies. An aerial photographic approach for supplementing traditional information is presented, which can find application throughout much of the Southeast.

A methodology for preparing several types of photohydrologic map supplements is described and illustrated. Photohydrologic map supplements are compared to traditional map information to demonstrate the increase in useful detail which is possible. Associated costs for the generation of the map supplements are discussed. The methodology is summarized using illustrations from an actual application in the Valley and Ridge physiographic province in southeastern Tennessee.

REGULATION OF WATER WITHDRAWALS IN GEORGIA

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Since December 1, 1974 a permit has been required from the Georgia Environmental Protection Division (EPD) to withdraw ground water in excess of 100,000 gallons per day (gpd). Since July 1, 1977 an EPD withdrawal permit has been required to withdraw surface water in excess of 100,000 gpd on a monthly average. The Water Resources Management Branch administers both permit programs, and all final permit decisions are made by the Director, EPD. Permits are not required for agricultural water use.

Ground water permit applications request: 1)amount of withdrawal; 2)type of use; 3)aquifer(s) used; 4)well construction and location information; 5)drillers logs. In the application review process EPD considers: 1)amount of water requested; 2)aquifer properties; 3)other water users; 4)recharge; 5)importance of use. Surface water permit applications request: 1)amount of withdrawal; 2)location of intake; 3)type of use; 4)water conservation and drought contingency plans; 5)inter-basin effects. Permit decisions are based on: 1)protection of low flow (7Q10); 2)location of other withdrawals; 3)location and type of discharges; 4)importance of requested withdrawal; 5)protection of downstream users.

All permits require the periodic submission of water use reports.

Although not required to obtain a permit, agricultural water users (both surface and ground) must report to their respective County Agent by April 1st of each year their monthly water use (or information necessary to calculate water use) for the previous calendar year.

The withdrawal permits are management tools to enable the State to put its water resources to beneficial use to the fullest extent to which they are capable, while at the same time protecting and conserving these resources.

WATER USE IN GEORGIA

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The Georgia Water Use Program is a joint effort of the Georgia Geologic Survey and the U.S. Geological Survey. The purpose of the program is to collect, store, and disseminate information on water use. The microcomputer-based Water Use Data System holds this information in four data files. IRRIGATION contains site-specific irrigation system data, W&D holds site-specific municipal and industrial withdrawal and discharge information, MITH gives all water-use permit information, and ENTITY summarizes all water user types and totals. Data for W&D and MITH were collected from Environmental Protection Division files, and irrigation data were generated by a 1979-80 Soil Conservation Service survey. IRRIGATION will be updated using the new Irrigation Reporting System. Currently the program is in a maintenance phase with updates occurring annually.

Water-use figures generated by the program show a total water use in Georgia for 1980 of 6,772 million gallons per day (Mgal/d), 66 percent of which is used for cooling thermoelectric power plants. The next largest user is self-supplied industry at 818 Mgal/d, then public supply at 773 Mgal/d. The most significant growth in water use occurred in irrigation, increasing by a factor of 12 during the last decade to reach 578 Mgal/d in 1980. Minor amounts of water are withdrawn for rural domestic and livestock. The water-use figures can be used to make regional comparisons, for water-resource management studies, or at greater detail as input to modelling efforts.

SEDIMENT SOURCES AND TRANSPORT IN KINGS BAY AND VICINITY, GEORGIA AND FLORIDA

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Water-quality, bottom-material, suspended-sediment, and current-velocity data were collected during November 1981 and July 1982 in Kings Bay and vicinity to provide information on the sources and transport of estuarine sediments. Kings Bay and Cumberland Sound, the site of the Poseidon Submarine Base in southeast Georgia, are experiencing high rates of sediment deposition and accumulation, which are causing serious navigational and operational problems.

Velocity, bathymetry, turbidity, and bottom-material data suggest that the area in the vicinity of lower Kings Bay is accumulating deposits of suspended sediment transported from Cumberland Sound on the floodtide and from upper Kings Bay and the tidal marsh drained by Marianna Creek on the ebbtide. Suspended-sediment discharges computed for consecutive 13-hour ebbtides and floodtides showed that a net quantity of suspended sediment was transported seaward from upper Kings Bay and Marianna Creek. A net landward transport of suspended sediment computed at the St. Marys Entrance, Cumberland Sound, and the entrance to Kings Bay indicated areas seaward of St. Marys Entrance may be supplying sediment to the shoaling areas of the estuary, including lower Kings Bay.

PRECIPITATION MEASUREMENT FROM SPACE

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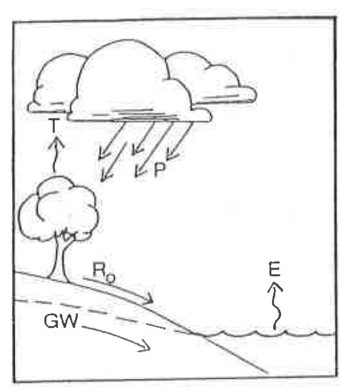
Spaceborne rain measurement techniques can be grouped in three categories: 1) visible/infrared (VIS/IR), 2) passive microwave, 3) radar. The VIS/IR techniques are presently being widely applied using existing sensors on both low orbit and geostationary satellites. While these techniques are subject to criticism because of the lack of a theoretical framework, they nevertheless work to a useful degree, particularly for cumuliform precipitation. Passive microwave measurements may be grouped into two regimes: centimeter and millimeter. Radiometry at centimeter wavelengths (10-40 GHz) is capable of making very good measurements of stratiform precipitation over the ocean. In the millimeter regime (75-300 GHz), the measurements have been shown to be sensitive to frozen hydrometeors near the top of the precipitation forming layers; this may prove useful in measuring rain over both ocean and land backgrounds. Although radar has been used extensively for ground based precipitation measurements, it has not yet been tried as a spaceborne technique. The geometry of the spaceborne radar creates a difficulty in separating the ground clutter from the rain signal except very near the sub-satellite track. For the future, a combination system using the existing visible and infrared sensors supplemented by radiometers and radars could provide precipitation measurements useful to a wide variety of disciplines.

PAPERS



MACRO AND MICRO HYDROLOGY OF THE OKEFENOKEE SWAMP

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ABSTRACT

The Okefenokee Swamp is a precipitation-evapotranspiration driven system whose major hydrologic components respond in a tightly linked manner. Within each component are factors which attenuate the microhydrological response. Precipitation (60%) and surfacewater runoff (39%) are the major inputs. Water loss from the swamp is primarily evapotranspiration (47%). Thirty-six percent leaves as surfacewater runoff from the Suwannee River (75%), St. Marys River (11%), and Cypress Creek (14%). Loss to ground water or subsurface storage is low (17%).

INTRODUCTION

The Okefenokee Swamp, located in Ware, Clinch, and Charlton Counties of Georgia and Baker County, Florida, is the largest freshwater wetland in the United States. The swamp occupies about 47% of a 3781 KM^2 watershed and is the source watershed of the Suwannee River, which flows into the Gulf of Mexico, and St. Marys River, which flows into the Atlantic Ocean (Figure 1).

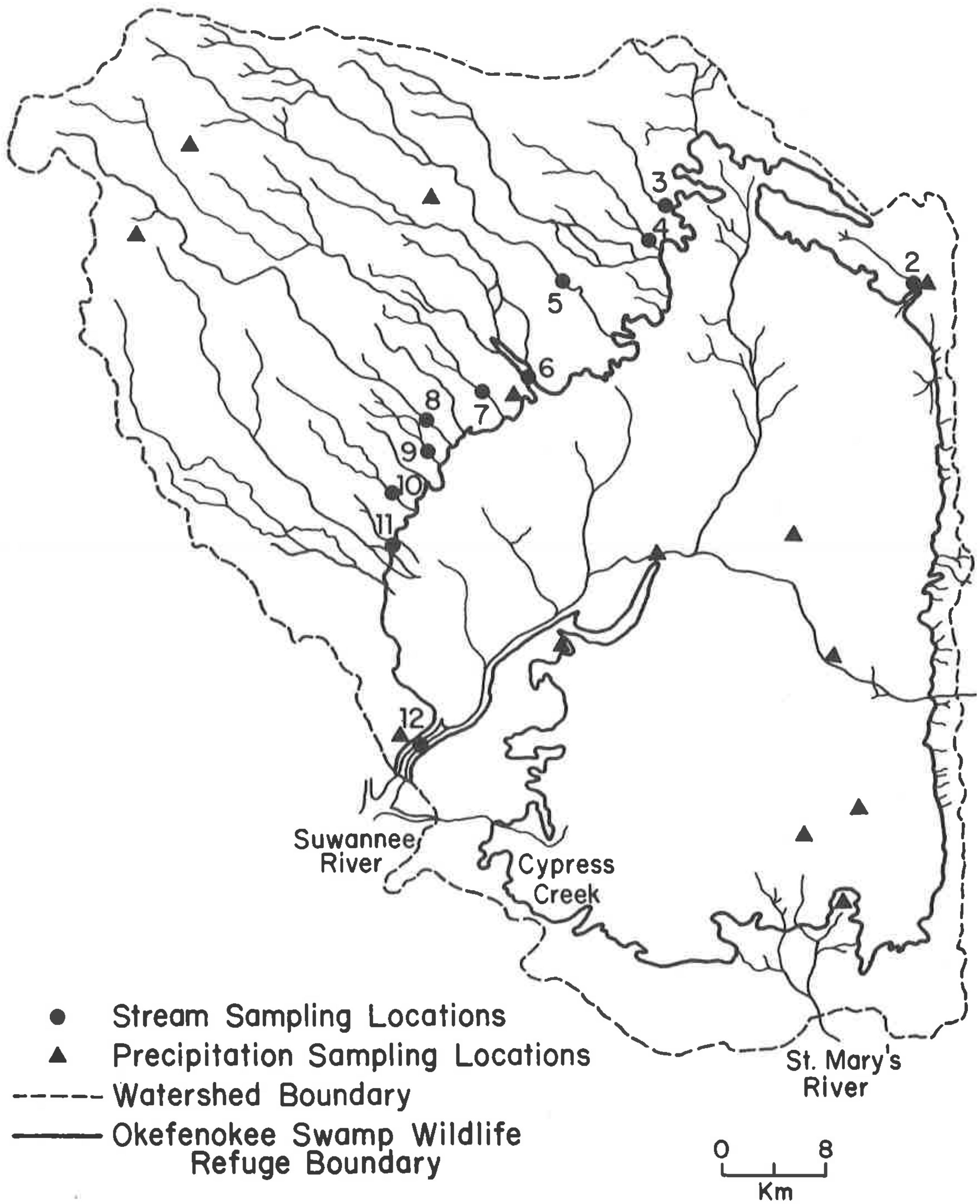
Okefenokee is a complex wetland ecosystem of distinctive habitats which interconnect in a heterogeneous landscape array of subsystems. The spatial and temporal heterogeneity of the swamp fluctuates in response to a variable time series of water balance, hydroperiod, and catastrophic disturbances. Throughout history, disturbances have played a vital role in forming and maintaining the swamp's complexity, controlling the spatial and temporal expression of successional end points (Hamilton 1981), and hydrologic dynamics. Important natural phenomena and anthropogenic intrusion include drought, fire, hydroperiod, boat trails and canals, lumbering, sill construction and channelization (Blood 1981, Duever 1979 Rykiel 1977, Hamilton 1981, Auble 1982, Flebbe 1981).

Existence of the swamp has been attributed primarily to the presence of a sandy barrier (Trail Ridge) on the eastern side which rises 12 m above the swamp (Doering 1960) and to the relative impermeability of the Hawthorne formation underlying the Okefenokee region. This formation prevents vertical seepage and causes "ponding" of Okefenokee waters (Callahan 1964, Smedley 1968, Herrick 1970, Rykiel 1977).

Previous reports indicate that precipitation is the most important source of water to the swamp (Rykiel 1977). The primary aquifer is located below the swamp, and although some interaction between shallow and deep ground water on the uplands may occur, contribution from deep ground water to the overall swamp hydrology is probably minimal. (Callahan 1964, Matthews et al. 1979, Rykiel 1977, Blood 1981).

Recent studies (Blood 1981, Rykiel 1977, Patten & Mattis 1982, Flebbe 1981 Duever 1979, Auble 1982) have quantified various portions of the hydrologic budget and dynamics of the Okefenokee Swamp. The purpose of this paper is to summarize and synthesize information of the general hydrology of the swamp. The objectives are to: calculate an overall water budget, quantify temporal swamp dynamics, identify and quantify hydrologic components responsible for the observed dynamics, and determine the relative influence of modifications on swamp hydrology.

Figure 1. Okefenokee Swamp.



METHODS

Hydrologic variables were assessed from a variety of sources. Swamp water-level data were obtained primarily from the Okefenokee National Wildlife Refuge (1950-1980). These data were supplemented by water-level measurements in habitats encompassing major vegetation subsystems for 1977-1980 (Duever 1979, Auble 1982, Flebbe 1981). Data for streamflow output from the swamp were taken from publications of the U.S. Geological Survey (1950-1980) for the Suwannee and St. Marys Rivers. Discharge from Cypress Creek was calculated from biweekly measurements from August 1978-January 1980. These measurements were related ($R^2 = 0.86$) to discharge from Suwannee River and used to extend the hydrologic record to include 1975-1980. Eleven upland streams also were monitored from August 1978-January 1980 to assess surface-water input to the swamp. Input surface-water discharges were also correlated with water discharges from the St. Marys and Suwannee Rivers and the hydrologic records extended to encompass 1975-1980. When empirical data were compared with calculated data, annual estimates are very close ($R^2 = 0.965$). Precipitation input is determined using the Thiessen method (Linsley, Kohler and Paulhus, 1958). Data were obtained from the National Oceanic and Atmospheric Administration for 1950-1980. In 1978, additional precipitation sampling stations were established to provide a better areal estimate of precipitation and to allow evaluation of differential (uplands versus swamp) inputs to the watershed. Potential evapotranspiration was calculated for 1950-1980 by Thornthwaite's method (Thornthwaite and Mather 1957). When evapotranspiration calculated by the difference ($P = R + E$) was compared with that calculated by Thornthwaite's method mean values differed by less than 3% (Rykiel 1977). Complete details of methodology are given in Blood 1981, Rykiel 1977, Duever 1979, Auble 1982, Flebbe 1981 .

RESULTS

Climate

Climatological dynamics are dominated by maritime tropical air masses which produce a hot, wet climate. The average annual temperature is approximately 20°C to 27°C. The largest temperature ranges, however occur in the winter months. In January 1976, the recorded low was -6°C and the high 26°C (Rykiel 1977). Annual precipitation averages 1000-1500 mm (Table 1). Precipitation is not distributed equally throughout the year. The majority of precipitation occurs from May to October. Moderate amounts occur from January to May and the least input occurs from October to January. Evapotranspiration ranges from 500 to 1500 mm annually. Monthly losses follow temperature dynamics with maximum losses occurring from May to October (Table 1).

Geology and Vegetation

Basin topography is relatively flat, varying in elevation from 31 to 49 m above mean sea level. The watershed is located on a marine terrace covered primarily with Pleistocene sands ranging in particle size from .20 - .25 mm (30%) and .25 to .50 mm in diameter (Smedley 1968, Pirkle 1972). Within the swamp, these sands are covered with an accumulation of peat. The peat depth varies with vegetative habitat and ranges from 31 - 384 cm (Cohen 1973).

Upland vegetation is dominated (76%) by managed pine-cypress stands. The upland wetter areas comprise about 6%, with open water 0.5%, and cypress swamps 5.5%(Blood 1981). No major industrial sources are within the watershed, urbanization is limited to approximately 2%. Vegetation within the swamp is a mosaic of wetland communities ranging from open water lakes (7%) through aquatic macrophyte and grass sedge prairies (21%) to a variety of forested communities including shrub thickets (34%), bay forests, cypress stands and extensive *Nyssa* forests (total forested areas 29%) (McCaffrey and Hamilton 1980). Although the swamp was extensively logged from 1891-1927, no trees have been removed since designation as a wildlife refuge in the 1940's. Fire and hydroperiod are thought to be the important regulating factors for vegetation (Hamilton 1981).

Swamp Surface Water Level

Okefenokee is a deepwater swamp-marsh complex with mean water depth of 0.7 m in average hydrologic years, but up to 2 m in certain areas (Finn and Rykiel 1979). Residence time of swamp surface water at steady state is 190 days (Rykiel 1977). Fluctuations in water level vary temporally and spatially. Normal annual amplitude is about 80 cm (Table 1). Although there is larger year to year variation in amplitude, the annual pattern is fairly consistent. Water levels are highest from January to May then decrease to lowest levels in September or October. Water levels have the greatest annual variability from September to January (Rykiel 1977).

Water level dynamics vary across the swamp (Best pers. comm., Duever 1979, Auble 1982, Flebbe 1981, Finn and Rykiel 1979). The greatest water depths occur in the Suwannee River basin and show the strongest annual pattern. Eighty-five percent of the uplands contribute to the Suwannee basin. Runoff from upland streams are strongly influencing the water level dynamics by enhancing response to precipitation input (Blood 1981). Variation in water level is dampened in the St. Marys River and Cypress Creek subwatersheds. Uplands contributing to these basins are less than 5%. The deepest accumulations of peat occur in these areas (Cohen 1973). Therefore water level response may be a more direct response to precipitation dynamics.

Vegetation influences the hydrologic response of the swamp. Macrophyte prairies and deep water Cypress habitats have the deepest water depths (36-56 cm) but show the greatest annual variation (± 56 cm). Macrophyte prairies have the longest hydroperiods (346 days-period of inundation) (Duever 1979, Auble 1982, Flebbe 1981). Cypress habitats located in the St. Marys basin and blackgum forests have intermediate water levels but exhibit the lowest variation (41-43 cm). Shrub habitats have the shortest hydroperiod (246 days), lowest water levels (23-31 cm), and intermediate variation (38-51 cm) (Duever 1979, Flebbe 1981, Auble 1982).

In 1954 a severe drought occurred in the southeastern United States. During this period the swamp became desiccated and nearly 80% of the swamp burned. To prevent recurrence of such extensive peat fires an earthen dam was constructed on the Suwannee River at the swamp boundary. As a result of this construction mean monthly waterlevels increased by 42 cm in the immediate area and 11 cm at Camp Cornelia (29 km from Sill). This water level increase has substantially altered surface water gradients and decreased the head between Camp Cornelia and outflow via the Suwannee River. The resultant decrease in flow rates across the swamp attenuates water level response to precipitation. A reduction of 18-30% of normal variation in water level has occurred. The increased water levels also have caused ponding of water above the peat surface, therefore, reducing the swamp's peat hydrologic buffering capacity. Approximately 28% of the total swamp area has been affected, primarily in the Suwannee River basin (Finn and Rykiel 1979). The reduction in buffering capacity has increased stormflow peak discharges and decreased recession time from peak discharge for the Suwannee River.

Streamflow Runoff

The swamp may be divided into 3 subwatersheds based on discharge of water from the swamp. Eighty-five percent of the water shed contributes to runoff from the swamp by the Suwannee River. The remainder contributes runoff via the St. Marys River (11%) and Cypress Creek (4%). The twenty-five year annual discharge from the swamp was 414 m^3/sec (44-1150 m^3/sec). This was based on discharge from the Suwannee and St. Marys Rivers. Average annual discharge from 1975-1980 was slightly higher (Suwannee 813, Cypress Creek 152, St. Marys 136 m^3/sec).

Streamflow runoff is not evenly distributed throughout the year. Discharge is bimodal. A spring peak corresponds to reduced evapotranspiration during the cool months. A smaller peak in late summer is related to heavy rainfall input which occurs during the hot months. Forty-seven percent of annual runoff occurs from January through April, while only 16% occurs from October to January (Rykiel 1977).

Although a good linear relationship exists between annual runoff and annual precipitation ($Y = -765.89 + 0.81X$, $R^2 = 0.83$), runoff peaks are not coincident with rainfall peaks. The response is attenuated by the storage capacity of the swamp. An exponential relationship between Suwannee River flow and water level (Suwannee River log discharge = 33.064 + 1.852X, $R^2 = 0.80$) indicates the swamp is acting as a linear reservoir (Rykiel 1977). The relationship of discharge to precipitation and waterlevel also varies with swamp outlet (St. Marys log discharge = 0.569 + 0.628 log precipitation, Suwannee River log discharge = 2.50 + 0.335 log precipitation). The smaller basin (St. Marys) responds sooner but the overall contributions to discharge is less for a given input of precipitation. During the drought of 1954 the Suwannee and St. Marys discharge declined to zero. Regression analysis of the rate of decrease in flow for these streams gave turnover times (time required for 63% of total response to occur) as 21 days for Suwannee and 10 days for St. Marys (Rykiel 1977).

The majority of the streams transporting water to the swamp are located in the northwestern portion of the watershed and contribute only to the Suwannee basin. These streams are intermittent with average annual flows varying considerably among streams — 5.6 m^3/sec to 251.9 m^3/sec (Table 2). Streams transporting water to the St. Marys basin are ephemeral and contribute only 8% of total input. Cypress Creek receives no surface water runoff.

Drainage areas for input streams range from 15 to 196 km^2 and stream lengths from 6 to 94 km. Drainage areas form an elongated nearly parallel pattern on the western portion of the watershed. Basin slope is very gentle ranging from 25 cm/km to 85 cm/km. The majority of the streams entering the swamp are third order or less with 72% of total stream segments in the first order. The average bifurcation ratio is 2.91. Twenty-five percent of total stream lengths are channelized.

Temporal dynamics and response to precipitation varies among streams and with channelization. In general, stream discharge exhibits the same bimodal distribution as swamp water levels. Maximum discharges occur from December to May with a smaller peak coincident with periods of high precipitation in late summer. Surface-water inputs show similar dynamics to surface water output, correlations between input and output discharges range from R^2 = .75-.95. Output discharge is therefore a good predictor of input discharge (Blood 1981).

Channelized stream discharge dynamics are greatly attenuated (2 to 5 times less discharge than unmodified streams). Channelized streams have lower baseflows and a longer no flow period (Blood 1981). Streams in the upper half of the watershed have discharges strongly correlated (R^2 = .60 - .77) with precipitation while those in the lower portion do not respond directly to precipitation inputs. Unmodified stream discharges are correlated with precipitation ($R^2 = 0.74$) but channelized stream discharge is not. Unmodified streams transport twice as much water per unit of watershed than do channelized streams (4.49m - channelized, 9.64 m - unmodified).

Ground water

Deep ground-water contribution to the Okefenokee watershed appears to be negligible. The swamp is perched 12 m above the potentiometric surface of the principal artesian aquifer and the presence of a relatively impermeable formation below the swamp probably inhibits downward seepage. The aquifer is deepest and the confining layer thickest in the portion of Georgia where the swamp is located (Callahan 1964). Callahan estimated loss from the swamp to the aquifer as less than 1% of average annual rainfall input. Mass balance hydrologic models by Rykiel (1977), Blood (1981) and Patten and Mattis (1982)

Table 1. Summary Statistics

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (c°)	11.7	12.5	15.6	19.4	23.2	26.0	27.0	27.0	25.1	20.3	15.0	11.7
Rainfall (mm/month)	85	95	107	92	106	133	185	160	128	65	48	80
Evapotran-spiration	22	26	45	75	119	152	170	161	124	75	36	21
Total Stream-flow (mm/month)	23	30	41	40	18	16	18	28	27	21	12	13

*Matthews, S.E., Hester, W.G., and C'Byrne, M.P., 1979, Ground-water Data for Georgia, 1979, U.S. Geological Survey Open File Report 80-501, pp 93.

* - Omitted from reference list.

Table 2. Input Streams

	Drainage Area (km^2)	Length (km)	Percent Channelization	Discharge (m^3/sec)
Cowhouse	68	16	100	5.6
Gum Swamp	43	9	53	41.1
Black River	49	6	0	32.4
Greasy Branch	182	78	34	27.7
Suwannee River	196	94	25	251.8
Cane Creek	143	91	38	101.2
Surveyor's Creek	156	60	6	27.3
Barnum Branch	15	16	88	14.9
Big Branch	51	26	73	8.9
Tatum Creek	157	73	29	17.8

estimate losses from 3% to 7% of incoming precipitation.

Although some interaction of shallow ground water with the primary aquifer is possible in the uplands, ground water chemistry and response to precipitation indicate that it is minimal. Ground water pH averages around 5 units with the dominant ions sodium, sulfate and chloride. Swamps with substantial deep ground water have higher surface water and ground water concentrations of carbonate, bicarbonate, calcium, and magnesium contributing to the hydrologic dynamics (Gibbs 1970, Heinselman 1970).

Water budget

The 1975-1980 water budget is similar to the 25-year average calculated by Rykiel (1977). Evapotranspiration (PE) is slightly higher, 78% of incoming precipitation. Precipitation contributes 60% of the total water entering the swamp. The remaining 39% of swamp surface water originated as runoff from the upland streams. A small portion (1%) of this runoff may enter the swamp surface water as shallow ground water from the uplands (Hyatt pers. comm.). Analyses by Patten and Mattis (1982) indicate the small percent of water transported to the swamp as shallow ground water enters the swamp subsurface component and not the surface water. Rykiel (1977) estimated surface water runoff to be 30% of the swamp's input. Of the total water entering the swamp (precipitation plus surface water) 47% is lost as evapotranspiration, 36% is lost as surface water discharge from the swamp, 10% is stored as subsurface storage and 7% is lost to ground water or seepage. Water exiting the swamp leaves primarily from the Suwannee River. Seventy-four percent of swamp surface water discharge exits from Suwannee River, 12% from the St. Marys, and 14% from Cypress Creek. Estimates of discharge for 1975-1980 fall within the range of values for years 1950-1975 reported by Rykiel (1977). Runoff from the swamp ranged from 3% to 41% of incoming precipitation.

Monthly hydrological dynamics are based on a five year annual average from 1975 to 1980 (Figure 2). The period of highest precipitation was also the period of highest evapotranspiration. The high evapotranspiration results in a decrease in swamp water level, input streams drying out, and decreased surface water discharge. The highest swamp surface-water level and input-output stream surface water discharges occur from January to March. Minimal evapotranspiration and moderate precipitation also occur during this period.

DISCUSSION

The Okefenokee Swamp watershed is a tightly linked hydrologic system whose dynamics are regulated by an intimately coupled interaction between precipitation inputs and evapotranspiration losses. Surface water dynamics (discharge to and from the swamp and swamp water level) fluctuate in synchrony. Amplitude of fluctuations vary slightly with component. The high correlation between the various components and the ability of one component to accurately predict response in another substantiate the tight coupling of the system. The high year to year variation in surface water components (stream water and swamp surface water) appear to be a function of the rainfall input during the summer months.

Figure 3 represents the overall hydrologic regime of the Okefenokee Swamp as summarized by Rykiel (1977). The year can be divided into three parts. October through December is the normal dry season. January through April is a recharge or storage period for the swamp. May through September is the consumptive season in which water levels generally decline despite the heaviest rainfall input of the year. This period is the most critical for the swamp since normal rainfall will enable an adequate recovery from a below normal storage period, whereas below normal input during the hot, wet season will result in depleted storage at the beginning of the dry season.

Figure 2. Water budget for 1975 - 1980.

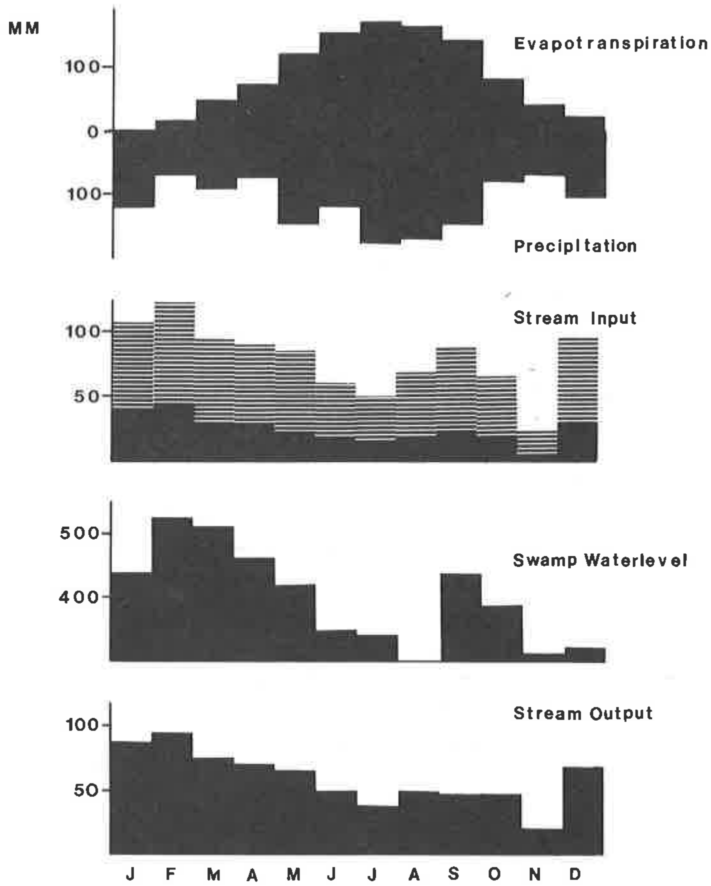
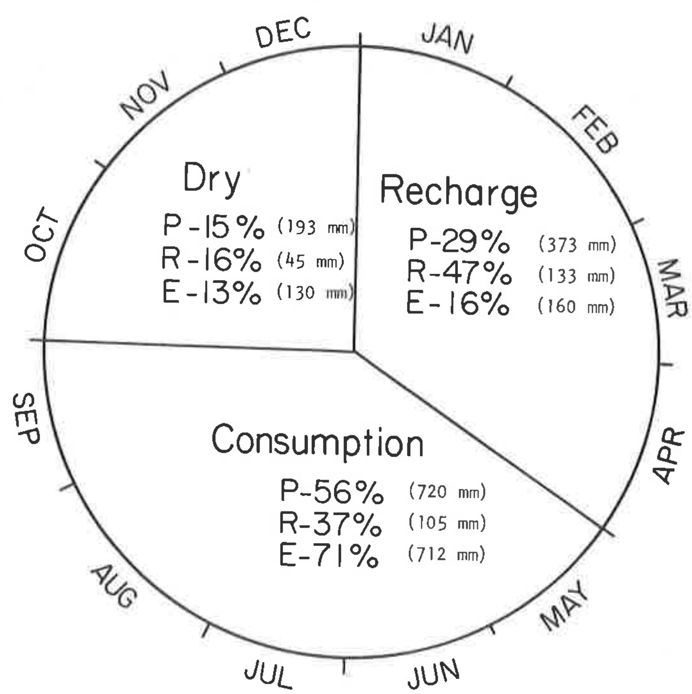


Figure 3. Overall hydrologic regime.



Although the macrodynamics of the swamp are regulated by climatological factors, hydrologic dynamics within the swamp are modified by the proportion of uplands contributing to overall budget, vegetative composition and anthropogenic activities. The Suwannee River basin shows a stronger annual cycle because of the extensive uplands component (90%) of the watershed. The amplitude of the variation is attenuated somewhat by construction of the sill and ponding of water.

These generalities are further complicated by the heterogenous vegetative structure. Portions of the watershed adjacent to the uplands have the greatest amplitude in water level while the extensive shrub swamps have the least. Extensive forested areas and macrophyte prairies also have lower and higher variations in water level, respectively. The St. Marys River and Cypress Creek watersheds show less of an annual cycle because upland influence is minimal and precipitation primarily regulates dynamics. Vegetation in these watersheds are dominated by shrub communities and macrophyte prairies. These factors combined with shallower water levels than the Suwannee basin result in attenuated hydrologic dynamics.

Although the three drainages are directly or indirectly linked periodically during high swamp water levels, they are hydrologically functionally distinct. The three major drainages' water inputs, and outputs vary, and how that water is distributed within each system is uniquely regulated by water depth and vegetative heterogeneity. Even though the swamp watershed dynamics are driven by precipitation-evapotranspiration dynamics, portraying the swamp as a single hydrologic unit without taking into account its complexity may lead to misconceptions about the relative importance of various ecosystem flows and functions.

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CHARACTERISTICS OF THE "SEVEN-DAY, TEN-YEAR MINIMUM STREAMFLOW" STATISTIC

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The "seven-day, ten-year minimum streamflow" (7Q10) is a statistic used widely in the water supply and water quality control fields as an estimate of a design drought streamflow level. In water supply planning, the 7Q10 is often used as the design minimum flow release from water supply reservoirs. The reservoirs are sized and operated to maintain an instream flow greater than the 7Q10 to meet the needs of the downstream water users. In wastewater planning, the 7Q10 is used as the design low streamflow in water quality models. Permit limitations for wastewater discharges along the stream are set so that the treated wastewater will not cause a violation of the stream quality standards when the streamflow is above the design low streamflow, or 7Q10.

CALCULATING THE 7Q10 STATISTIC

The "7-day, 10-year minimum flow" is a statistical parameter which, like the median or the variance, describes the frequency distribution of streamflow values. This statistical parameter corresponds to a streamflow level with a defined frequency of occurrence, or probability. The calculated 7Q10 value is an estimate of the lowest 7-day period of streamflows which would occur an average of one year in a 10-year period. Thus, there is a probability of 1 in 10 that an actual 7-day period of streamflows lower than the 7Q10 will occur in any given year.

The 7Q10 is calculated from the multi-year record of daily streamflow values at a gaging station by a statistical procedure. First, the streamflow for the lowest 7-day flow period during each year is identified and tabulated. Thus, 40 flow values would be tabulated for a streamflow record of 40 years. The smallest streamflow value of these 40 flow values is an estimate of the lowest 7-day streamflow in a 40-year period. The fourth smallest of these 40 flow values is an estimate of the lowest 7-day streamflow in a 10-year period, or the "7-day, 10-year minimum streamflow" (7Q10). This estimation procedure is not exact because the 40-year streamflow record is only a sample, and may not represent the true population of annual low streamflows.

The "recurrence interval" for any one of the 40 streamflow values is calculated by the equation R.I. = N/M, where N is the number of years of record and M is the order number of the streamflow value. For example, for the eighth lowest streamflow value (order number M = 8) in a 40-year record, the recurrence interval is 5 years. The U.S. Geological Survey's procedure for estimating the 7Q10 is more correct statistically. The U.S.G.S. (Carter and Putnam, 1978) uses a computer program to mathematically fit the flow data versus its recurrence interval of (N+1)/M to a log-Pearson Type III distribution. The 7Q10 value from this mathematical fit is used, unless better results can be obtained from a graphical procedure. For the graphical procedure, a smooth curve is drawn through the data points (flow versus recurrence interval) plotted on extreme log-data graph paper. The 7Q10 value is then taken from the curve at the 10-year recurrence interval.

ACCURACY OF 7Q10 ESTIMATE

A non-parametric procedure for calculating the confidence coefficient for the 7Q10 estimate is given here, as adapted from Neter (1978). The procedure stems from the observation that the 7Q10 is basically an estimate of the tenth percentile for the population of annual 7-day minimum flows. That is, for an infinitely long streamflow record with identically distributed flows, ten percent of the annual 7-day minimum flow values would be less than the 7Q10 value. The confidence interval $Q_L \leq 7Q10 \leq Q_U$ for the population tenth percentile, or 7Q10, has a confidence coefficient given by:

$$P\{L \leq B \leq U\} = \sum_{i=L}^{U} \binom{N}{i} (.1)^{i} (.9)^{N-i}$$

where Q_L and Q_U are the lower and upper interval estimates for the 7Q10 value, L and U are the order numbers for the lower and upper interval estimates, N is the number of years of record, and B is the number of sample observations below the 7Q10. Note that B is a binomial random variable with parameter p = 0.1.

A reasonably tight confidence interval for the 7Q10 estimate can be obtained using this non-parametric method. For example, for the 80-year record period at U.S.G.S. Gage #3875 in northwest Georgia, there is a 0.65 probability that the true 7Q10 value lies between 311 cfs (Q_6) and 325 cfs (Q_{10}). The standard error for this estimate is less than 4% of the mean 7Q10 value. For the 40-year record period (1939-1978) at U.S.G.S. Gage #2030 in the upper coastal plain, there is an 0.80 probability that the 7Q10 value lies between 1.54 cfs (Q_2) and 2.03 cfs (Q_6), which represents a standard error of about 0.25 cfs, or 14% of the mean 7Q10 value. A parametric procedure given by Hardison (1969) may provide a tighter confidence interval for the 7Q10 estimate.

The accuracy of the 7Q10 estimate is a function of the streamflow record length and the time period sampled. Errors due to sampling during an atypical time period, such as a series of unusually rainy years, are called time-sampling errors. Time-sampling errors can be illustrated by the streamflow data taken at U.S.G.S. Gage #3875 on the Oostanaula River near Resaca, Georgia. One of the oldest streamflow gages in Georgia, the Resaca gage has operated continuously since 1893. Based on the first forty years of record (1893-1933) at this site, the 7Q10 value is approximately 307 cfs. However, for a later forty years of record (1937-1977), the 7Q10 value is approximately 385 cfs, or about 25% higher. The 7Q10 value given by U.S.G.S. for the full eighty-year record length is 340 cfs (Carter and Putnam, 1978). The 7Q10 estimates are different because the earlier time period (1893-1933) included more dry years than the later time period (1937-1977). In fact, at the Resaca gage, nine of the ten driest years in the past century occurred before 1937, as Table 1 shows. Since most of the streamflow gages in the Resaca area of northwest Georgia were installed after 1937, their streamflow records only represent the area's wetter time period since 1937. The 7Q10 values for these gages installed after 1936 may be biased on the high side.

To minimize any potential bias, the 7Q10 estimates for gages with short record periods could be adjusted by correlation with streamflow records from nearby long-term gages. Unfortunately, there are few remaining long-term gages in Georgia, as Figure 1 shows. Of the 136 gaging stations shown, only a few were operated before 1930, and most of these long-term gaging sites now have regulated flows from reservoirs. The addition of a reservoir above a gage site effectively alters the streamflow regime so that the new streamflow record is not consistent with the flow record before reservoir construction.

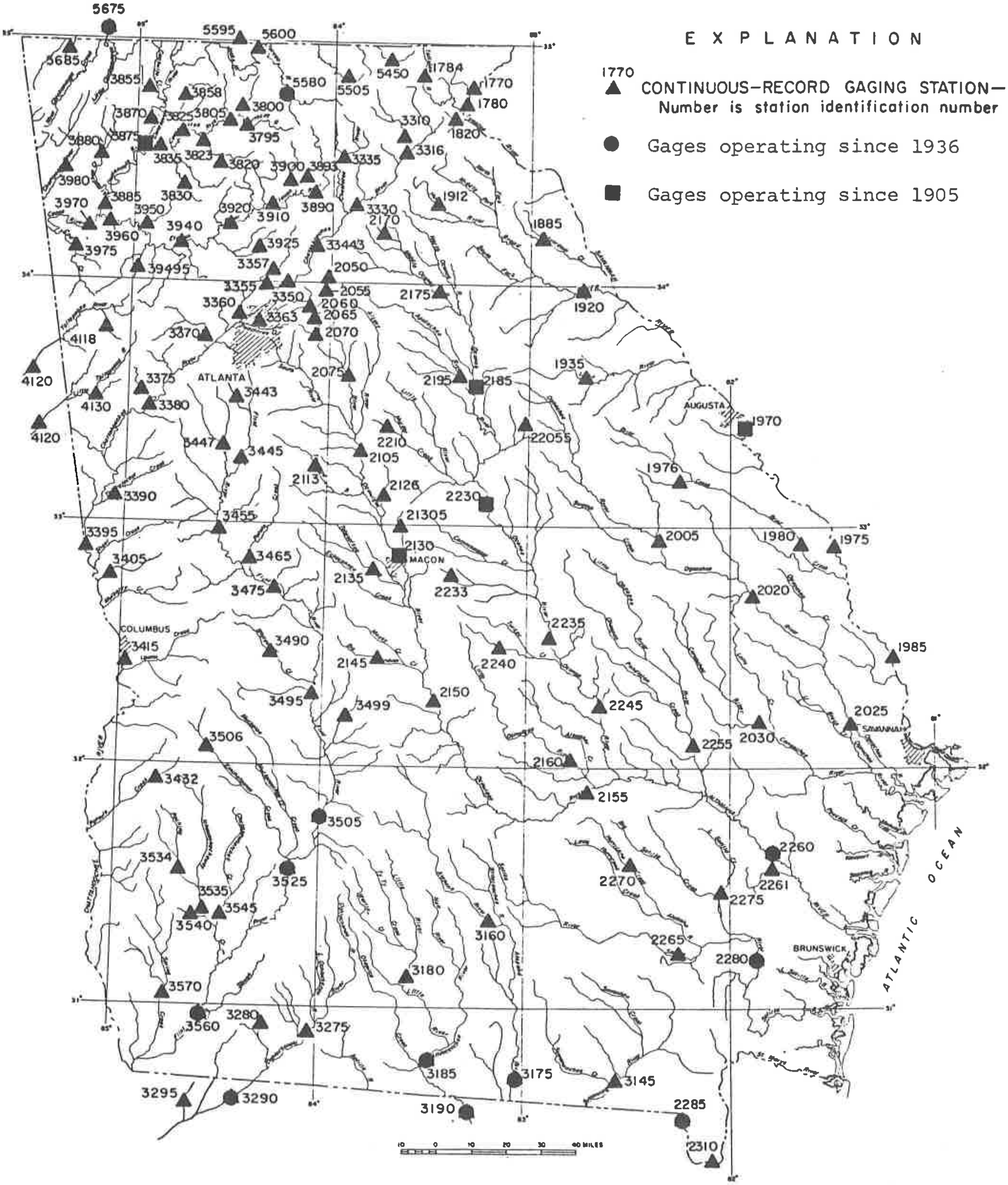

Figure 1. Location of USGS continuous-record gaging stations.

(Reference: Map from Carter and Putnam, 1978.)

In general, the 7Q10 estimates are more accurate for longer record periods, if no major physical changes have been made in the watershed above the gage site. The statistical methods are based on the assumption that the probability distribution of the annual low flow events stays the same over all the years of record. However, the longer the record period and the more interesting the gage site, the more likely it is that the hydrologic regime has been altered. Common alterations are (1) increased upstream withdrawals or discharges, (2) land use changes which can alter the infiltration and runoff pattern for the watershed, (3) increased ground water pumping which can alter the water table levels and base flows into the stream, and (4) construction of impoundments.

Table 1. Summary of Low Flow Events for U.S.G.S. Gaging Station #3875, Oostanaula River at Resaca, Georgia, for Years 1894-1974 (N = 80).

Order Number (M)	Year	7-day Minimum Streamflow** (cfs)	Recurrence Interval (N+1)/M	Probability of Occurrence (in any one year)
1	1926	203.	81.0	0.0123
2	1905	234.	40.5	0.0247
3	1936	275.	27.0	0.0370
4	1895	280.	20.3	0.0493
5	1919	307.	16.2	0.0617
6	1932	311.	13.5	0.0741
7	1909	311.	11.6	0.0862
8	*1955	312.	10.1	0.0990
9	1897	325.	9.0	0.1111
10	1912	325.	8.1	0.1235
11	*1942	337.	7.4	0.1351
12	1898	343.	6.8	0.1471
13	*1956	364.	6.2	0.1613
14	*1958	385.	5.8	0.1724
15	1904	385.	5.4	0.1852

*Droughts during the more commonly recorded period of 1937-1974.
**7-day minimum streamflows are from Inman (1971), page 211.

WATER BUDGETS AT 7Q10 CONDITION

For calculating a water budget for a river at the 7Q10 flow condition, it would be convenient to simply add the 7Q10 values for the river's tributaries. However, since 7Q10 values are statistics, rather than actual streamflow measurements, they are essentially non-additive. For example, the Resaca gage on the Oostanaula River lies below the confluence of two tributaries, which join to form the Oostanaula River as shown in Figure 2. One would expect that the actual streamflow in the Oostanaula River would be slightly larger than the combined flows from its two main tributaries, but this is not the case for its 7Q10 statistic. The reported 7Q10 value of 340 cfs for the Resaca gage is, instead, smaller than the combined 7Q10 flow of 364 cfs for the two tributaries. This inconsistency is primarily due to the time-sampling error. The 7Q10 for the Resaca gage is based on 80 years of record, including the nine dry years before 1937, whereas 7Q10 values for the tributaries are based on shorter streamflow records taken since 1937.

Figure 2. Gaging Stations on the Oostanaula River and Main Tributaries.

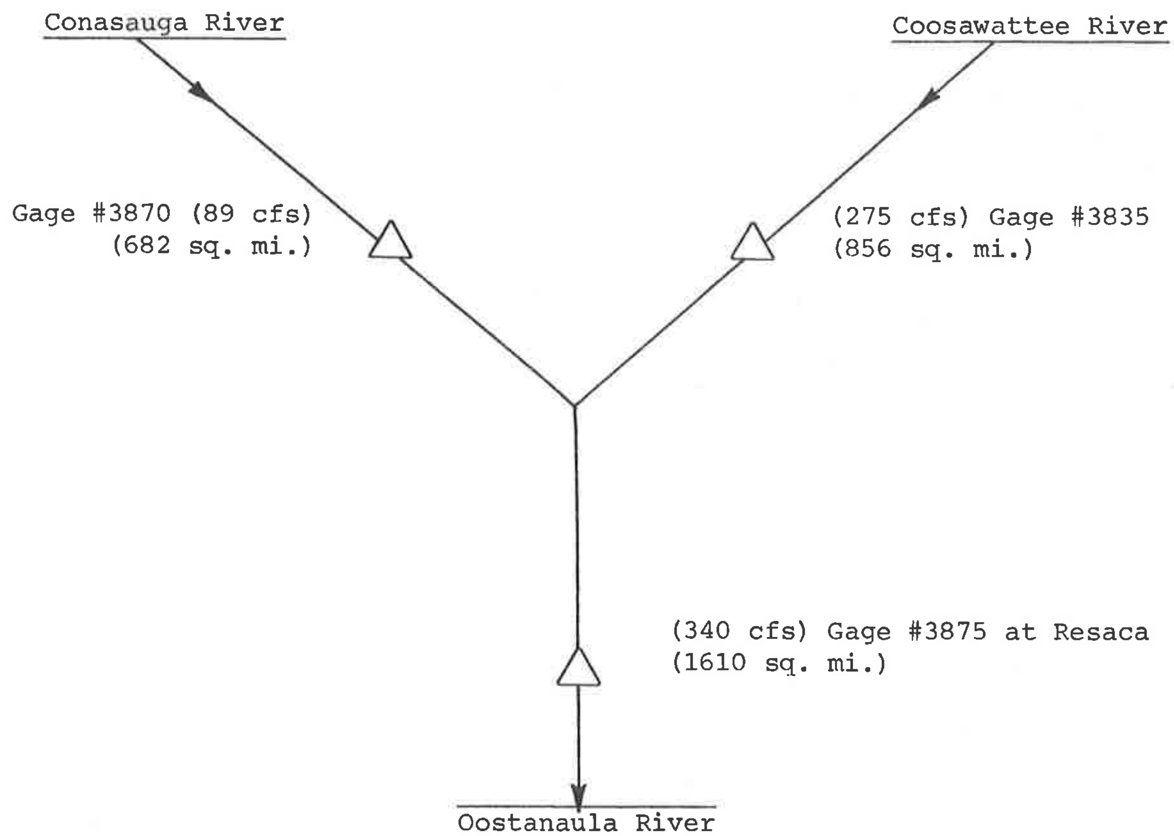

Table 2. Summary of 7Q10 Stream Flows for Oostanaula River and Tributaries.

River	Gage #	Published 7Q10*	Drainage Area*	Period of Record	Length of Record-
Conasauga	#3870	89. cfs	682 sq. mi.	1937-74	37 years
Coosawattee	#3835	275. cfs	856 sq. mi.	1939-74	35 years
Sum of Above	-----	364. cfs	1538 sq. mi.	-------	--------
Oostanaula	#3875	340. cfs	1610 sq. mi.	1894-74	80 years

*Values are from Carter and Putnam (1978).

The 7Q10 statistics from tributaries are generally non-additive, even when the gaging stations have identical record periods. The tributary flows would only be additive if the annual low flow events for each tributary occurred simultaneously, which isn't likely because rainfall patterns and aquifer conditions differ for each tributary.

7Q10 IN WATER QUALITY ANALYSES

In the water pollution control field, the 7Q10 value is used as the design low flow for a stream receiving a wastewater discharge. The discharge permit limitations and treatment levels are set so that the treated wastewater will not cause a violation of the stream quality standards when the streamflow is above the design low flow, or 7Q10. The regulations developed under the Georgia Water Quality Control Act specify that "Specific criteria or standards set for the various parameters apply to ... all streamflows equal to or exceeding the 7-day, 10-year minimum flow." In effect, this provision specifies that the required frequency for maintaining the water quality standards will be equal to the frequency that the streamflow exceeds the 7-day, 10-year minimum flow. Or, conversely, the allowable frequency of sub-standard water quality is equal to the number of days the streamflow is less than the 7-day, 10-year minimum flow. Recently, permitting agencies have considered using a less stringent design streamflow which occurs more frequently than the 7Q10. If a less stringent design streamflow is used in setting discharge permit limitations, then the water quality will fall below the standard level more frequently. In this section, the occurrence frequency of the 7Q10 is illustrated and compared to the occurrence frequency of a proposed design streamflow statistic called the "monthly 7Q10."

The terminology, "seven day, ten year minimum streamflow," leads some people to believe that the 7Q10 streamflow is a relatively rare event that occurs only once in ten years. While it is true that a seven-day period of streamflows lower than the 7Q10 value occurs about once in ten years, 7Q10 flows of one-day duration occur more frequently. This means that substandard water quality conditions of one-day duration also occur more frequently. For example, Table 3 shows the frequency of recorded daily streamflows lower than the 7Q10 value for U.S.G.S. Gage #2030 on the Canoochee River. The streamflow was below the 7Q10 on 110 days and during 7 years out of 42 years of record (1938-1979).

Table 3. Number of Recorded Daily Streamflows Less Than the Annual 7Q10* Value (1.6 cfs) for U.S.G.S. Gage #2030 on the Canoochee River at Claxton, Georgia.

Month /Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total days per Year
1941						7							7
1954							4	23	12	31	5		75
1955							3						3
1958										4			4
1962								1					1
1973										15			15
1978											5		5
Total days/mo.	0	0	0	0	0	7	7	24	12	50	10	0	110 days

Annual 7Q10 is 1.6 cfs for the period 1938-1974 (Carter and Putnam, 1978).
Source: Table is taken from Hatcher (1982), page 45.

In the last three years the U.S. Geological Survey has published values for a new statistic called the "monthly 7Q10" (Carter and Fanning 1982, and Forbes, 1980), in cooperation with state agencies which issue wastewater discharge permits. Using these new statistics, the state agencies can issue permits which allow a discharger to vary his treatment level by month, according to the design low flow in the receiving stream for a particular month. These variable discharge permits can save a significant percentage of the wastewater treatment cost.

The "monthly 7Q10" is calculated by a statistical procedure which is similar to that for the annual 7Q10, except the minimum 7-day period is taken from a given month for each year of record. The first row in Table 4 shows the monthly 7Q10 values calculated for the U.S.G.S. Gage #2030 on the Canoochee River. Note that the lowest "monthly 7Q10" value, which is 2.8 cfs for October, is higher than the annual 7Q10 value of 1.6 cfs. The interpretation of the "monthly 7Q10" for October is that it is the lowest 7-day period of streamflows which would occur, on the average, once in ten years during an October. Similarly, the November 7Q10 is the lowest 7-day streamflow which would occur, on the average, once in ten years during a November. Considering all twelve months, a 7-day streamflow lower than its

Table 4. Number of Recorded Daily Streamflows Less Than the Monthly 7Q10 Value for U.S.G.S. Gage #2030 on the Canoochee River at Claxton, Georgia.

Monthly* 7Q10 (cfs)	41	57	110	33	9.6	4.2	4.1	5.3	3.6	2.8	3.0	6.8	
Month/ Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total days per year
1938	25				2				1				28
1939												15	15
1940	26	7			8								41
1941			1		12							3	16
1943												6	6
1944					1	22							23
1945				3		1	13						17
1946								2					2
1947								1					1
1950	2	27	5	2	10	18	2						66
1951							6	2					8
1952							2						2
1954						6	29	31	27	31	15	27	166
1955	31	7	28	4		15	14						99
1957			5										5
1958									3	10		1	14
1960								15	7	12	12	17	63
1961	14	5											20
1962								10					10
1967				10									10
1968			5	9	11				11	15			51
1972									16	31	21	5	73
1976				12									12
1978									2	14			16
Total days/mo.	74	46	69	40	44	62	66	61	65	101	68	68	764 days

*Monthly 7Q10 values from Carter and Fanning (1982), in units of cubic feet per second (cfs).

monthly 7Q10 is expected to occur twelve times in 10 years -- once for each month of the year. By comparison, a 7-day streamflow lower than the conventional annual 7Q10 is expected to occur only once in ten years. Thus, when using "monthly 7Q10" flow values as design streamflows for determining discharge permit limitations, one would expect more instances of streamflows below the design flow and more days with water quality below the stream standards. Table 4 shows the frequency of recorded daily streamflows lower than their monthly 7Q10 value for U.S.G.S. Gage #2030. The streamflow was below its monthly 7Q10 value on 764 days and on 24 years out of the 42 years of record.

ACKNOWLEDGEMENT

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FOREST CUTTING AND WATER QUALITY, QUANTITY AND TIMING IN THE GEORGIA PIEDMONT

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ABSTRACT

Clearcut harvesting, site preparation and mechanical planting of an 80-acre Piedmont watershed was carried out between 1973 and 1980 on a pair of experimental watersheds in Putnam County, Ga. The results constitute the best test of the effects of normal southern silviculture on non-point source pollutants currently available. Measured rates of sediment delivery, dissolved mineral exports (N, P, K, Ca, Mg, Na, TKN, pH and total electrolytes), thermal loading of streams, flood water discharge, and total basin water yield are all related directly to a full-scale forest operation. In addition to the experimental pair, 20 small forested basins in the vicinity were analyzed over a full year for dissolved mineral concentrations, and these were related to past land use through field measurements and 1939 aerial photographs. Results are available in a series of publications.

INTRODUCTION

All forest activities associated with silviculture have been classified as potential "non-point sources of pollution" (Envir. Prot. Agency, 1977). These activities include road-building, harvesting, site preparation and stand regeneration. The attributes of stream water possibly affected are sediment load, water temperature, mineral exports, stormflows and the total water yield of watersheds. In their simplest form, the questions to be answered are: Exactly what management activities cause undesirable changes in water quality; how large are the changes; how persistent are they over time; can they be predicted? Non-point sources of pollution cannot be effectively regulated until these questions are answered. This paper summarizes results from a comprehensive experiment on clearcutting and regenerating a Southeastern Piedmont watershed. Detailed reports are listed in References.

Methods and the Experimental Area

Two unbranched streams draining 80 and 105 acres (32.5 and 42.5 hectares) of forest land in Putnam County, Georgia, were selected in the spring of 1973 to determine the effect of forest harvesting and regeneration on the quality, quantity and timing of water flows from Piedmont land. The intent was to find out the extent to which hydrological and mineral cycles are altered by "normal" forest practices, and to predict the effects in a manner useful to forest land managers and to planners of "best" management practices under Section 208 of the Environmental Protection Act of 1972 (1977).

Rainfall into the two basins and streamflow out of them were measured continuously during a calibration period (one year). During the experimental period beginning January 1, 1974, one basin was clearcut, site prepared and planted to pine using methods currently considered normal for the region. The 105-acre basin served as a control. A number of internal watershed segments (subbasins) were equipped with devices to monitor waterflows, erosion products and rainfall energies.

The 80-acre basin was clearcut (winter 74-75), roller-chopped twice (spring and fall of 1975), and planted by machine (spring 1976), all by separate contracts with local operators. Cecil, Pacolet and Mecklenburg soil types together accounted for 60% of the total experimental area. These soils were severely eroded under cotton farming between 1880 and 1920. Presently the loamy B-horizon is overlain largely by a sandy-loam plow horizon, except where the old gully network exposes deep B-horizon material. The soils are nearly all in the B or A "hydrologic group" and have an average soil erodibility factor (K) of 0.24 (USDA, 1960).

In order to estimate base levels of erosion and transportation of eroded materials to perennial streams, twelve sub-basins were instrumented, eight in the clearcut and four in the control basin. The drainage areas of the segments range from 0.5 to 4 acres (0.2 to 1.6 ha) and each was equipped with a small H-flume, water-level recorder and a self-operating proportional sediment sampler. Coarse sediments (greater than 25 microns in diameter) were trapped and measured storm by storm in a rubber-lined box above the flume. Fine sediments (less than 25 microns) were collected separately by Coshocton wheels and splitters. Combined coarse and fine sediment delivery at the base of the segments was assembled by sampling periods in units of kg/ha/cm of stormflow, the latter measured by the H-flume and water level recorder on each sediment trap. The trapping devices were of particular interest in that they allowed the separation of coarse sediments from storm waters before the water was split twice to collect one part from every two thousand parts of water yielded by the segment. The sample was accumulated in a horse trough below and subsampled after nearly every storm. The separation of fine and coarse permitted unusual insight into the source and causes of sediment exports under forest operations.

A pair of recording thermometers continuously measured water temperature to the nearest degree centigrade at the mouth of each basin. A buffer zone, about 40 feet wide, was only partially cut during harvest and regeneration. Later, a small tornado took down one quarter of the remaining overstory, leaving the entrenched stream channel with about 50 percent vertical coverage by the remaining hardwood.

Dissolved mineral export at the main flumes was monitored by weekly grab samples. Self-operating vacuum samplers were used from January 1975 to January 1977 to suck filtered samples of stream water during stormflows. In addition to continuous monitoring on the two experimental basins, occasional grab samples from about 20 surrounding first, second and third-order streams allowed relative classification of the experimental pair.

Changes in stormflow (potential flood waters) were measured two ways, as the total volume of stormflow in centimeters over the entire basin, and as the highest (peak) rate of discharge during the stormflow period. These two variables represent the effects of rainfall, season and forest practices on flooding and erosion potential. The volume of water discharged during the storm (stormflow or direct runoff) plays an important part in flooding and sediment delivery downstream from the site under study, while the peak discharge plays the dominant role in flooding and sediment movement on site.

Continuous stream discharges were measured by a 4-foot H-flume on each basin at 15 minute intervals. Water yield by storm, month and year was computed. Rainfall was measured by two weighing bucket recorders plus four Weather Service standard gages.

After a calibration period of one year, which was sufficient to show that water quality, quantity and timing were predictable from the control basin, WS 14 was clearcut using timber jacks, tree-length hauling, tractor-trailers, and a D12 Cat for road work. Cutting began in October 1974 and ended in early February 1975. Approximately 11,200 board feet per acre, mostly loblolly, were removed from the 80.3 acres of WS 14.

In April 1975, the harvested area was roller chopped (one drum roller behind a TD-25), allowed to rot down during the summer, and again chopped with tandem rollers in October 1975. The area was planted to loblolly by a Coulter-type machine with a 6-foot V-blade in front. The V-blade was pushed at an average depth of about 4 to 6 inches, exposing B-horizon materials over about 45 percent of the watershed area. An attempt was made to stay more or less on the contour during tree planting, but about 50 percent of the mineral soil surface was exposed for the first year and surface waters were concentrated at points along the road system and in the old gullies.

STATISTICAL CONTROLS

In the paired watershed experiment, one basin (WS 15) was left as a control to account for climatic variation. Streamflow and mineral concentrations were measured on both basins for a calibration period, to separate inherent differences in the basins from the treatment effect. Then, the treatment basin (WS 14) was clearcut, site prepared and planted.

The effects of forest operations were tested by comparing the residual error from a full regression model containing the treatment effect with a reduced model without the treatment effect; this was accomplished by using a dummy variable technique (Gujarati, 1978). One form of the full model (the one used for the dissolved mineral export analysis) with a treatment and recovery phase is:

$$\hat{Y}_t = a_1 + a_2 T_1 + a_3 T_2 + (b_1 + b_2 T_1 + b_3 T_2)Y_c + \varepsilon \qquad (1)$$

where $\hat{Y}_t$ is the predicted monthly value of the variable Y on the treatment basin; Y_c is the actual monthly value of the variable Y on the control basin; T_1 and T_2 are the dummy variables for the treatment and recovery phases (T_1 equals 1 during treatment and 0 during calibration and recovery, and T_2 equals 1 during recovery and 0 during calibration and treatment); and a_1, a_2, a_3, b_2 and b_3 are the parameters to be estimated by regression on the measured data. The reduced model is:

$$\hat{Y}_t = a_1 + b_1 Y_c + \varepsilon \qquad (2)$$

The errors (ε) are assumed additive in these models. The null hypothesis ($a_2 = a_3 = b_2 = b_3 = 0$) is tested by the F-statistic to determine if treatment had a significant effect on Y_t. The F-statistic is calculated:

$$F = \frac{(SS_1 - SS_2)/(df_1 - df_2)}{EMS1} \qquad (3)$$

where SS_1 is the sum of squares due to regression for the full model, SS_2 is the sum of squares due to regression for the reduced model, df_1, df_2 are the degrees of freedom of regression for the full and reduced models respectively, and EMS1 is the mean square error of the full model.

EROSION AND SEDIMENT DELIVERY TO CHANNELS

Erosion consists of three stages: Detachment of soil by rain and water energy as well as by equipment; transportation of the soil by flowing water; and deposition of the soil somewhere downslope. Sediment delivery to the channel was measured in this study at the bottom of the basin segments. These measurements did not account for road and channel damage, which was estimated by field surveys as the volume of soil removed after 4 years of operation.

Variation in exported material among the segments was related to the degree of soil disturbance within each segment. The idea was to determine what pattern of forest activity contributes most to detachment, movement and deposition of erosion products. The following impact model, a modification of Wischmeier's "universal" formula (A = RKSLCP; USDA 1965), for use where bare soil occurs in patches rather than in fields, was derived from the segment data:

$$E = 76\ R\ K\ S^{\frac{1}{2}}\ W^{\frac{1}{2}}\ e^{\varepsilon} \tag{4}$$

where E is the total sediment yield to the perennial channel in lbs/acre/per 4-month period, R (rainfall erosivity) and K (soil erodibility) are exactly as defined by Wischmeier, S is mean land slope, and W is a new sediment hazard index. Not enough variation in K occurred among segments in our experiment to justify computation of a regression parameter other than 1.0, as it is now represented in USLE. Slope no longer has the same meaning it has in the USLE; the square root of S is assumed on the basis of the Chezy-Manning formula which states that water velocity increases in direct proportion to the square root of the slope gradient. Slope is less important as a cause of sediment delivery under forest practices than it is under crop cultivation because the roughness of flow paths greatly reduces water velocity. The derived formula was plotted for both fine and total sediments.

The Sediment Hazard Index (W) reflects both the amount of bare soil and its proximity to the stream channel, and therefore the channel expansion zone. W for a watershed or segment is the sum of the relative area (a_i/A) of each patch of bare soil weighted by its relative distance (l_i/L) from the water divide.

$$W = \sum_{i=1}^{i=n} (a_i\ l_i) \ /\ (A\ L) \tag{5}$$

where W is the Erosion Hazard Index, a_i is the area of the ith bare soil patch, l_i is the ith horizontal distance from the lower edge of patch a_i to the water divide. A is the total horizontal area of the basin segment or sub-basin, L is the total distance from the water divide to the perennial stream, and n is the number of identifiable patches of bare soil (minimum area about 10 square feet) on the segment.

W ranges from zero under complete forest cover (with the forest floor intact) to 1.0 under complete cultivation of the soil surface. When W equals 1.0, a equals A, and 1 equals L. However, under normal forest practices, W will seldom exceed 0.5. The values computed for W in this study, together with other data, are shown in graphs and tables. In practice, W would be roughly estimated, not measured in detail.

The index W is founded on the three premises. First, the erosion hazard of a site is directly related to the proportion of the watershed that is bare soil. Second, in forest soils bare areas are not uniformly distributed as is the case with cultivated fields. Third, sediment will not be delivered to the perennial stream channel from a particular patch of bare soil unless that patch is connected to the perennial channel by rills or gullies that carry water during stormflow. The variable source area as described by Hewlett and Hibbert (1967) is the zone into which the perennial stream channel expands during stormflows as the result of emerging subsurface flow or expanding overland flow. The closer a patch of bare soil is to the perennial stream channel, the greater the probability that the patch will be in the channel expansion zone, and the greater the chance a detached soil particle will be delivered to a stream.

Ninety percent of all mass export from the basin anticipated over a 30-year rotation is attributable to the road and channel damage. If roads are layed out properly and the streamside management zone is kept free of vehicles, nearly all this sediment export can be avoided. In effect W in Eq. 4 remains close to zero by design.

Eq. 4 might be used to establish a limit on W if, for example, the tolerable limit on total sediment yield under a 4-month phase of the forest operation is restricted to 300 lbs/ac. Under that limit, the model suggests that the average basin index must not exceed 0.21. The spatial pattern of forest operations can be estimated in advance to determine if W is apt to exceed the limit. Guidelines for patterning of operations and location of logging roads have been offered on the basis of these results (Hewlett et al., 1979).

EFFECT OF CLEARCUTTING ON STORM FLOWS

Are forest activities adding to flooding and flood damage in amounts sufficient to justify regulation of forest management practices? The Environmental Protection Agency's "Procedural Handbook" (Envir. Prot. Agency, 1980) dodges the issue of forest effects on floods, and concludes only that "the state of the art in hydrology does not allow the presentation of a regionalized, process-oriented methodology for evaluating the impact, if any, of site disturbance on the storm hydrograph." On the contrary, a number of good experiments now offer quantitative estimates of the impacts (Hewlett, 1982).

Separation and analysis of 90 storm hydrographs in this study showed that small storm flows on dry soil may be increased 50 percent or more, but that larger flood discharges from wet soil were increased only 10 to 15 percent, if at all (Hewlett and Doss 1983). The annual flood, the one usually considered in design work, is apt to be of the latter type. The conclusion here is that concern about the effects of forest operations on downstream flooding of creeks and rivers is unwarranted.

The volume of stormflow relates to downstream flooding; peak flows relate more to on-site damage. Peak rates of discharge immediately below the operation increased 30-45%, resulting in a 55-percent annual increase in storm flow erosivity (Williams' index) during the 4-year cycle of harvesting, site preparation and machine planting. The increase in erosivity of storm flows, when considered in light of the accompanying increase in erosion hazard due to soil disturbance, warns the forest manager to increase his vigilance over road design, the selection of regeneration methods and the maintenance of stream-side protection zones. It is not the increased flood waters from forest activities that count, but the increased exposure of the soil to erosion, and the pattern of that exposure over the basin. Forest harvesting, without subsequent cultivation or overgrazing of the basin, has negligible effects on flood levels in the valleys below the operations.

In this study, on-site peak rates were increased importantly enough to be considered in the sizing of culverts at the mouth of the small basin containing the forest operation. However, a 35-percent increase in expected discharge during the average annual storm would require little more than the next larger-sized culvert (6-inch increase in diameter) to carry the increase. Since culverts are usually oversized anyway in anticipation that they will fail more often from debris blockage than from hydraulic inadequacy, even local peak increases seem to be of little practical importance in hydraulic design.

STREAM WATER TEMPERATURE

Stream water temperatures were increased by clearcutting as much as 20°F even though a partial buffer strip of trees and shrubs were left in place to shade the stream. Winter-time minimum stream temperatures were lowered as much as 10°F by the same treatment. A stream temperature model recommended in WRENS (Envir. Prot. Agency, 1980) did not predict such elevated temperatures. Forest cover reductions in areas of gentle land relief may elevate the temperature of shallow ground water moving to the stream even with a substantial buffer strip in place.

Effluent ground water temperatures, as indexed by stream temperature in the control stream under high forest cover at Grant Forest, vary from 45°F in January to 70°F in July. From this we conclude that ground water cooling of heated streams in summer, and warming of chilled streams in winter, are not as large a normalizing factor in Georgia as may be the case further north, or in steep terrains where effluent ground water may have a deep origin. It is possible that an inadequate buffer strip, and exposure of lower slopes just outside the strip, can cause an increase in the temperature of ground water as it migrates toward the stream. Such an effect may be important in flat terrain where ground water along buffer strips is within a foot of the soil surface.

The Grant Forest study suggests re-examination of the conclusions in the WRENS Handbook (Envir. Prot. Agency, 1980) that 1) evaporation and radiant cooling under shade may be neglected in computing stream temperature change due to overstory manipulations, and that 2) the temperature of effluent ground water will not respond to elevated soil temperatures outside the buffer strip of trees.

There is no evidence that coastal plain and piedmont streams of the south contain fish highly sensitive to the range of temperature changes measured in this study. Just what changes fish in natural waters can tolerate seems to be unsettled at this time.

MONTHLY WATER YIELD INCREASES

Using regression analysis as outlined under "Statistical Controls," changes in the total monthly yield of water due to forest operations were determined. Monthly water yields from WS 14 and 15 before harvesting were highly correlated

(R^2 = 0.98). As universally reported from similar cutting experiments, water yields increased substantially, in this case totalling 19 cm/yr the first year after harvesting, dropping to 9 cm/yr the second year. The increased yields have retreated toward normal as recovery of vegetation occurred. Increased yields reflect higher average soil water contents on WS 14 since cutting. Increased water yield is of prime interest in relation to mass sediment exports, dissolved mineral exports and stormflows, because more water means increases in each of these.

CHANGES IN BASIN MINERAL CYCLING

Eutrophication of streams and loss of soil fertility are suspected to result from clearcutting and other normal silvicultural practices (e.g., Swank and Waide, 1980). Nitrogen particularly is often mentioned as subject to substantial alteration with "forest disturbance." While research has reduced this concern over the last decade, there remains a popular belief that clearcutting is a questionable silvicultural practice because of nutrient loss alone. The belief finds apparent support in the concern of foresters that intensive plantation management on short rotations may ultimately result in reduced timber yields (Wells and Jorgensen, in State Univ. of NY, 1979). This effect, if demonstrated, might result from a number of causes, either mineralogical, biological or mechanical. One cause could be increased mobilization and export of dissolved nutrients in stream water. This experiment throws doubt on the importance of the latter mechanism, at least for normal rotations in the Southeastern Piedmont.

Stream water concentrations (mg/l) were mostly diluted by clearcutting, but a monthly water yield increase of 1 to 2 cm flushed an extra 0.15 kg/ha/mo of nitrate-nitrogen from the basin during a two-year period following harvesting. Analysis of the weekly grab samples and additional storm flow samples by methods outlined under "Statistical Controls" clearly showed that increases in monthly exports of dissolved N, P, K, Ca, Mg, Na, TKN, and total electrolytes were short-lived and less than 0.5 kg/ha/mo, and may therefore be considered minor for all practical purposes. The net effect of clearcutting on the treated basin's mineral balance is summarized in Table 1.

Nitrate-N exports from the treatment basin were 28 percent of those from the control basin before clearcutting, rising to 50 percent during clearcutting, and then to 73 percent of the control during recovery. The unexpected continuation of the increase in N export during recovery, despite the lack of change in concentration in the water, is produced by three months of high streamflow during 1978-79. Overall correlation between monthly mean N concentration and monthly discharge on the treated basin was virtually zero, therefore the continued rise in export is due simply to flushing under high rainfall. In any case, clearcutting did not increase N export even to the level of the control (uncut) basin. By 1981, N concentrations were back to 31 percent of the control.

Phosphorus alone showed no significant effect due to clearcutting. Calcium and magnesium showed increased export in amounts averaging 0.25 kg/ha/mo during both treatment and recovery periods, equivalent to one to two standard errors of estimate. Potassium export increased a similar amount during treatment but returned almost to calibration levels during recovery. Sodium showed a definite increase, 0.7 kg/ha/mo during treatment, returning to 0.4 during recovery.

Twenty additional forested basins were sampled monthly for one year, showing that the experimental pair was representative of the general levels of dissolved minerals in the Georgia Piedmont, both before clear-cutting and afterward.

Table 1. Dissolved mineral exports (kg/ha/mo), paired by monthly means for WS 14 and 15, and summarized as means by phase of the experiment (1973-79). CAL, TRT and REC are calibration, treatment and recovery periods, respectively.

PHASE	n	WS 14 (clearcut) Mean	S. Dev.	Range	WS 15 (control) Mean	S. Dev.	Range
	mo	kg/ha/mo					
NITRATE-NITROGEN							
CAL	13	.010	.01	.00- .03	.036	.03	.00- .09
TRT	24	.016	.02	.00- .06	.032	.03	.00- .09
REC	37	.016	.03	.00- .15	.022	.03	.00- .18
TOTAL PHOSPHORUS							
CAL	12	.07	.11	.00- .39	.07	.10	.00- .33
TRT	22	.14	.12	.00- .43	.10	.09	.01- .35
REC	36	.17	.25	.00-1.22	.12	.18	.00- .69
POTASSIUM							
CAL	8	.50	.57	.04-1.38	.38	.50	.06-1.34
TRT	23	.79	.68	.01-2.84	.45	.52	.01-2.30
REC	34	.41	.55	.04-2.59	.30	.47	.02-1.94
CALCIUM							
CAL	11	.76	1.02	.10-3.39	1.31	1.33	.16-3.52
TRT	24	1.47	.95	.30-3.76	1.79	1.56	.17-5.91
REC	34	.91	1.04	.10-4.85	1.05	1.42	.06-6.87
MAGNESIUM							
CAL	12	.29	.28	.03- .77	.60	.60	.07-1.75
TRT	24	.74	.50	.05-1.88	.97	.92	.03-3.67
REC	34	.38	.42	.07-1.83	.44	.59	.03-2.58
SODIUM							
CAL	11	1.09	1.13	.19-3.04	1.38	1.42	.21-4.14
TRT	24	2.24	1.43	.51-5.67	1.89	1.67	.17-6.53
REC	33	1.17	1.41	.12-6.50	1.04	1.58	.06-7.17
WSC[1/]							
CAL	11	190	200	15-486	245	228	29-583
TRT	24	205	142	43-582	221	208	21-884
REC	34	133	161	23-769	125	185	6-942

[1/] WSC is weighted specific conductance (μmhos/cm) x (cm monthly streamflow).

Differences (mg/1) among basins, except for a few outlying values in calcium, were small for all ions, and variation in pH was negligible among the streams (averaged 5.9). P and Na concentrations hardly vary with season or among basins, although treatment reduced Na on WS 14, presumably by dilution. Indian Creek, a stream draining more than 1000 km^2, including the 20 basins described, contains 7 times the N concentration, twice the K, but about the same P as these 20 basins (Hewlett, 1979). Indian Creek basin is about 40 percent pastures, row crops, dairy farms and other non-forest uses.

Results of the 20-basin study suggested that prior land use affects nitrate-N concentrations (and consequently export rates) for at least 40 years. Basins with higher percentage of fields in 1939 now have higher average nitrate levels in the stream than do the basins already in forests in 1939. That streams draining the more intensely farmed basins should still exhibit somewhat higher levels of nitrate seems explainable either as 1) the ability of the early settlers to pick the most fertile soils, or 2) the stimulation of nutrient cycling, at least in the lower wetter parts of the basin, by land clearing, tillage and animal husbandry.

SUMMARY AND CONCLUSIONS

This experiment is currently the only source of comprehensive data relating clearcut silviculture to water quality, quantity and timing in the Southeast. The salient finding is that fears about the drastic effects of silviculture on sediment and mineral exports in the Piedmont are largely unfounded, while the effects on water temperature, annual water yield and stormflows are about what might be expected from previous work.

The current analysis shows clearly that dissolved nutrients and mineral exports were either not changed in important amounts by treatment, or were merely increased from a low precutting level to about the normal level for the surrounding forested basins. Even the limited increases in export, caused chiefly by increased water yield, disappeared within 2 or 3 years. Increased nitrate-N export in the two years following clearcutting was about 0.3 kg/ha, a mere fraction of the 200 to 400 kg/ha removed in harvestable material at age 20 to 40 years (Wells and Jorgensen, State Univ. of NY, 1979), and probably no more than one tenth of the nitrate carried in by rain and dust (Haines, 1979). Therefore results tend to strengthen the conclusions of Currier and O'Hayre (in Envir. Prot. Agency, 1980) that normal forest practices do not eutrophy streams or adversely affect soil fertility.

However, the concensus of foresters and soil scientists across the country that poor road location, construction and maintenance, along with unnecessary disturbance of perennial and intermittent channel areas by equipment, are the cause of unacceptable exports of sediment, was verified and reinforced by this study. Burns and Hewlett (1983) reported increased sediment exports of about 1000 kg/ha/yr for the two years corresponding to the harvesting and regeneration period in this experiment. Also, for the same period, Hewlett and Fortson (1982) reported an average 8-degree C increase in midsummer stream temperature on the clearcut basin, a substantial effect that nevertheless produced no observed damage in these (non-trout) waters.

The reduction of evapotranspiration after forest removal, and the consequent increase in streamflow, appears to be the sole cause of the small increase in mineral loss shown in this study. Increased flushing of the variable source area for streamflow increased the export of dissolved minerals. The ability of the basin ecosystem to retain mobile nutrients seems largely related to its ability to evaporate water on site.

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RADIOACTIVITY LEVELS IN GEORGIA WATER SUPPLIES

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ABSTRACT

Results are reported for radionuclide analyses performed since 1979 for all community water systems in the state. Water samples were screened by gross alpha particle activity measurements, and those with elevated activity levels were analyzed for radium (Ra-226 and Ra-228) and uranium (U-238) contents. Water supplies with elevated radionuclide levels were reanalyzed periodically. Of 1,500 systems that were monitored, 33 exceeded radium concentrations of 5 pCi/L and 15 exceeded uranium concentrations of 15 μg/L; very few systems exceeded both of these radium and uranium levels. All elevated levels occurred in ground water. The locations of these elevated supplies are given and the geographical patterns and fluctuations with time are discussed.

INTRODUCTION

In common with other states, Georgia has monitored the radioactivity content of community water systems since 1979. Analyses are performed according to specifications in the Federal and Georgia regulations for the Safe Drinking Water Act (EPA 1976, EPD 1977). The initial set of analyses was completed in 1981, and samples are now being processed for the first of continuing 4-year reanalyses cycles. This report considers the geographical distribution of elevated radioactivity levels and the variability of levels measured in the same system over a period of years, based on data summarized for the initial set of analyses (Cline et al. 1983) and additional measurements obtained since then. The cited summary describes analytical procedures and reproducibility.

The analytical scheme for natural radioactivity specified by the regulations consists of screening all water samples by gross alpha particle activity measurement, performing Ra-226 analysis if the gross alpha particle activity exceeds 5 picocuries per liter (pCi/L), and performing Ra-228 analysis if the Ra-226 activity exceeds 3 pCi/L. If the gross alpha particle activity exceeds by 15 pCi/L the activity that can be attributed to Ra-226 or its short-lived progeny, then uranium should be measured. The maximum contaminant level (MCL) is 5 pCi/L for combined Ra-226 and Ra-228 and 15 pCi/L for gross alpha particle activity including Ra-226, but not radon and uranium. The scheme was developed to maintain reasonable costs by not requiring that all systems be tested for Ra-226 and Ra-228 content. A similar scheme is given for man-made radionuclides but these analyses are not discussed here because few measurements were performed, none of the results exceeded the MCL, and only one system showed detectable radioactivity levels (H-3 at 3,000 pCi/L).

A summary by Cothern and Lappenbusch (1984) of national trends based on completed analyses for 50,000 of 60,000 community water systems in the U.S.

suggests that approximately 500 systems will be found to exceed the MCL, almost all of them groundwater supplies, and most due to elevated Ra-226 content. Gross alpha particle activity was found by Cline et al. (1983) to be a reasonable indicator of Ra-226 plus uranium concentrations in Georgia. The Ra-226 screening for Ra-228, however, is considered unsatisfactory by Michel and Moore (1980), McCurdy and Mellor (1981), and Kriege and Hahne (1982). They observed that the Ra-228/Ra-226 ratio varies widely in well waters and can be far greater than the value of 2/3 used to derive the screening program. These findings suggest that the screening scheme may miss systems with elevated Ra-228 levels.

Results of uranium analyses in water not related to the drinking water program indicate that between 25 and 650 community water systems in the U.S. have concentrations above 20 pCi/L (Cothern and Lappenbusch, 1983). Highest concentrations found in both surface and ground water were approximately 600 pCi/L. These authors also note that U-234 and U-238 are not always at the 1:1 ratio assumed when uranium is analyzed fluorometrically as specified in the regulations and the concentration is multiplied by the factor 0.67 pCi/μg to convert to radioactivity level. For such measurements, only concentrations reported in terms of U-238 μg/L would be accurate, although few samples are expected to have ratios beyond the range from 0.5 to 1.0 pCi/μg. No MCL exists for uranium at this time; the maximum permissible concentration of uranium in water listed in Title 10, Code of Federal Regulations Part 20 is 1,000 times higher than the 30 pCi/L listed for Ra-228 and Ra-226. More recent dose evaluation suggests, however, that limits for U-234 and U-238 should be near those for Ra-226 and Ra-228 (ICRP, 1979).

The data presented here are based on composite water samples from 1,380 community water systems analyzed in the initial set of four successive quarterly composites, as well as 99 new systems that were approved during the first cycle of reanalyses. In total, 4,000 samples were analyzed for gross alpha particle activity and approximately one-fourth that number for specific radionuclides. The additional samples consist of (1) repeat single samples on the 4-year cycle for systems in which radioactivity values are below one-half the MCL; (2) repeat composites for systems that are between the MCL and one-half that value; (3) quarterly samples for systems that exceed the MCL; (4) screening samples for new systems; and (5) samples collected for special purposes, e.g., to examine the contributions of individual wells in a multi-well system or the effect of collecting water at different taps.

RESULTS AND DISCUSSION

Among 1,479 community water systems, 33 exceeded 5 pCi/L for Ra-226 and Ra-228, as shown in Table 1. All of the elevated values were for relatively small groundwater supplies. The highest Ra-226 concentration was 200 pCi/L, whereas the highest Ra-228 concentration was only 8 pCi/L. The elevated radium values in Table 1 are all from composites in the initial set of samples because new wells with elevated levels in the screening sample were rejected for system use without further analysis. In the absence of a definitive screening scheme for Ra-228 or prior knowledge of regions in which Ra-228 levels are elevated, some systems with elevated Ra-228 levels could have been overlooked.

Among these community water systems, 15 had uranium levels above 15 pCi/L, i.e. 22 μg/L. In three systems with acceptable radium concentrations, the difference between gross alpha particle activity and summed uranium and

Table 1. Number of Community Water Systems in Georgia with Elevated Radioactivity Levels

Type of analysis	Total No.	Number with concentration exceeding: 5 pCi/L	15 pCi/L	50 pCi/L
gross alpha	1,479	101	27	8
Ra-226	158	15	6	3
Ra-228	66	2	0	0
combined radium	66	24	6	3
uranium	46	--	11	4

Notes: 1. Of these systems, 1365 used ground water; all elevated samples were from ground water.
2. Uranium concentration is 0.67 x μg/L.

Ra-226 levels exceeded 15 pCi/L, but not necessarily due to the presence of another radionuclide. This difference may have been caused either by relatively large standard deviations in measuring the gross alpha particle activity and the uranium concentration, or by nonequilibrium between U-234 and U-238. The highest U-238 concentration among these samples was 157 μg/L.

Elevated Ra-226 levels in ground water (see Figure 1) occur in three of the four physiographic regions in Georgia -- the Coastal Plain south and east of a line drawn from Augusta through Macon to Columbus, the Piedmont to the north and west of that line, and the Blue Ridge on the east at the extreme north. No elevated levels were found in the Valley-and-Ridge region in the extreme northwest. A number of wells with elevated levels were directly at the Fall Line between the Piedmont and the Coastal Plain. A distinction is made between the composite samples (closed circles) and single samples (open circles), but the information presented below suggests that even single samples are reliable indicators of elevated levels.

The many gross alpha particle activity measurements below 3 pCi/L for well water at other locations throughout Georgia suggest that only the areas indicated on the map have groundwater with elevated Ra-226 concentrations. This conclusion must be modified by the realization that not all depths have been sampled by the existing community water supplies. Some wells may not reach the aquifer with elevated Ra-226 levels or may have been cased to greater depths. Figure 1 shows elevated values clustering in a band passing from southwest to northeast in the Coastal Plain, near Macon at the Fall Line, and to the north from there through the Piedmont.

The following sources of the uranium precursor of Ra-226 are known to exist in the various regions: in the Coastal Plain, phosphate deposits in sedimentary rock formations, in the Piedmont, granitic formations, and in the Blue Ridge, schist and gneiss types of host rock (Cline et al., 1983). Elevated Ra-226 levels at the Fall Line in adjacent South Carolina have been attributed to uranium-bearing detritus deposited from ore bodies in the Piedmont (Michel and Moore, 1980).

A few wells with elevated Ra-228 levels were found along the Fall Line and in northeast Georgia (see Figure 2). Thorium ores in which Ra-228 originates occur in this area and in the resulting Fall-Line detritus.

Elevated U-238 levels occur in a definite band in the Piedmont, as shown in Figure 3. The wells are in the area of a monazite belt or granitic formations (Michel, 1983). The highest level in a single sample was 960 μg/L. In most instances, high U-238 levels were associated with low Ra-226 levels and vice versa. This difference in concentration indicates the influence of the chemical environment in the aquifer on uranium and radium solubility, since U-238 and Ra-226 both originate in uranium ore bodies and Ra-226 is descended from U-238 and U-234. A survey by Drury et al. (1981) of 1,695 groundwater samples from Georgia measured under other programs, notably the National Uranium Resource Evaluation Program (Fay et al., 1981) showed 6 samples with uranium concentrations between 18 and 423 μg/L, 50 samples between 1 and 15 μg/L, and all others below 1 μg/L. Most samples were collected in the Piedmont and Blue Ridge regions. The highest values measured earlier were in the same area as the elevated values in Figure 3.

The requirement in the regulations for repeated quarterly analyses of systems that exceeded the MCL provided a test of the uniformity of results over a period of time. The range of values for these repeated analyses for gross alpha particle activity, Ra-226, Ra-228, and U-238 is compared with the value of the initial composite sample in the Appendix. The listed system number corresponds to that in Cline et al. (1983). Because of the program in Georgia to phase out wells that exceed the MCL and replace them with new wells that are logged and cased to assure low radium levels, however, some wells with elevated levels of radioactivity had too few repeat values for comparison.

The range of individual Ra-226 concentrations measured at approximately 3-month intervals is generally consistent with the concentration of the quarterly composites measured initially, as shown in Figure 4. In 13 of 17 systems, the range either includes the composite value or is very near it, and the range is relatively narrow. In three systems, however, the composite value differs significantly from all subsequent measurements, while in one system the composite value is within the range, but the range is extremely wide. In several systems identified by arrows, one or two values are very different from all others, and system No. 38 (not included in Figure 4) appears to have at least two distinct sets of values. For Ra-226, the standard deviation of the analysis is approximately 4 percent (Cline et al., 1983) for these values, generally much smaller than the range of results.

The consistency of gross alpha particle activity data is similar to that for Ra-226, except that the initial composite value for system No. 29 is much larger than all subsequent values (see Appendix). The standard deviation of measurement of 7 percent is larger than for Ra-226, but small compared to the range of values.

The few elevated values listed in the Appendix for Ra-228 and U-238 in initial composite samples and subsequent single sample ranges are consistent at 4 locations for the former and 7 for the latter. They differ for U-238 in systems No. 13 and 17. The standard deviations of analysis in the observed range for Ra-228 were 0.7 pCi/L and for U-238 were 18 percent above 28 μg/L and 3 μg/L for lower values.

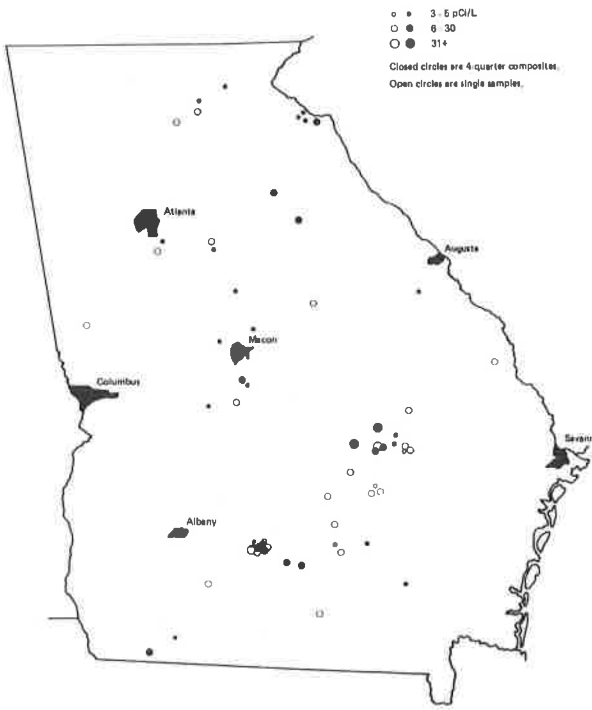

Figure 1. ^{226}Ra in Georgia Community Water Systems.

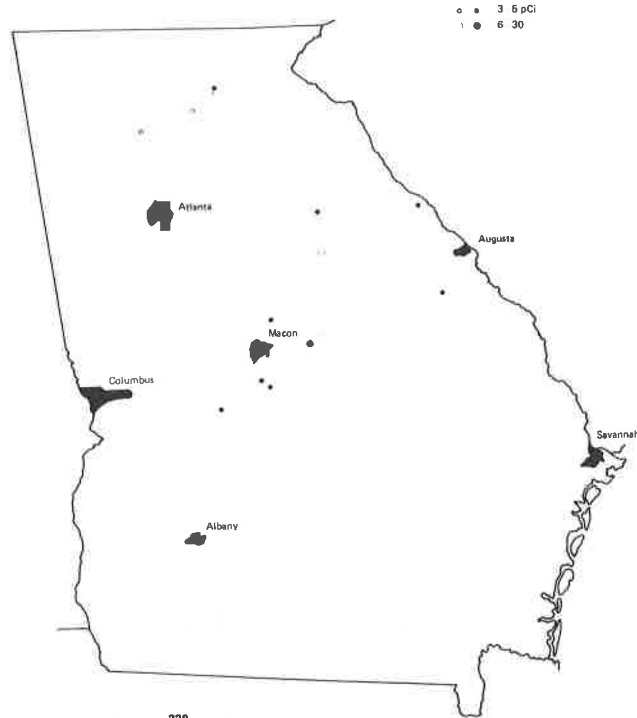

Figure 2. ^{228}Ra in Georgia Community Water Systems

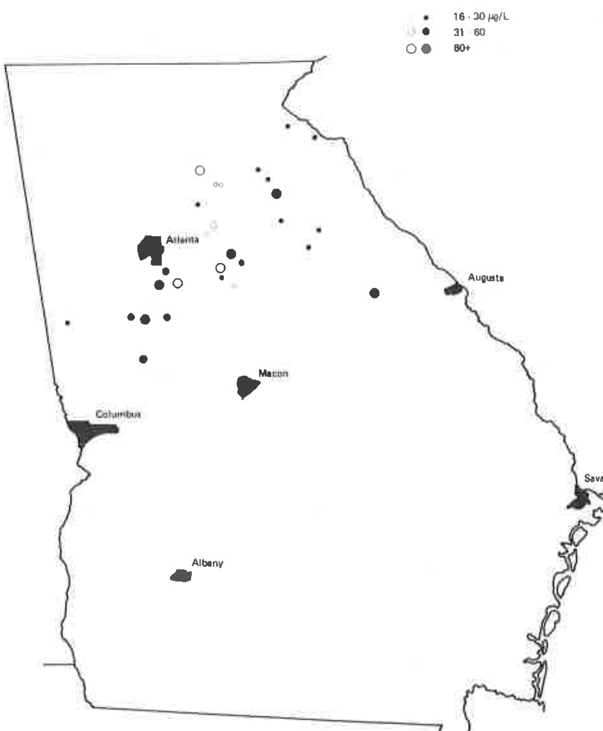

Figure 3. ^{238}U in Georgia Community Water Systems.

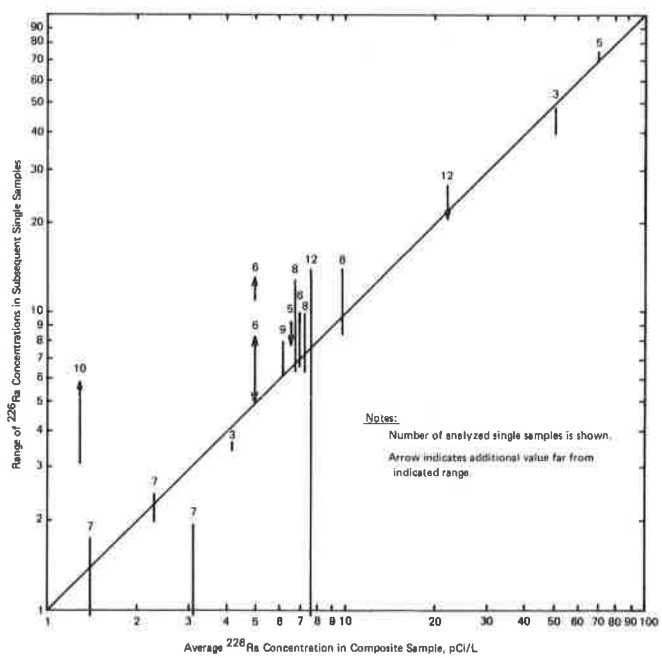

Figure 4. Consistency of ^{226}Ra Analyses.

Repeated sampling for Ra-226 and Ra-228 analyses reported by Michel and Moore (1980), Kriege and Hahne (1982), and Holtzman and Gilkeson (1983) found only small fluctuations in most wells. One cause of the variability observed here, especially for occasional abrupt changes in radioactivity levels, is that most of these systems had two or more wells. Unfortunately, no information is available concerning pumping rates for individual wells to document changes in relative flow rates that could cause such variability in radioactivity levels.

CONCLUSIONS

The occurrence of elevated radioactivity levels for Ra-226, Ra-228, and U-238 in Georgia well-water supplies shows definite geographical patterns. The patterns are different for each of the three radionuclides. Knowledge of the pattern can assist in predicting whether water from a newly drilled well will have an acceptably low level of radioactivity. Further studies are recommended to improve this predictive capability: geological studies to relate specific aquifers to ore bodies that yield these radionculides, and chemical studies to understand the distinction between chemical environments that leads to elevated levels of U-238 or Ra-226 separately, but rarely together.

The information concerning Ra-228 levels is incomplete because that radionuclide was only measured when Ra-226 levels were elevated. Observations in other states indicate that the two radionuclides are not in association at a fixed ratio. Gross beta particle activity measurement or some other screening procedure is recommended to assure absence of elevated Ra-228 levels in Fall Line and eastern Piedmont wells.

In most cases, repeated radioactivity analyses at quarterly intervals for as long as three years were consistent with the initial analysis of a four-quarter composite, indicating uniformity of radioactivity levels throughout the period. The causes of some large fluctuations, however, should be determined. One possible cause is a change in individual pumping rates for a system that has two or more wells.

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APPENDIX

Comparability of Repeated Analyses

System No.	No. of samples	Gross alpha, pCi/L I	Gross alpha, pCi/L R	^{226}Ra, pCi/L I	^{226}Ra, pCi/L R	^{228}Ra, pCi/L I	^{228}Ra, pCi/L R	^{238}U, $\mu g/L$ I	^{238}U, $\mu g/L$ R
2	6	4	<4-12	6.6	7.7- 9.3 < 0.1	< 1	< 1	---	---
3	9	6	4- 9	6.2	6.1- 8.0	< 1	---	---	---
5	8	36	19-47	7.3	6.3-10.3	< 1	< 1	19	18-75
7	6	19	17-42	5.0	4.9- 8.5 0.3,19.4	< 1	< 1	40	18-45
11	9	10	5-21	6.6	6.4-12.8	< 1	< 1	7	<3- 9
13	6	11	42-60	5.0	11.0-13.4 24	< 1	<1-3	3	19-76
15	7	14	4-11	3.0	0.5- 1.9	2	---	3	---
17	12	10	4-26	7.6	0.7-13.9	< 1	< 1	6	9-19
20	8	13	15-22	9.8	8.5-14.9	4	2-4	3	<3- 3
28	10	7	8-11 23	3.8	3.1- 5.8 11.9	2	1-4 6	---	< 3
29	10	20	2-7	2.3	2.0- 2.4	2	2-4	3	---
34	4	30	25-35	51	40-48	1	< 1	3	< 3
38	6	61	46-61(2) <2-2(4)	9.1	10.2-11.8(2) 0.1- 1.0(2)	5	14-15(2) <2-2(3)	29	10(1)
40a	6	11	6-10	7.0	6.7- 9.8	< 1	<1-2	---	---
41	5	68	52-81	70	72-74	< 1	< 1	3	<3- 6
42	12	15	14-29 5	22	22-26 10.7	< 1	<1-2	3	<3- 3
46	3	4	4- 8	4.2	3.4- 3.6	< 1	< 1	---	---
49	7	14	<2- 7	1.4	0.2- 1.7	6	2-7	3	---

I: Composite of initial 4 successive samples;
R: Range of subsequent quarterly samples
Values for a system listed on the second line are outside the range; parentheses indicate number of such samples.

AN OVERVIEW OF GEORGIA'S WATER RESOURCES

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From a water resource perspective, Georgia is a paradox. Who would expect that the largest state east of the Mississippi River, a state located in the humid Southeast with an average 50 inches of precipitation annually, a state with some 20,000 miles of streams, and a state with a vast ground water resource would be faced with water problems? Water resource concerns, however, are evident throughout the state, from Rome to Brunswick and from Athens to Bainbridge. It is this paradox that spawned this conference.

To provide an overview of this paradox, four questions must be considered:

1. What are the water resources of Georgia?
2. How are these water resources used?
3. What water resource problems are evident?
4. What is being done to resolve these problems?

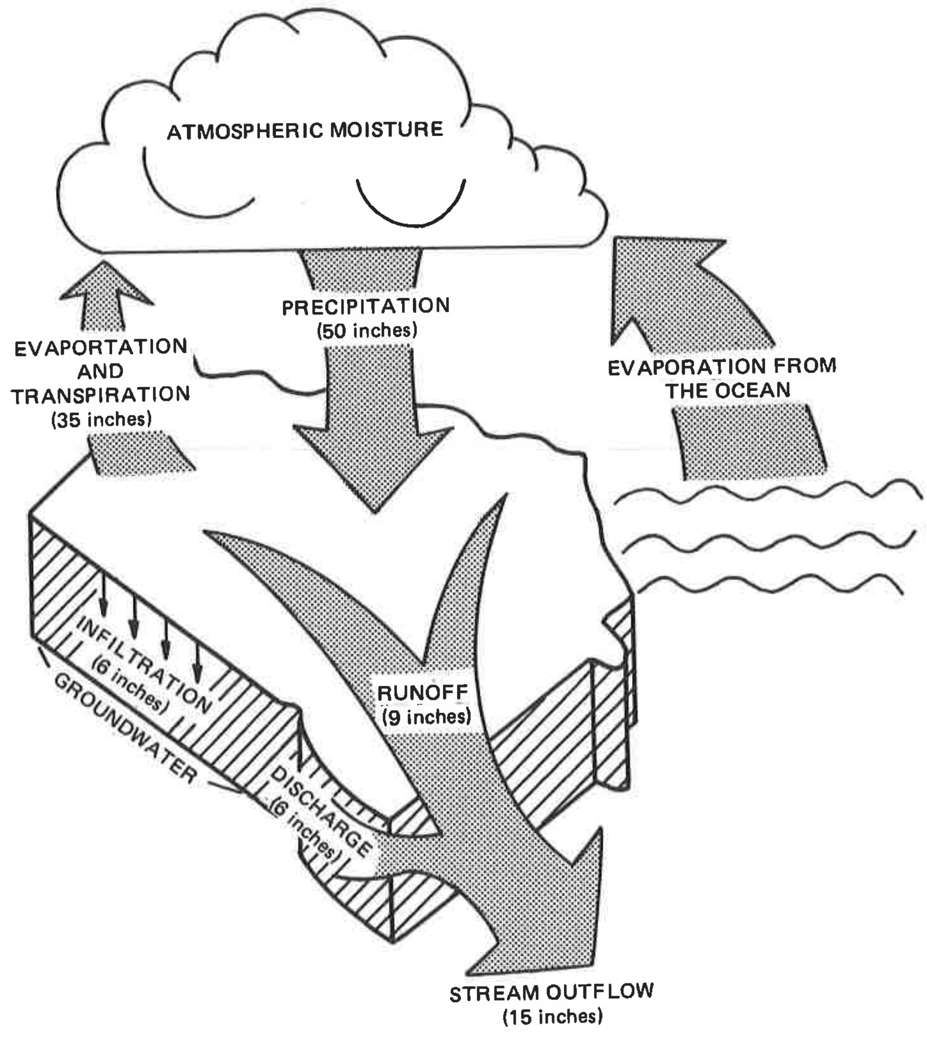
Although this overview will address the questions, the research projects that compose the rest of the program will attempt to provide the answers. Great progress has been made during the past decade, but much remains to be done. This conference provides the opportunity to pull together our efforts to date and serves as a launchpad for our future water resource efforts.

WHAT ARE THE WATER RESOURCES OF GEORGIA?

Two factors determine the availability of water in an area: the climatic conditions and the geologic settings. Climatically, Georgia is located in the humid southeastern United States and receives annually an average of 50 inches of precipitation. Statewide this averages about 140 billion gallons of precipitation each day. The U.S. Geological Survey (1979) estimates that about 70% of this water is returned to the atmosphere through evapotranspiration, about 18% becomes surface water, and 12% infiltrates the soil to become ground water (see Figure 1). It is this annual 15 inches of surface and ground water which we depend on for fish and wildlife habitat, hydro- and thermoelectric power generation, recreation, waste assimilation, industrial processes, domestic supplies and agricultural uses.

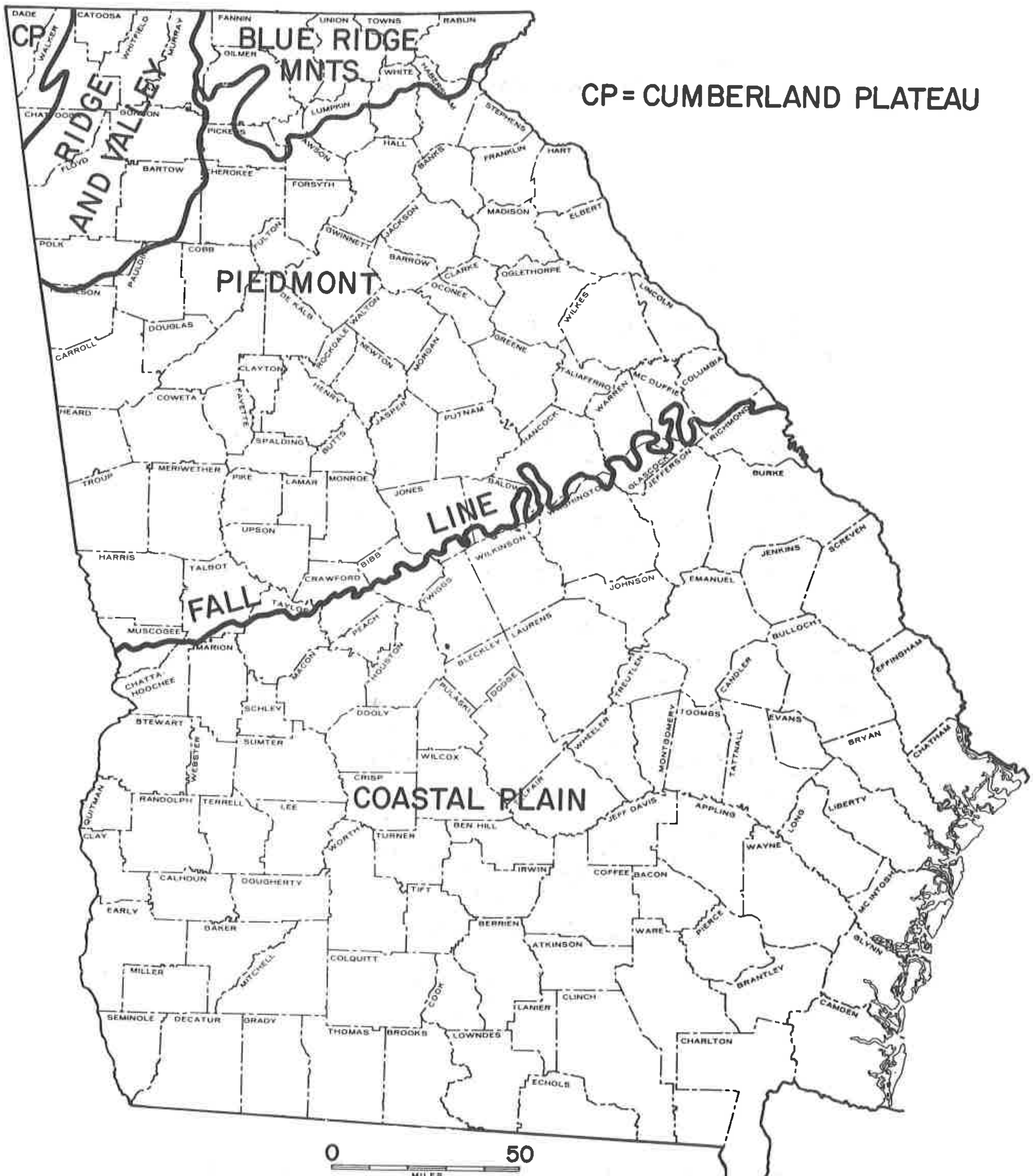
Georgia encompasses parts of four major physiographic provinces: the Ridge and Valley Province, the Blue Ridge Mountain Province, the Piedmont Province, and the Coastal Plain Province (see Figure 2). From a water resources standpoint, however, the state can be divided into two major parts with the northern portion of the state depending on surface water and the southern portion having bountiful ground water resources. Since the Blue Ridge and Piedmont Provinces are underlain by hard, compact, crystalline rock, ground water in these provinces is limited to the pore spaces between soil particles and cracks and fissures in the bedrock. In the Ridge and Valley Province, sedimentary layers do provide more extensive ground water resources, but the faulting has led to considerable spacial variations.

Figure 1. Hydrologic cycle of Georgia



SOURCE: U.S. Geological Survey, Water-Resources Investigations in Georgia, 1979.

Figure 2. Physiographic Provinces of Georgia



SOURCE: William Z. Clark, Jr. and Arnold C. Zisa, Physiographic Map of Georgia (Atlanta: Georgia Department of Natural Resources, Geologic and Water Resources Division, 1976).

As shown in Figure 3, the coastal plain is underlain by three major aquifer systems: the Principal Artesian Aquifer, the Cretaceous Sand Aquifer, and the Clayton Aquifer. These aquifers form one of the most prolific ground water resources on earth.

Although Georgia has some 20,000 miles of streams, no major rivers flow into Georgia; they all originate within the state or along its borders. As shown in Figure 4, these rivers tend to flow from north to south. A major divide follows the eastern rim of the Chattahoochee-Flynt basin. Water falling to the north and west of this divide will flow toward the Gulf of Mexico, while water falling to the east and south will flow toward the Atlantic Ocean. This divide runs through the Atlanta metropolitan region.

Since the northern part of Georgia is geologically old, the natural barriers producing lakes have long been eroded away. As a result, no natural lakes exist in this part of the state. However, Georgia has 26 major reservoirs, covering about 300,000 acres, and one major reservoir under construction -- Richard B. Russell on the Savannah River (Kundell, 1980).

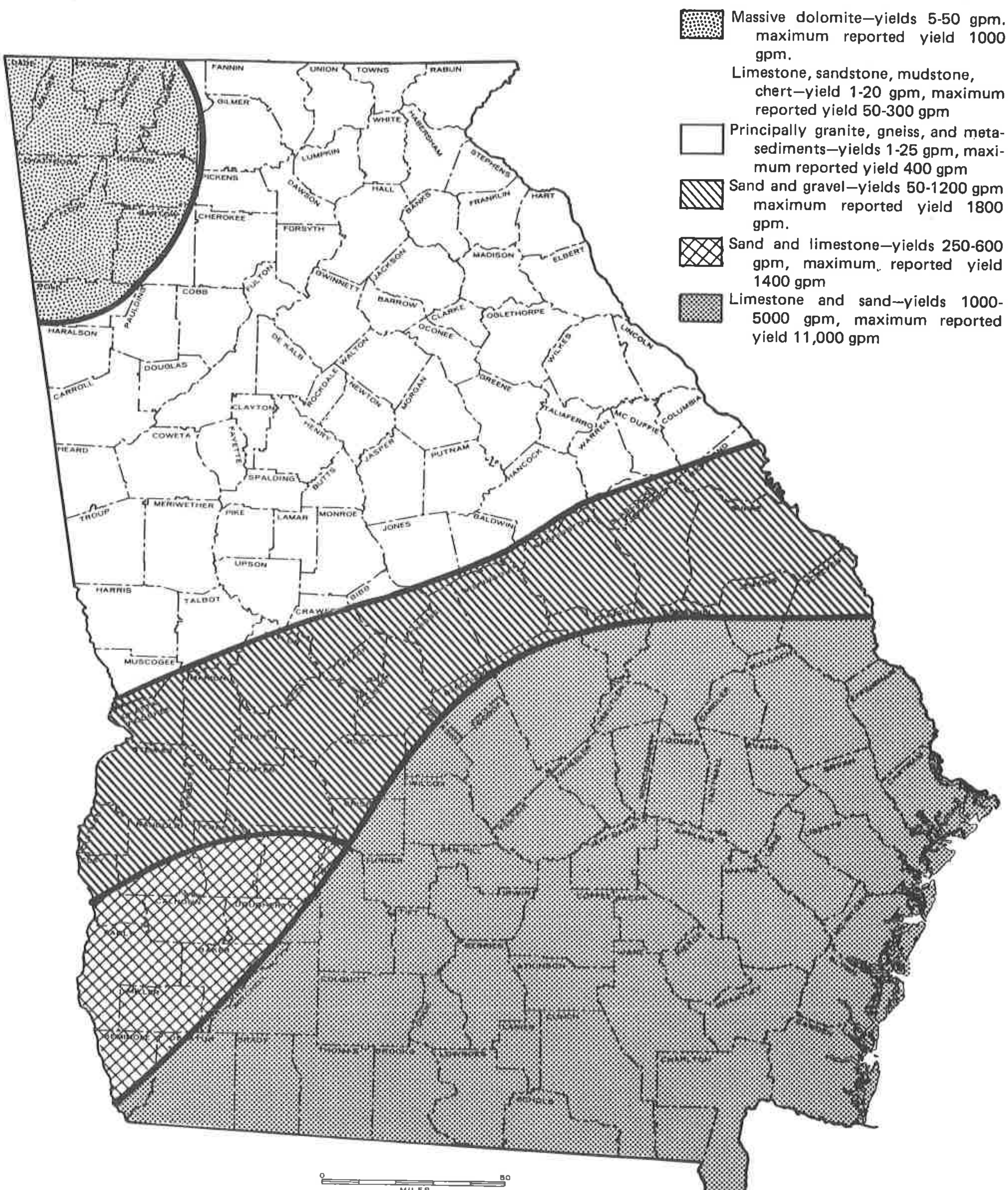
HOW ARE THE WATER RESOURCES USED?

Each day in Georgia about seven billion gallons of water are withdrawn (Pierce and Barber, 1982). This quantity may be divided into five categories of major offstream use: thermoelectric, industrial, public supply, irrigation, and rural. Rural uses of water, primarily for domestic supplies, are dispersed throughout the state and overall have less impact on the water resources than other major water users. Between 1970 and 1980, the demands for water increased by about 25%. During the same period, the population of Georgia increased by 19.1%. This indicates that the per capita withdrawal of water has increased. Surface water withdrawals have increased by only about 16%. Apparently we are shifting to a greater dependence on ground water on a statewide basis. Ground water use during the past 10 years has nearly doubled. Much of this increase reflects the increase in irrigation in the state.

Not all water that is withdrawn is consumed. Most of the water that is withdrawn is returned to the system. It may contain organic matter, it may contain chemicals, it may be warmer, it may be impaired in some way, but given enough time the system ought to be able to assimilate the wastes and the water may be used again. Of the seven billion gallons of water that are withdrawn each day, about one billion gallons are consumed. They are not returned to the system. Most of this is lost through evapotranspiration. Irrigation is the major consumer of water, since it is nearly 100% consumptive.

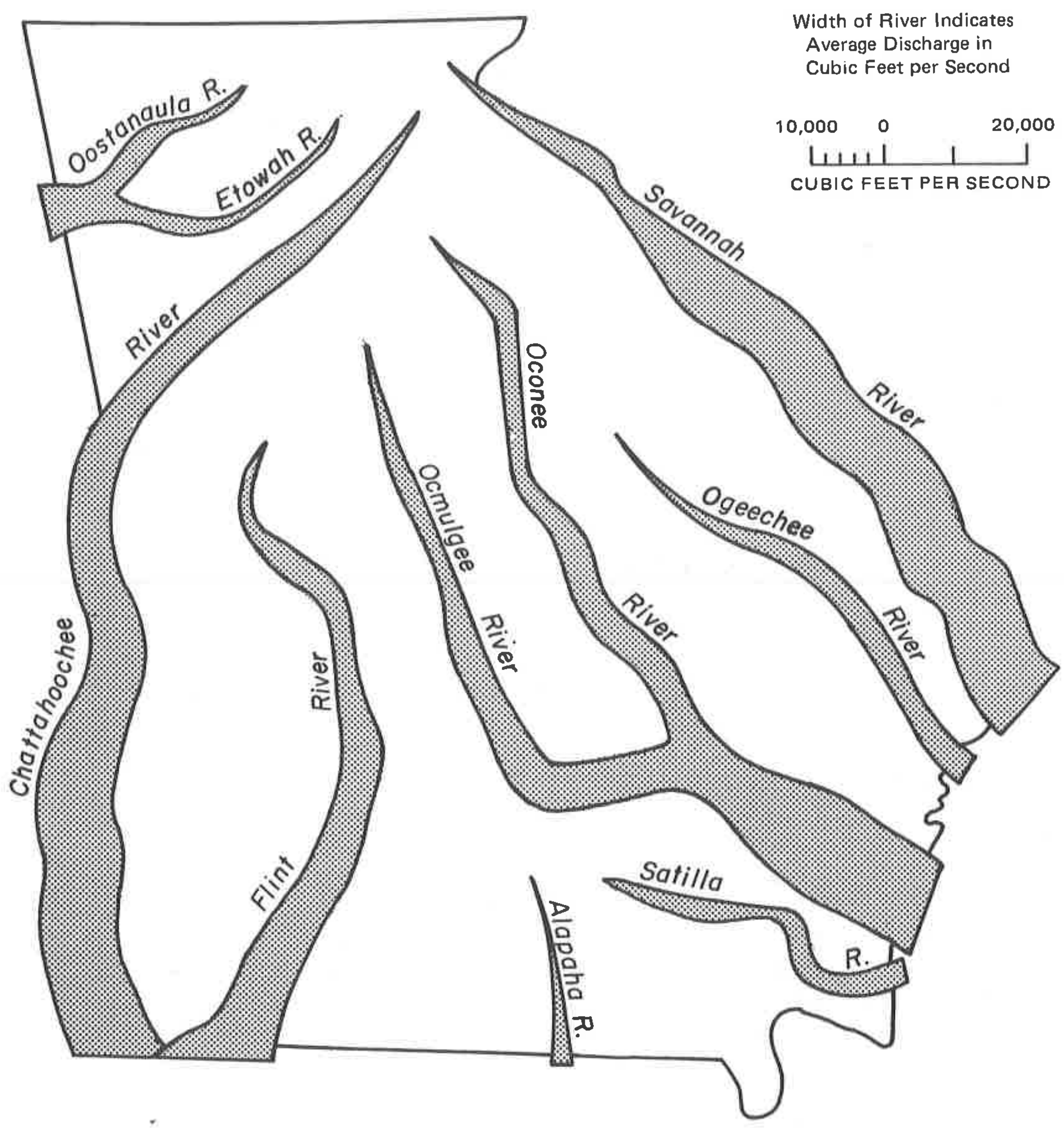
Water withdrawals have increased substantially during the past 30 years. Thermoelectric water withdrawals are primarily used for cooling in electric generating plants. Since most of this water is returned to the system, this is generally considered a nonconsumptive use of water. In the past, much of the water was returned to the streams in a warmer form than when it was withdrawn. Newer plants, however, use cooling towers; their withdrawals replace that water lost to evaporation. There was a substantial increase in thermoelectric water usage during the 1960's followed by a leveling off during the 1970s (Pierce and Barber, 1982). Under construction at this time is plant Vogtel, a nuclear power plant. When it goes on line in the mid-1980s we can expect that thermoelectric water use will increase.

Figure 3. Availability of ground water



SOURCE: U.S. Geological Survey, Water-Resources Investigation in Georgia, 1979.

Figure 4. Major rivers in Georgia



SOURCE: U.S. Geological Survey, Water-Resources Investigations in Georgia, 1979.

As shown in Figure 5, industrial water use experienced a fairly consistent increase through the 1960s, but has apparently leveled off, or even declined, during the past few years. This is most likely the result of major conservation efforts by some industries. Because of the Sunbelt development, industries are being attracted to Georgia. We can expect this to continue. Most of the industries that have located in the state are not major water-using industries, but collectively they will put an increasing demand on the water resources. One concern facing the state relates to the siting of major water-using facilities, since the number of sites with sufficient water for both industrial processes and waste assimilation are becoming very limited.

Municipal water use has increased consistently during the past 30 years. This corresponds to the population increase in the state. By the year 2000, the population of Georgia is expected to reach about seven million people, increasing by 80,000 to 100,000 people each year. Meeting the demands of these people for water supply and sewage treatment will increase costs to municipalities. With a decrease in federal funds for construction of water treatment facilities, municipalities may be hard pressed to meet water demands in the future.

Prior to 1975, irrigation constituted a minor use of water in the state. Since that time, however, irrigation has increased significantly. Currently, over one million acres are under irrigation in Georgia (Harrison, 1983). Irrigation is concentrated in the southwestern part of the state and extends across the upper coastal plain. Large irrigation systems are, however, being installed throughout the state.

As offstream uses of water have increased, so too have instream uses. Demands for instream uses such as waste assimilation, recreation, hydroelectric plants, and fish and wildlife habitats are directly related to population changes. The greater the population, the greater the demand for these instream uses of water.

WHAT WATER RESOURCE PROBLEMS ARE EVIDENT?

Water resource usage figures indicate that demands are increasing and will likely continue to increase in the future. But what problems are related to this increase in demand for water? Most of the problems evident in the state relate to excessive demands being placed on the resource, either for waste assimilation or offstream use. The type of problem varies, however, from region to region.

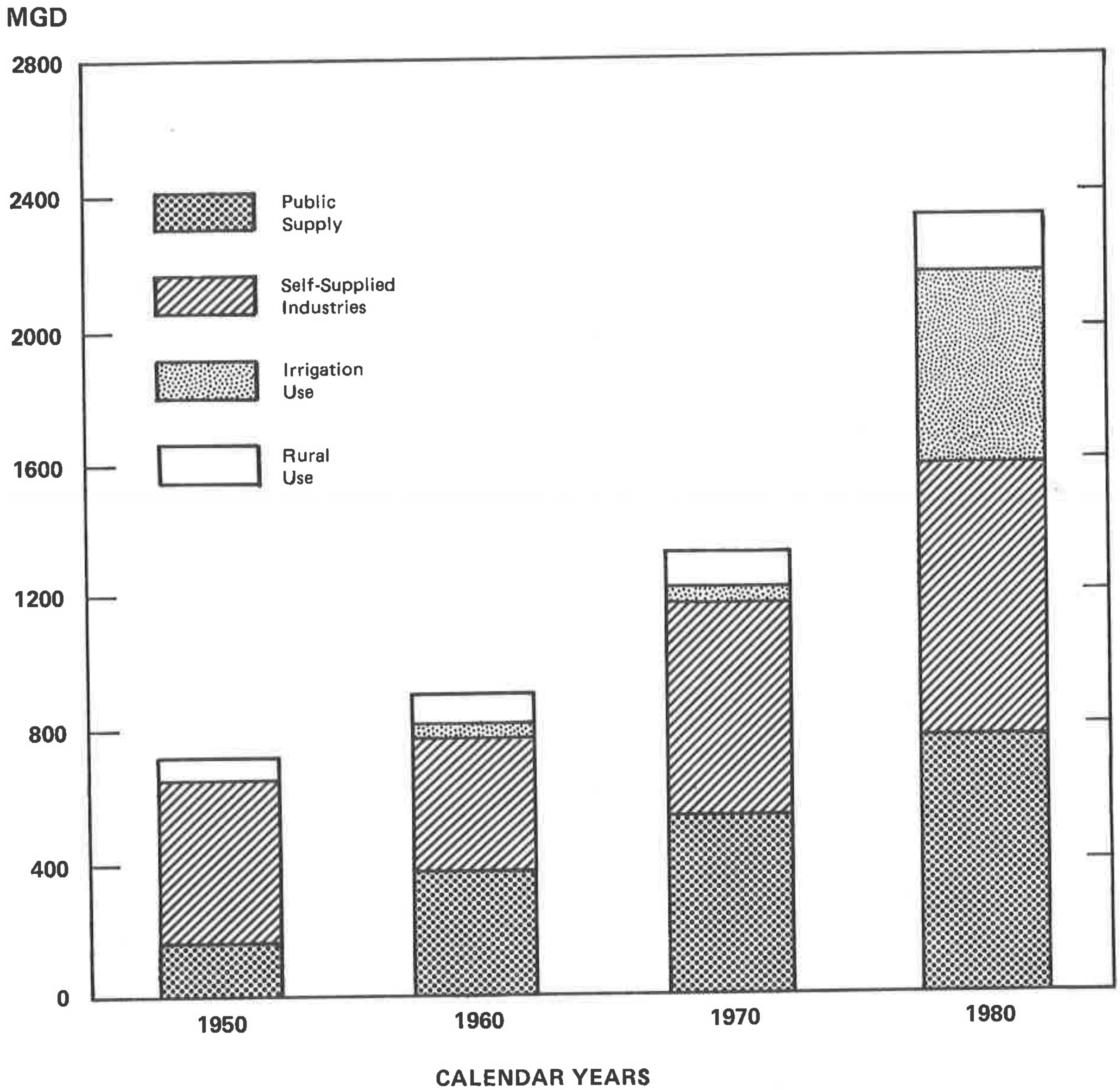
To understand the water problems in the northern part of Georgia, four points should be considered:

1. The northern part of the state (Ridge and Valley, and Piedmont Province) is the major urban-industrial region of the state. Atlanta, located in the Piedmont Province, is higher in elevation than any other major metropolitan area in the country, except Denver. All other large cities are located on coasts or major rivers.

2. This major urban-industrial region is located in an area of limited ground water.

3. This urban-industrial area is located near the headwaters of the state's major rivers. Consequently, these rivers flow

Figure 5. Water use trends in Georgia



SOURCE: U.S. Geological Survey.

through this high demand area before they have reached their full capacity.

4. Because this urban-industrial area is geologically old, there are no natural lakes in the region.

These factors combine to create a situation of high demand in an area of very little natural storage of ground or surface water. As a result, both water supply and water quality are of concern in the northern part of the state.

The Coastal Plain of Georgia, on the other hand, is underlain by layers that store vast quantities of water. The problems in this region relate to the withdrawal of too great a quantity of water from any one place. The problem has materialized as a potential saltwater intrusion from the Atlantic in the Savannah area, an intrusion of highly mineralized conate water in Brunswick, and a possible intrusion of poor quality surface water in Valdosta.

Besides ground water quality, water level declines have been a concern. These are most evident with the Clayton Aquifer, which has experienced substantial declines in piezometric pressure levels for several years. The major question raised has been about the effect of irrigation in southwest Georgia on both the Clayton and Principal Artesian aquifers. The fact that Radium Springs, the largest spring in the state, went dry for the first time in history in 1981 -- an event not accountable to lack of precipitation alone -- indicates that levels may be dropping, at least on a periodic basis, in the Principal Artesian Aquifer.

WHAT IS BEING DONE TO RESOLVE THESE PROBLEMS?

Resolution of water resource problems may take many forms: from research to regulations, from monitoring to operation of a wastewater facility, from funding of programs to communications between people. All these efforts contribute to the management of water resources. Of major importance, however, is the framework established by state and federal water laws and the implementation of these laws by state and federal agencies.

For water management in Georgia, 1972 was a "watershed" year. Three laws were passed that have had considerable impact on the water management program. At the federal level, the Water Pollution Control Act established the national goal of having "fishable and swimmable" waters by 1983. Although we did not reach this goal, substantial water quality progress has been made. Funds were provided for the following activities:

1. creating the National Pollution Discharge Elimination System (NPDES) to control (permit) the discharge of industrial and municipal effluent into the nation's waterways
2. constructing wastewater treatment facilities
3. classifying streams
4. monitoring water quality conditions
5. regulating dredge and fill operations
6. determining the nature and extent of nonpoint source pollution

Authority to implement this law was assigned to the U.S. Environmental Protection Agency, which could then delegate this authority to states that had demonstrated their ability to fulfill the mandates of the law. Georgia has received the authority to implement this program.

Two state laws were passed in 1972 that laid the foundation for Georgia's water management program. The first was the Ground Water Use Act. The impetus for this law was the perception of ground water problems in the Savannah and Brunswick areas resulting from uncontrolled industrial and municipal withdrawals and the lack of case law resolving ground water disputes. The Ground Water Use Act provided the state with the authority to allocate ground water withdrawals in excess of 100,000 gallons per day through a permit system.

The second 1972 state law, which has had a lasting impact on the water management program, was the Executive Reorganization Act (Kundell and Bremen, 1982). This law created the Department of Natural Resources (DNR) and assigned to it functions previously conducted by a mixture of distinct but functionally related commissions, boards, authorities, agencies, councils, and departments. This reorganization created within DNR the semiautonomous Environmental Protection Division (EPD) and assigned to it virtually all environmental responsibilities, including those related to water resources. EPD is thus the single state agency with water management responsibilities in Georgia.

These three laws established the legal foundation for dealing with water quality and water quantity and created the organizational framework that has led to Georgia's statewide, integrated water management program. In 1977, the General Assembly amended the Georgia Water Quality Control Act to include the requirements for a permit to withdraw in excess of 100,000 gallons per day of surface water, the same approach used for ground water. Thus the state has adopted an administrative approach to managing its water resources.

Both the Ground Water Use Act and the amendments to the Water Quality Control Act exempted agricultural uses from the permit requirement. In 1972, ground water concern focused on industrial and municipal water use; irrigation was not a major use of water. The exemption was not a significant problem at that time. What was not foreseen was the major increase in irrigation during the late 1970s and early 1980s. As a result of this increase, irrigation is now the major consumer of water in Georgia. It is important that in some way agricultural water use be included in the state's water management program.

The water management program being developed in Georgia is of interest nationally because it enables integration of decisions related to all aspects of the water resources (i.e. surface water quality, ground water quality, surface water quantity, and ground water quantity). The water laws provide the legal authority to manage the water resources, and the organizational structure of a single state agency with all permitting authority allowed under state and federal laws enables EPD to integrate its decision-making process. Since 1980, with the creation of the Water Resources Management Branch, EPD has been actively developing this program.

CONCLUSIONS

Georgia has come a long way since 1972. The demands on the water resource have increased substantially, supporting the need to manage the resource in an efficient, effective manner. Toward this end, research has been conducted, laws have been passed, and agency capabilities have expanded. But problems still exist. In my opinion, our efforts in the near future will have to focus on five points:

1. Development of a data base. Both research and monitoring will be required to provide the data on the nature and extent of the water resources, how the resource is being used, problems with the resource, and alternative mechanisms for resolving the problems.

2. Development and implementation of a management program. EPD is currently developing an integrated water management program. Since saying that an integrated water management program is being developed is easier than developing an integrated water management program, problems will be encountered. Methods for resolving these problems will have to be developed.

3. Alteration of the water management program to include all major water resource users.

4. Assessment of the roles of federal, state, and local agencies. Agency roles will have to be assessed to determine the level or branch of government, or the private sector, best qualified to perform various functions.

5. Improvement of communication and coordination linkages between water users and water managers.

Inherent in all these points is the cost of managing the state's water resources. Research, monitoring, allocation, treatment, and enforcement activities all require funding. Adequate financial support will be required to ensure water quality and water supply.

Georgia is in the enviable position among states of having a substantial amount of high quality water. By understanding these resources and fully implementing an effective water management program, we should be able to optimize the use of the state's water resources for both current and future water users.

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PARAMETER ESTIMATION OF THE CLAYTON AQUIFER NEAR ALBANY, GEORGIA

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ABSTRACT

The use of numerical methods in predicting ground water level patterns or piezometric head distribution in a confined, semiconfined or unconfined aquifer is a well accepted and widely used research procedure. Most of such studies are aimed towards the determination of piezometric head distribution and flow rates in an aquifer given the hydraulic parameters of the aquifer. It is well known that results generated by such models can only be at the accuracy level of the field data used. Unfortunately, besides being too costly, direct field and laboratory measurement techniques often provide scattered and inaccurate information about the spatial distribution of these parameters. Thus, numerical models often fail to serve as reliable management tools due to what appears as an almost chronic lack of appropriate field data.

In this study a numerical optimization model is developed which automates the trial and error model calibration procedure. The algorithm utilizes the finite element method along with a non-linear least squares minimization algorithm. The technique developed is used to estimate transmissivity values of a portion of the Clayton aquifer near Albany, Georgia given steady state potentiometric data.

INTRODUCTION

Deterministic numerical models used to analyze ground water flow problems have proven to be an invaluable tool in aquifer analysis. The numerical accuracy of these techniques are well established in the literature. Thus, the major limitation of these models is not the accuracy but the reliability of input parameters, such as transmissivity data, recharge, sources/sinks, and leakage. In the past, parameter estimation or model calibration has been a trial and error process involving modeling expertise. In such studies subjective judgement has been used to adjust the parameters such that there was a minimization between errors in observed field data and computed response of the model.

Recently, automation of model calibration has been attempted using various optimization techniques. For this study a computer program was developed using the standard least squares minimization criteria in an algorithm which automatically adjusts the transmissivity values while minimizing the difference between observed and computed piezometric head values (Kuniansky, 1982). While the program written for this study only adjusted transmissivity values in a confined aquifer, the algorithm could be used to adjust other unknown parameters and has much wider application.

Using information supplied by the Georgia Geologic Survey, transmissivity estimates of two portions of the Clayton aquifer near Albany, Georgia were obtained (Aral and Kuniansky, 1983). The trends in the estimated transmissivity values were similar to expected trends over a major portion of the modeled region.

In this paper, a brief discussion of the optimization algorithm along with a description of the results of a field application is given. More detailed discussions of these items can be found in the reports referenced above.

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1. Graduate Research Assistant
2. Associate Professor

OPTIMIZATION ALGORITHM

The optimization or regression technique was iterative and started by guessing two initial sets of transmissivity values over a bounded aquifer region. The steady-state ground water flow equation, Equation (1) below, was solved for nodal piezometric head values by the finite element method using three

$$\frac{\partial}{\partial x}\left(T(x,y)\frac{\partial h(x,y)}{\partial x}\right)+\frac{\partial}{\partial y}\left(T(x,y)\frac{\partial h(x,y)}{\partial y}\right)=0 \tag{1}$$

where T = transmissivity
h = piezometric head values
x,y = cartesian coordinates

nodal triangular elements as discussed in Aral, 1974 and Zienkiewicz, 1977. These computed piezometric heads were then interpolated to the location of observed water levels. The computed head values, observed head values and element transmissivity values were input into the optimization algorithm which computes the changes in transmissivity. These transmissivity increments are then used to update the element transmissivities. Resulting transmissivity values were next inserted into Equation (1) and new piezometric head values were computed for the next iteration. Several approximation techniques used in this optimization algorithm will be discussed in the following sections.

The algorithm was based on the standard least squares minimization criteria, therefore some function of the unknown parameters must be minimized with respect to the sum of the squares of the error between observed piezometric head values and computed head values as shown in Equation (2) below.

$$\min_{T_1,\ldots,T_L} F(T) = \sum_{j=1}^{M} W_j\,[\bar{h}(x_j,y_j)-h(x_j,y_j)]^2 \tag{2}$$

subject to

$$T_i^{\ell} \le T_i \le T_i^{u} \qquad i = 1,\ldots,L$$

in which

$\bar{h}(x_j,y_j)$ = observed values of the piezometric head at the location (x_j,y_j)

$h(x_j,y_j)$ = calculated values of the piezometric head at the location (x_j,y_j)

T_i = transmissivity at a bounded homogeneous region R_e (element)

L = number of bounded homogeneous regions

M = number of observation points

ℓ,u = subscripts used to denote lower and upper bounds of parameters

W_j = weighting coefficient ($0 \le W_j \le 1$)

While the true relationship between T values and computed head values was given by Equation (1), insertion of Equation (1) into Equation (2) would result in a non-linear system of equations, therefore a Taylor's series expansion was used to approximate this relationship as shown by Equation (3).

$$h_j^{n+1} = h_j^n + \Delta T_i \frac{\partial h^n}{\partial T_i} + o\ (\Delta T)^2 \tag{3}$$

where n is the iteration number and $\Delta T_i = T_i^n - T_i^{n-1}$

The linear portion of the Taylor's series was substituted into Equation (2) yielding Equation (4) which was minimized via standard Least Squares technique.

$$F(T) = \sum_{j=1}^{M} W_j\ [\bar{h}_j - (h_j^n + \Delta T_i\ (\frac{\partial h}{\partial T_i})^n\ ]^2 \tag{4}$$

This process results in a set of normal equations, Equation (5).

$$[A^n]\ \{\Delta T\} = \{B^n\} \tag{5}$$

where,

n = is the iteration number

$\{B^n\} = [J]^T\ \{\bar{h}-h^n\}$

$[A^n] = [J]^T\ [J]$

[J] represents the Jacobian matrix which was defined as shown in Equation (6)

$$[J] = \begin{bmatrix} \frac{\partial h_1^n}{\partial T_1} & \frac{\partial h_1^n}{\partial T_2} & ---- & \frac{\partial h_1^n}{\partial T_L} \\ \frac{\partial h_2^n}{\partial T_1} & \frac{\partial h_2^n}{\partial T_2} & ---- & \frac{\partial h_2^n}{\partial T_L} \\ \\ \frac{\partial h_m^n}{\partial T_1} & \frac{\partial h_m^n}{\partial T_2} & ---- & \frac{\partial h_m^n}{\partial T_L} \end{bmatrix} \tag{6}$$

The difference form shown in Equation (7) was used to approximate the gradient terms of the Jacobian matrix.

$$\frac{\partial h_j^n}{\partial T_i} = \frac{h_j^n - h_j^{n-1}}{\Delta T_i} \tag{7}$$

Use of these approximations yields a linear system of equations shown in Equation (5). Due to the non-orthogonality of the estimated parameters with respect to the hydraulic gradients, numerical instability is a common problem for such formulations. In the literature, several techniques have been developed to aid solution of non-orthogonal least squares matrices (refer to: Levenberg, (1944); Marguardt (1963); Hoerl and Kennard (1970, a,b). Several of these techniques were examined and it was found that the technique suggested by Levenberg (1944), was the simplest and most efficient technique to overcome such numerical instabilities.

Two stopping criteria were used in the program, one was a total number of allowable iterations and the other was a check on the magnitude of the root-mean-square

(RMS) error between observed and calculated head values as defined by Equation (8) below.

$$\mathrm{RMS} = \frac{\sqrt{\sum_{i=1}^{m} (h_{i_{obs}} - h_{i_{calc}})^2}}{m} \tag{8}$$

Because of noise in observed data the allowable RMS error is expected to be of the order of magnitude of the error in the field observations.

There is much uncertainty involved in ground water models and many forms of error are incorporated into the modeling process. Errors are introduced by simplification of the aquifer system and in discretizing the system for numerical solution. In order for a non-weighted standard least squares minimization to give the best estimate of the unknown parameters all of these errors should be normally distributed and the residuals between observation data and model response should also be normally distributed. If the minimax criteria were used in weighting the standard least squares such that regions in which there were small residuals between observed data and calculated model response are weighted less than regions where the residuals were large, the best estimate of parameters would be obtained if all errors were exponentially distributed (Neuman, 1973).

Errors in the problem formulation and observation data are not usually known, thus sample statistics of the residual between observed and computed heads were calculated. Spatial variograms and histograms of the residual were used to graphically show the fit between model response and observation data. These serve as a tool for evaluating the estimated parameters and the model formulation.

Because of the nonuniqueness of the parameter estimation problem, all known geologic information should be incorporated into the parameter estimation scheme. For this reason, upper and lower bounds on transmissivity could be imposed on the solution if ranges of transmissivity are known in the modeled region.

FIELD APPLICATIONS

The study area is located to the north of Dougherty and Calhoun Counties near Albany, Georgia. Comparison of recent and historic water levels showed that there have been large declines in the potentiometric surface of the pumped aquifers forming a cone-of-depression around Albany. For this reason, these aquifers are currently under study by the Georgia Geologic Survey in its Accelerated Ground Water Program, Ripy et al., (1981). There are four main producing aquifers near Albany from deepest to shallowest, they are: the Providence (sand), the Clayton (limestone), the Tallahatta (sand), and the Ocala (limestone), (Hicks et al., (1981)). The Clayton, which was chosen for this study, is confined above by the clayey Tuscahoma sand and below by the silty upper Providence-lower Clayton sequence. Because the Clayton is mostly limestone, observed transmissivities are quite variable ranging from 200 ft^2/day to 11,000 ft^2/day. Thickness of the aquifer ranges from less than 50 ft in eastern Dooly and Crisp counties to 450 ft in southern Early and Miller counties. The Clayton aquifer is nearly horizontal with a dip of about 17 ft/mi to the southeast.

Figure 1 shows the study area and the potentiometric surface of the Clayton aquifer during December 1979 (Ripey et al., 1981). The two regions shown in Figure 1 were studied separately. The assumptions made in modeling these regions were: 1) the aquifer was confined; 2) the north-south boundaries A-A, B-B, and C-C in Figure 1 were streamlines. Lines A-A and B-B were suggested as water divides by the Georgia Geologic Survey and line C-C was chosen by the authors; 3) the aquifer was horizontal; 4) there were no major sources or sinks inside the modeled regions; and 5) the potentiometric map for December 1979 represented steady-state conditions.

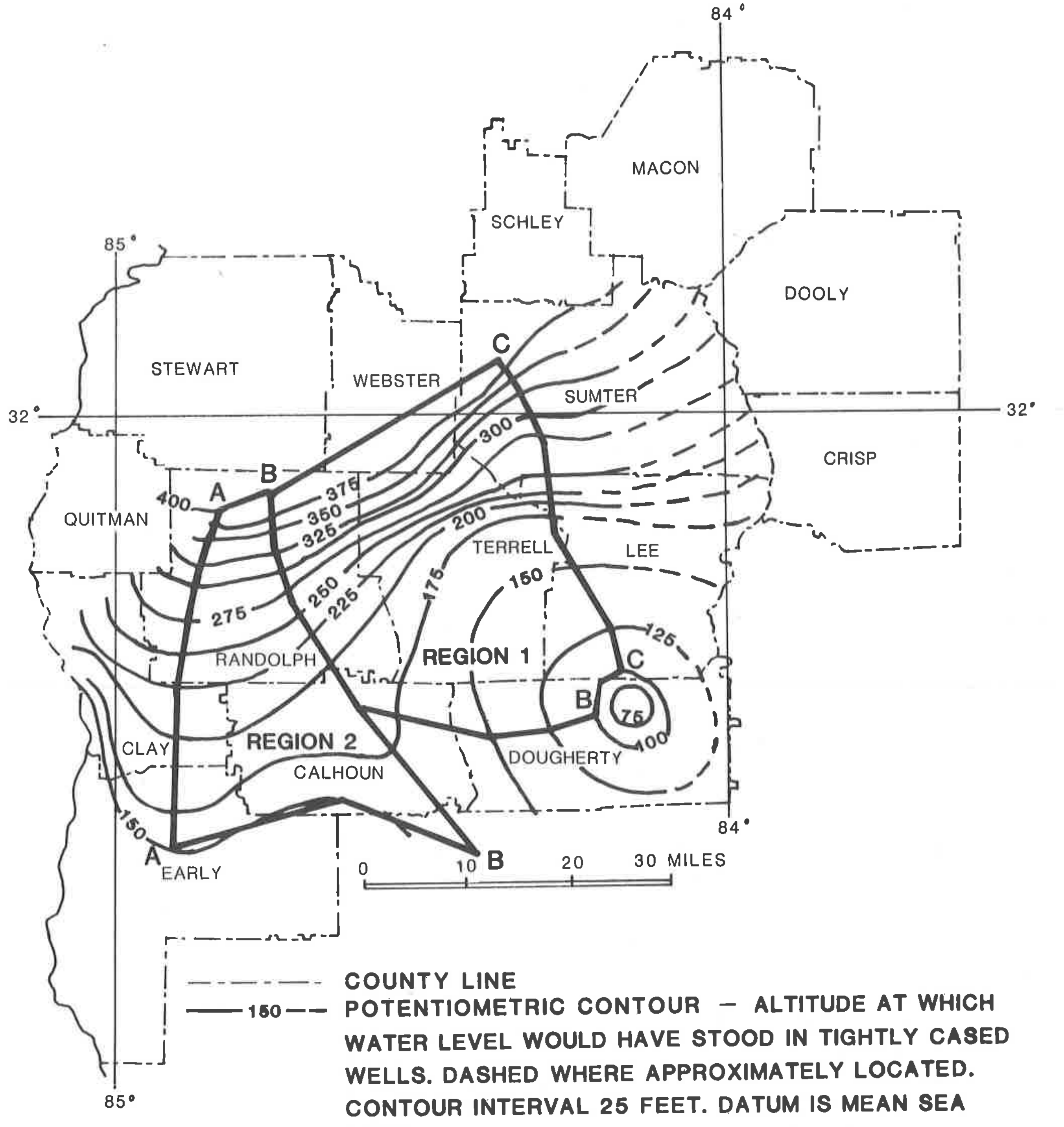


Figure 1. Potentiometric Contour Map of the Clayton Aquifer as of December 1979. Boundaries of the Two Regions Used for Transmissivity Estimation are Represented by Solid Lines A-A, B-B, and C-C.

Region 1 had an area approximately 173 mi^2. A hierarchical approach was used in modeling this region. First a coarse triangular mesh of 25 elements was used and the final transmissivity estimates from the coarse mesh were input as the initial transmissivity values in the finer mesh consisting of 81 elements. Initially, the only prior knowledge of transmissivity used was lower and upper bounds of 250-100,000 ft^2/day over the region. Transmissivity values from 5,000 to 4,000 ft^2/day were used as initial data in the coarse mesh. Figures 2a and 2b show the initial and final transmissivities for the coarse and fine mesh (initial values are in parentheses). After 200 iterations the RMS value decreased from 16.1 ft to 3.66 ft for the coarse mesh. With the fine mesh the initial and final RMS values were 2.35 and 2.32 ft respectively after 100 iterations. The only stopping criterion used for these runs was the total number of iterations. Statistics of the residuals between observed and calculated head were computed for all runs. In Figures 3a and 3b the spatial variogram and histogram for the fine mesh results are shown. The coarse mesh showed the same trends in residuals also having a histogram which resembled a normal distribution of residual error.

After consulting the Georgia Geologic Survey, it was discovered that the estimated transmissivities fit fairly well with available information with the exception of the very low transmissivity region forming an east-west band near line B-C at the top of Figures 2a and 2b. Based on this information, two runs were made in region 1 using bounds for transmissivity over some elements. Initial and final transmissivity values for the coarse and fine mesh are shown in Figures 4a and 4b. The initial and final RMS values for the coarse mesh after 100 iterations were 17.8 and 7.67 respectively. With the fine mesh only 50 iterations were used which resulted in initial and final RMS values of 5.57 and 5.59 ft. Figures 5a and 5b show the spatial variogram and histogram for the fine mesh run. As shown by the sample statistics (Figs. 5a and 5b), there was a much worse fit of the model when the transmissivity bounds were imposed. With the fine mesh there was also no decrease in the RMS value which deviated only slightly from the initial value of 5.57 ft. This slight deviation indicated there was no convergence or minimization of the deviation between observed and calculated head values. It is important to note that the transmissivity ranges imposed were not exact and the spatial location was adapted to fit the finite element mesh which may account for the worsening of fit. As can be seen in Figures 5a and 5b, the residual errors were not normally distributed and the sample variance was very large.

Only one mesh was used for the second region shown in Figure 1. The area was approximately 100 mi^2 and was divided into 37 triangles. For the first simulation a constant transmissivity of 4,000 ft^2/day was used as initial data over the entire region. After 25 iterations there was little change in the T values at each element and the initial and final RMS values were 1.32 ft and 1.27 ft respectively. The maximum deviation between observed and calculated head values was only 20 ft with a mean deviation of 4.2 ft; variance of 50 ft^2 and standard deviation of only 7.1 ft. The histogram resembled a normal distribution. Overall there was a very good fit of the model.

A second simulation was done inputting 2,000 ft^2/day as the initial transmissivity over region 2. Again after 25 iterations there was little or no change in transmissivity and the initial and final RMS value was 1.32 ft. The mean of deviations between observed and computed head was 4.6 ft; the variance 49 ft^2; and the standard deviation 7.0 ft. Both the sample statistics spatial variogram and histogram for this second simulation were identical to the first simulation of region 2.

The simulations in region 2 provide a good illustration of the nonuniqueness of parameter estimation when no flux boundary conditions are known and hydraulic gradient is fairly constant which implies a reasonably homogeneous transmissivity over the aquifer. The proper range of transmissivity in region 2 was 3,000-5,000 ft^2/day, but any constant transmissivity used in the region along with constant head boundary conditions would provide a good fit of the model. Thus, one should be extremely careful in utilizing the algorithm presented here. To avoid nonuniqueness problems one should either use flux boundary conditions on a portion of the

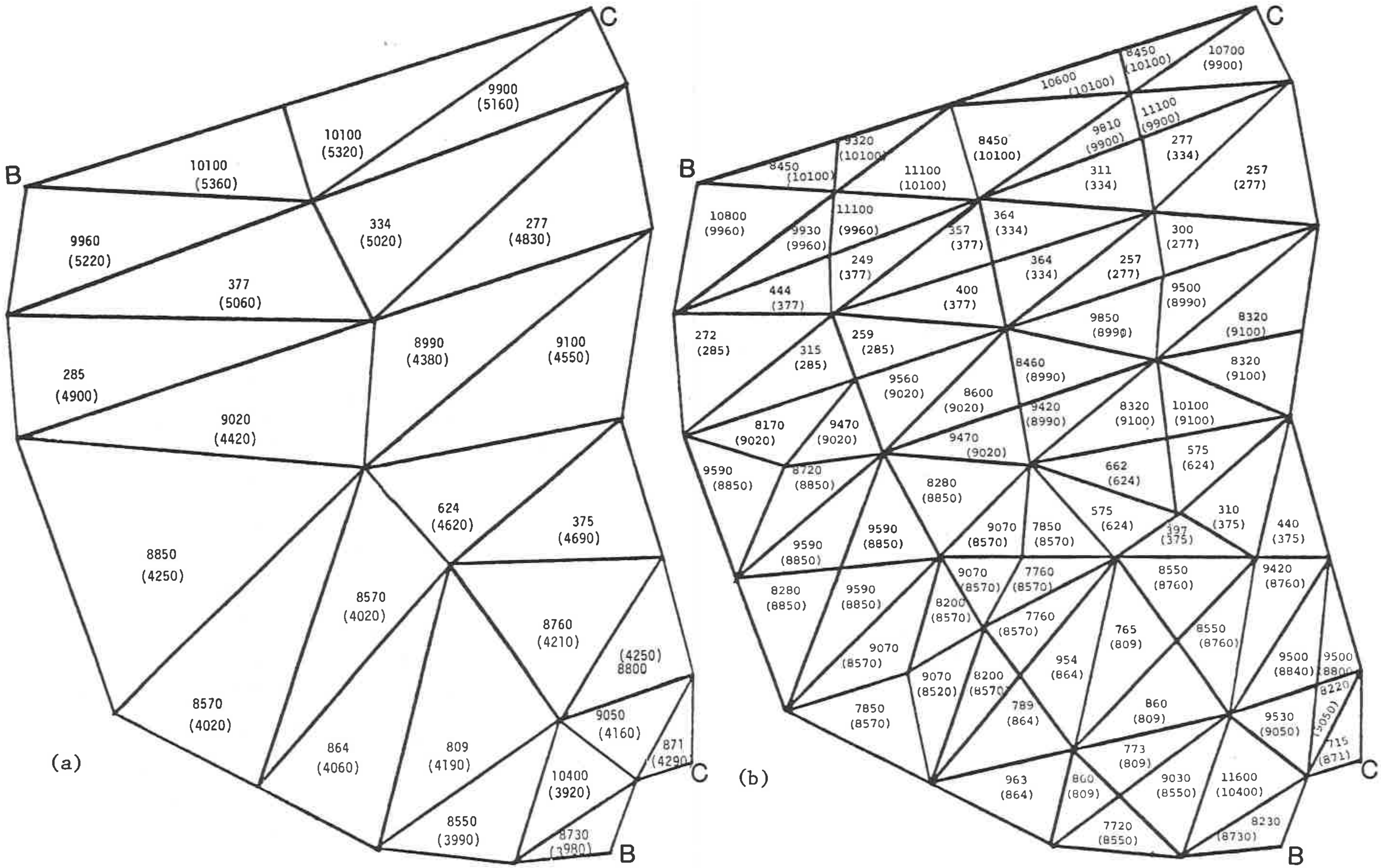
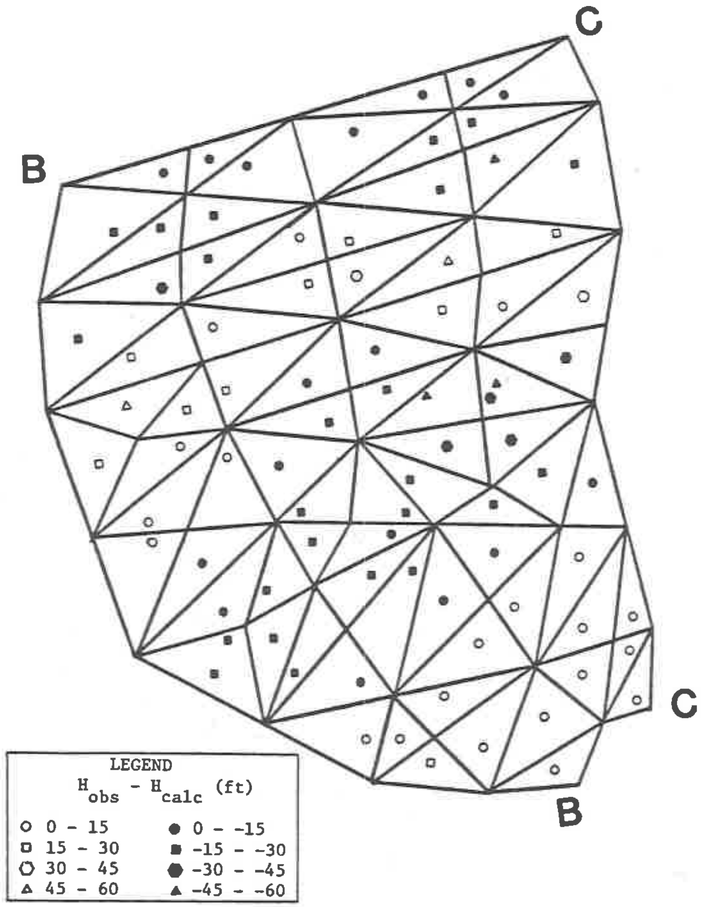
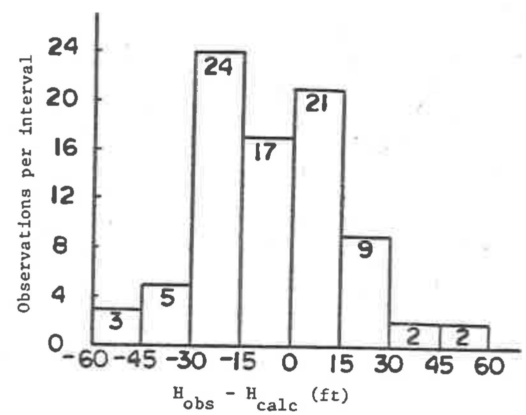


Figure 2. Initial and Final Transmissivity Values When no A Priori Knowledge Was Input (initial values are in parentheses). (a) Coarse Mesh (b) Fine Mesh.



(a) Spatial Variogram of $H_{obs} - H_{calc}$



Sample statistics: mean = -6.4 ft; variance = 421 ft^2; standard deviation = 20.5 ft; coefficient of variation = -3.2 coefficient of skewness = 0.22

(b) Histogram of $H_{obs} - H_{calc}$

Figures 3 (a) and (b). Sample Statistics for Fine Mesh Simulation Shown in Figure 2 (b).

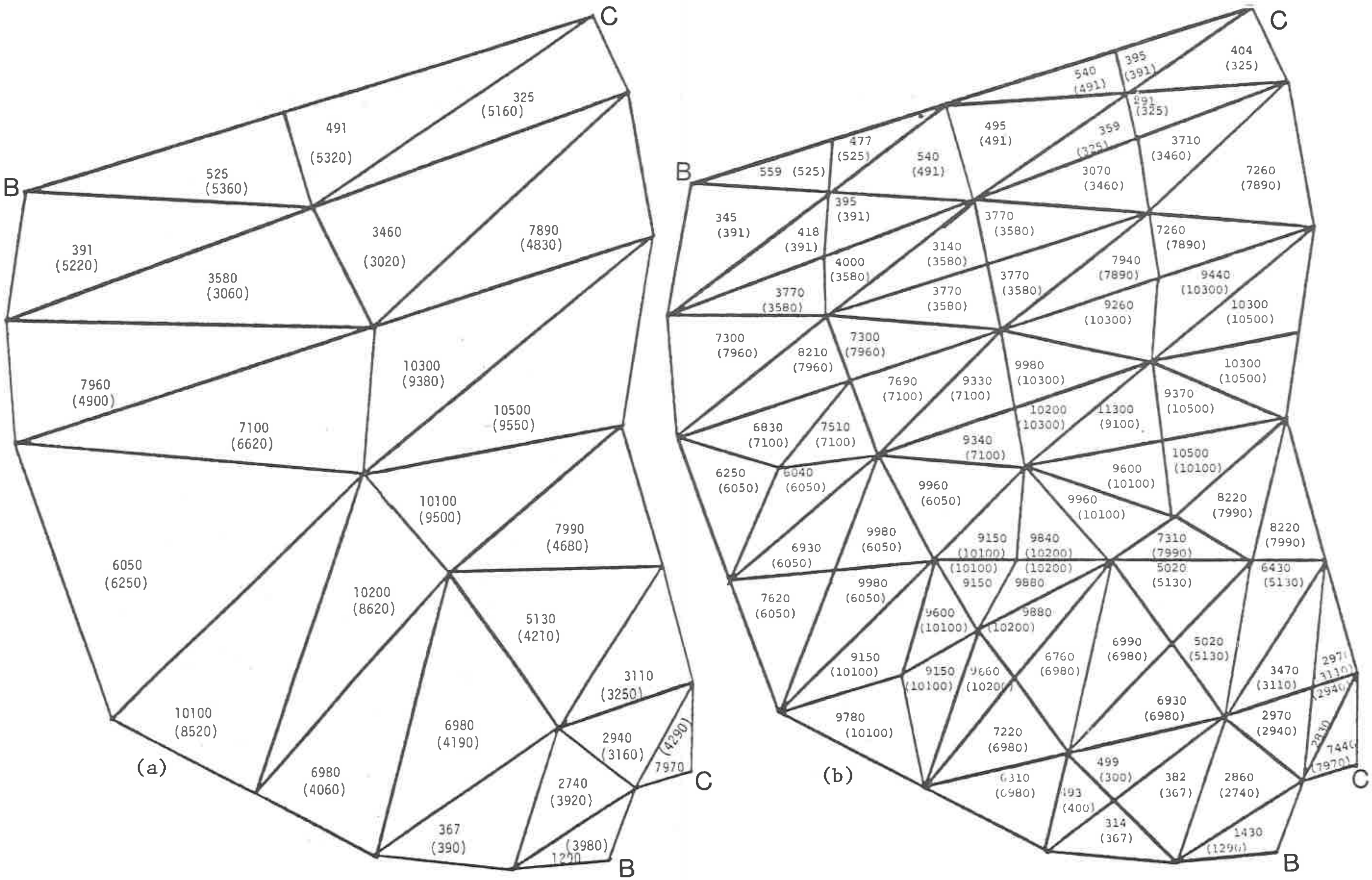
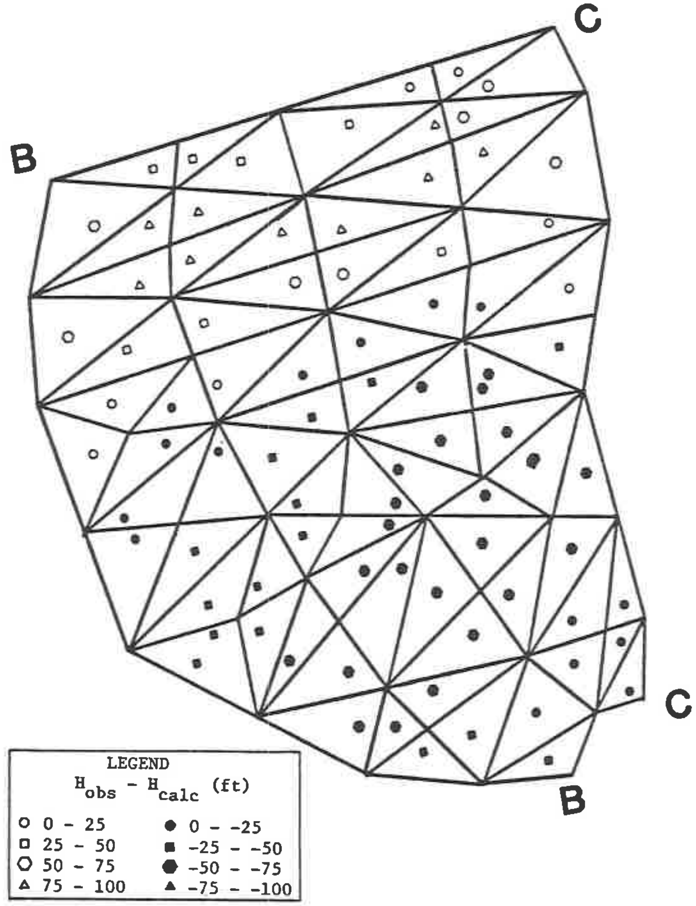
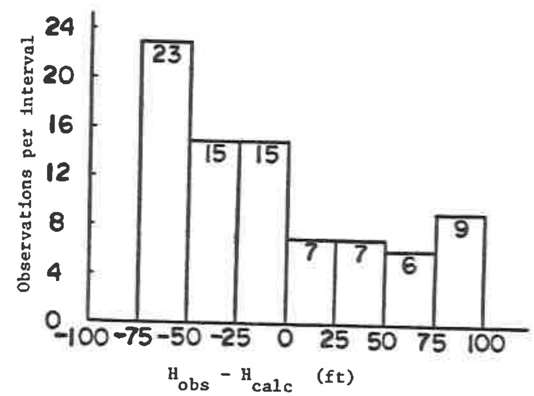


Figure 4. Initial and Final Transmissivity Values When A Priori Knowledge Was Input (initial values are in parentheses). (a) Coarse Mesh (b) Fine Mesh.



(a) Spatial Variogram of $H_{obs}-H_{calc}$



Sample statistics: mean = -6.1 ft; variance = 2616 ft^2; standard deviation = 51 ft; coefficient of variation = -8.3 ft; coefficient of skewness = 0.69

(b) Histogram of $H_{obs}-H_{calc}$

Figures 5 (a) and (b). Sample Statistics for Fine Mesh Simulation Shown in Figure 4 (b).

boundary or should rely on some field measurements of transmissivity when determining the initial transmissivity distribution data.

CONCLUSION

Critical to all regional subsurface hydrologic modeling studies is the estimation of aquifer parameters, and boundary conditions. Considerable modeling expertise is required for the development of a reliable set of parameters which will provide a good fit between observed field data and computed model response. Similar optimization algorithms, to the one developed for this study, have been used to automate the parameter estimation process and remove some of the subjective decisions made by modelers (Cooley 1977, 1979, Durbin 1979). Field application of the algorithm discussed in this paper does show much promise in the use of numerical parameter estimation schemes.

In all of the simulations, an overfitting of the model was done in order to examine the convergence trends of the algorithm. Generally, the RMS value decreased rapidly in the first few iterations and then began decreasing at a lesser rate. In a few cases the RMS value did not decrease from the initial value. For this reason, a third stopping criterion is recommended. This criterion would compare the RMS value of the previous iteration with its current value. If there were no significant decrease in RMS value the iterations would be stopped and results printed.

The spatial variogram and residual statistics were very useful in finding problem areas and evaluating model fit. No sensitivity analysis was done to determine which transmissivity values had the most effect on the computed heads, but this could also serve as a valuable tool for weighting the least squares. No weighting of any of the information for the optimization algorithm was used in this study.

The worsening of fit for region 1 when a prior upper and lower bounds was imposed on the transmissivity values could be due to error in observed field data, incorrect transmissivity bounds, and/or incorrect boundary conditions. Thus, there will always be some subjective decisions to be made by modelers such as to determine which information is the most reliable. Further improvements of the program developed for this study should be pursued, but the algorithm discussed shows much promise as a technique for automation of the trial and error model calibration process.

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THE CHANGING INFRASTRUCTURE OF WATER RESOURCES FINANCING

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Historical Overview of Georgia's Water Resources

Georgia has a rich and unique historical heritage in that many nations, cultures and orders participated in its founding and development. This background easily can be linked to the State's water resources. Since historians don't trace financial activities very closely it is difficult to know much of the detail of our financial support of water resources on a consistent basis. A few glimpses will indicate the nature of our financial interests. We would like to give you a complete and scholarly presentation on the progress in financing Georgia's water resources development and management. Unfortunately, the process has been so complex and the financial data so spotty that this cannot be done. At best, we can indicate only the recent nature of changes in Federal financing of water resources and speculate about how such changes may affect Georgia. We may suggest a few directions we should think together about in order to enhance our State's water resources and insure the high quality of life that abundant water resources support.

Early settlement and development of Georgia was limited to the Coastal Plain area served by the navigable rivers -- the Savannah, Ogeechee and Altamaha -- until after the Revolution of 1774. The abundant water resources of Georgia were the basis of the land measurements and the territorial boundaries as well as the chief transportation system from the beginning. The charter for the Colony of Georgia was originally drawn to include the lands between the Savannah and Altamaha Rivers from the Atlantic Ocean to their headwaters and thence west to the Pacific Ocean, wherever that was. During the time approaching the Revolution, 1763-1776, Georgia acquired all of the lands between the Savannah and Ogeechee Rivers to Augusta and northwest to the Appalachians and all the lands between the Altamaha and the St. Mary's Rivers. Georgia was now that land between the Savannah and St. Mary's Rivers as far west as one dared settle.

After the revolution, Georgia grew rapidly in both population and economic development. By 1790 Georgia had acquired all the lands between the Ogeechee and Oconee Rivers and claimed all that land between the Savannah and St. Mary's Rivers westward to the Mississippi River. In 1802 the westward boundary was fixed at the west bank of the Chattahoochee River. All lands west of the Chattahoochee River (west bank) were ceded to the United States in exchange for help against the Indians and to escape an untenable position created in the Yazoo land frauds.

This westward expansion demanded transportation and Georgia's rivers became the logical system of movement into and out of the interior. River channels were improved and opened for navigation first by private companies and next by the State itself after 1820. The major rivers carried most of Georgia's commercial traffic from the coast to the fall line until about 1850. Many turnpikes were built with private, Federal and State funds in the period 1800 to 1860. The short-lived National canal fever resulted in only one major Georgia canal which connected the Savannah and Ogeechee Rivers in 1831. The Georgia legislature actually created a "Board of Public Works" to finance statewide river and canal development. However, the privately financed railroads made this effort irrelevant and the Board was abolished.

By the 1850's the abundant water power available near the Fall Line, reaching from Augusta to Macon to Columbus, was well recognized and privately financed development was underway. The cotton gin made cotton production more profitable and released both capital and labor resources for the development of cotton manufacturing. Prior to 1848 most of the water power available in Georgia had been used on a small scale for operating grist mills and saw mills. The Graniteville Cotton Mill was established in 1848 at Graniteville, S. C., in the Savannah River Basin as the first textile manufacturing in the area. Cotton manufacturing was a major industrial activity wherever water power was available in the Piedmont and Fall Line cities.

The development of Georgia's water resources remained stable or in fact declined over the century from the 1850's to the 1950's. During this century water transportation declined relative to other forms of transportation. By 1900 the flowing waters of the State's rivers had been converted by private financing from the direct production of power for industrial activities to the production of electrical power for transmission to manufacturing facilities which could be located, in most cases, without regard to flowing waters. The exceptions were the process industries that developed after World War II such as the chemical, textile finishing and pulp-paper industries which required huge quantities of water for both processing and waste disposal.

The extremely poor financial condition of Georgia after 1865 led to increasing efforts to secure Federal support for developing the State's water resources through the Congressional authorizations for the Corps of Engineers' Civil Works Programs. Navigation and flood control were the primary purposes of Federal investment in the State's waters prior to World War II. Navigation has remained the major investment purpose in the Coastal Plain. Major Federal investments have been made upstream of the Fall Line for the development of hydroelectric power through civil works programs (Corps) and for flood control through small watershed programs (SCS). Both sources of Federal funding have produced, as a by-product, an enormous recreation industry and its benefits for the State.

The Federal Government, through the Corps of Engineers, has devoted its resources to the development of the two major interstate rivers, the Savannah and the Chattahoochee, while permitting private development of the Altamaha, Ocmulgee and Oconee systems. Federal investments on the Savannah River have been made for Clark Hill, Hartwell and the Richard B. Russell systems. All of these projects were authorized and designed or modified to provide navigation, flood control, hydropower generation and recreation. All of the projects on the Savannah River provide navigation benefits indirectly by providing the capability of maintaining a navigable channel south of Augusta to Savannah. None of these projects include locks for navigation into the headwaters but such provisions could be made since the Savannah soon will be a continuous lake from the Clark Hill Dam north to its headwaters above the Seneca-Keowee-Toxaway system and the Tugaloo system. The Chattahoochee is well endowed with Federal multiple purpose projects (navigation, flood control and power) with the Jim Woodruff, Andrews, Walter George, West Point and Buford Dam projects. The largest obstacle to further development of navigation on the Chattahoochee is the gaggle of small dams between Columbus and West Point.

Financing of Corps Water Projects in Georgia[1]

The oldest operating or active Federal navigation projects are the Chattahoochee-Flint River waterways (authorized in 1874) and the Savannah Harbor (also authorized in 1874). The Corps reports accumulated costs for navigation to the end of FY 1980 as: (1) $14.1 mil. for the Apalachicola-Chattahoochee-Flint to Columbus and Bainbridge - about $130,000 per year average; (2) $162.1 mil. for the Savannah harbor and channel to Augusta; (3) $3.1 million for the Altamaha-Oconee-Ocmulgee basin to Milledgeville and Macon; and (4) $30.8 million for the Satilla-St. Marys systems to Waycross and Trader Hill and the Brunswick Harbor. The accumulated direct navigation investment by the Corps in these projects is $210 mil., not including expenditures allocated to navigation purposes in multiple-purpose projects. This average of abut $2 mil. per year has been added to by the State and local interests in the form of port facilities and lands necessary to make the projects operational.

There are nine multiple-purpose projects in three interstate river basins in Georgia -- two in the Coosa basin, four in the Chattahoochee basin and three in the Savannah basin. The Allatoona and Carters projects in the Coosa basin had reported accumulated Federal costs for flood control, power, navigation and recreation of $177.3 mil. However, these projects were reported to have generated revenues of $52.8 mil. from hydropower sales. Nearly 30 percent of all project costs for both projects (61% for Allatoona) have been recovered (on a nominal, non-discounted basis) in a few years out of expected project lives of 100 years.

In the Chattahoochee basin the Federal Government has invested $409.5 mil. in four multiple purpose projects [$116 mil. in Walter F. George, $80 mil. in Sydney Lanier, $76 mil. in Lake Seminole (Jim Woodruff) and $138 mil. in West Point] for flood control, navigation, hydropower and recreation. These four Federal power projects have returned $137.4 mil. to the Federal Treasury or 33 percent of the accumulated costs in less than 30 years of their expected 100 year life. The real "cash cows" for the Federal treasury are the three power projects in the Savannah basin that each have installed capacities for hydropower of more than 300 mil. kw. Since the Russell project was only 41 percent complete in 1980, we will look at Clarks Hill (cost $114 mil.) and Hartwell (cost $120 mil.). The combined accumulated costs for navigation, flood control, power and recreation were $233.3 mil. Power revenues were reported as $147.2 mil. -- a cost recovery of 63 percent in less than 30 years of project operation. Clarks Hill project had recovered 76 percent of its total costs from power revenues, the highest in the state.

How much money has the Federal Government taken out of these Georgia projects from the sale of hydropower? Through 1980, the total reported power revenues were $337.3 mil. or 35% of the $957.6 mil. accumulated costs of the nine projects (including Russell at $138 mil.). If the projects last 100 years, as advertised, and the power is sold at today's average rates, these projects will gross out revenues from power alone in the order of $1.2 to 1.5 bil. for a cost of about $1.0 bil. We expect these projects to yield closer to $3.0 bil. than to 1.5 bil. in revenues, if the most modest adjustments are made in rates. Since the cost recovery (i.e. the estimated price of power) has been based on a 50 year period for only a part of project costs (i.e., those allocated to hydropower), these revenues will easily pay allocated project costs and a generous profit to the U.S. Treasury.

At the same time we will have enjoyed underpriced power and visitor recreation days that had reached 57 million annually in 1980. We have expectations of substantial increases in revenues and recreation as the newer projects have their rates adjusted and their facilities improved.

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[1] See various Corps reports on Water Resources in Georgia, esp. 1982.

We should include also the Federal Government's expenditures for single purpose flood control and beach erosion -- a total of $8.3 mil. to 1980. Over one-half of this or $4.5 mil., has been lost forever in the shifting sands of Tybee Beach.

In summary, the Corps estimates an expenditure of Federal funds for water resources from 1874 through 1980, on Georgia projects (excluding the intracoastal waterway costs of $14 mil.) of about $1176.1 mil. From this expenditure for all purposes, the Federal Treasury has recovered about $337.3 mil. from power revenues alone from the eight projects on line that have operated for less than one-third of their estimated life, with the power sold at a fraction of its true economic value.

Financing of SCS Projects in Georgia

The Soil Conservation Service (SCS) of the U.S. Department of Agriculture supports and finances the construction of demonstration small watershed projects (1944 act), planning and surveying, resource conservation and development and PL-566 (small watershed) projects. In the latter classification, SCS has completed 113 flood water structures, 17 multiple-purpose structures and 466 miles of channel work. These 30 odd projects have cost, in Federal PL-566 funds $28.65 mil. An additional $20.8 mil. of other funds (mostly lands, easements, land treatment and municipal water supply payments) result in a total project cost of $49.4 mil. The best estimate of Federal financing involved is the PL-566 cost of $28.65 mil. over a 30 year period or about two percent of the Corps investment. When one considers only the Corps multiple-purpose projects built since 1950, the SCS total for PL-566 projects is about 3 percent of the Corps total.

Other Sources of Federal Financing

In addition to Corps and SCS programs in Georgia, other Federal agencies provide substantial financing for water resources activities through loans and grants. In 1977, the Federal agencies, except the Corps, provided about $176 mil. for water resources to the State.[2] These funds included $44 mil. from the Department of Agriculture ($18 mil. of which was loans and $26 mil. direct expenditures on grants). Also, about $25 mil. of USDA funds was for water quality purposes. The Department of Commerce provided $2.1 mil., largely for weather services and coastal research. The Department of Interior was the source of $21 mil.; about one-half from the land and water conservation fund, about one-quarter for outdoor recreation and the other quarter for water resources maps and research.

The Environmental Protection Agency provided about $127 mil., nearly all as construction grants. Assuming the $127 mil. is reasonably correct, the State received about $11 mil. (for its 1978 budget) directly from these Federal water related programs while the remaining $116 mil. went directly to State and local governments or special districts and organizations. The total state funds expended for water and related purposes in 1978 was about $47 mil., of which about one-third ($17 mil.) went to recreational authorities, parks and historic sites and another one-third ($13 mil.) went to ports development.

Summary of Existing Financing

Accurate estimates of investments in water resources in Georgia are not readily available on any consistent basis. It would be foolish to claim any accurate accounting for the "water industry" because of its diversity of ownership,

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[2] Ronald M. North and Jackie Sellers. Analysis of Alternatives for Cost Sharing Water Resources Projects and Programs. ERC 07-82. Institute of Natural Resources. August 1982, pp. 83-84.

funding and management in a highly pluralistic system. The Corps cannot allocate its interstate project funds accurately among the states, the private sector investments in intrastate power projects are not well known and the enormous local government and private investments in water supply and waste treatment facilities and operations are scarce to non-existent. A very wild guess about the approximate annual level of funding of water resources in Georgia may look something like the figures in Table 1 for a year about like 1980.

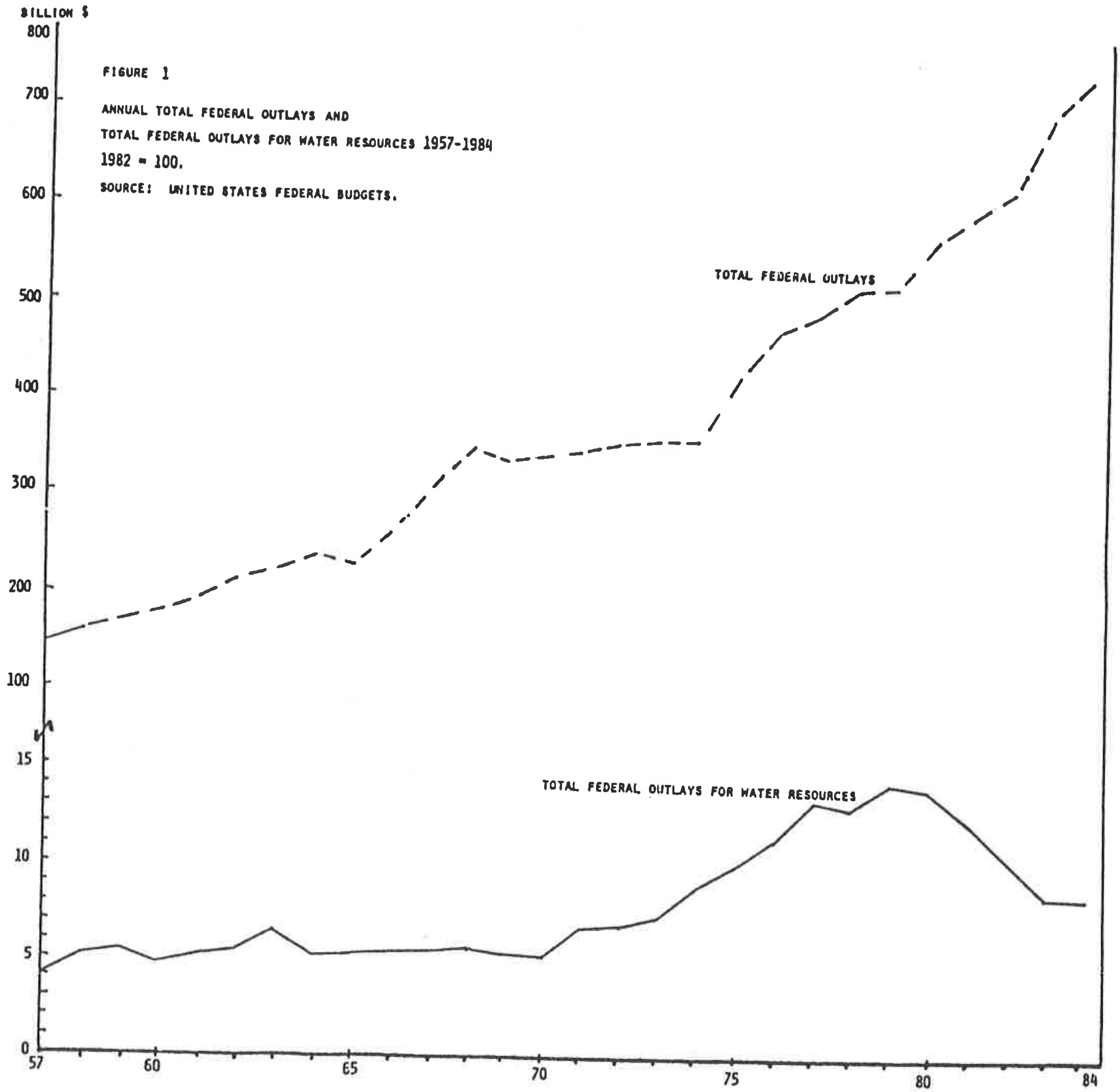
We do not know if these rates of spending, which include capital and most OM&R, are adequate to meet our needs. We do have compelling evidence that financial needs are shifting from a focus on capital needs to OM&R needs in all large multiple-purpose projects as well as for water supply and waste treatment systems. Since OM&R costs are traditionally underestimated and often deferred, and since many major systems are reaching or exceeding maturity rather quickly, we must expect fairly rapid increases in funding requirements for OM&R and rehabilitation. User fees and prices of water services, as well as bonding and subsequent debt services, are likely to grow rapidly in the next few decades. The Federal Government may offer some new kinds of financial services for water resources but the overall levels of Federal funding are likely to decline unless some provisions are made to revolve the potentially enormous power revenues back into the water industry.

Trends in Federal Financing

Federal Outlays for water resources reached a peak in constant dollars in 1979-80 (Figure 1). While total Federal outlays increased substantially after 1975, the outlays for water resources grew more slowly until 1977 when they began to level off and then decline in 1980. Federal outlays for 1984 will be about the same as they were in 1974. For the traditional purposes and sources, Federal funding is declining in absolute nominal and constant dollars and relative to GNP and the Federal budget. These declines should be red flags to the Nation. The nominal (current) dollars of outlays for all natural resources and environmental programs, including water supply and water quality have been summarized by the Office of Management and Budget (Table 2).

Three critical points are observable from these data. First, the declining funding is occurring in all categories of natural resources. Second the additional (by the author) data on water transportation reflect the critically increasing needs to devote more resources to project and program O&M. None of the O&M has been set aside or projected as an obligatory entitlement for traditional water resources projects. These O&M cost estimates are included in the project benefit cost estimates but the outlays are not provided for except through annual appropriations. This is especially critical for navigation and most non-power producing projects. The third point is the rapidly increasing receipts collected from these projects (most of which comes from power revenues). This cash flow source was detailed for Georgia early in the paper. These receipts are being used to offset net outlays so that the real declines (especially for the Corps projects that do not enjoy basin fund accounting) are more serious than a cursory examination reveals. As the revenues from all the power projects built in the 1950's and 1960's begin to balloon with price adjustments, we should seek to dedicate these revenues to the water industry to meet new needs for construction, rehabilitation and O&M.

One possibility is that of setting up basin funds for all the river basins that have Federal projects. Consolidation and transfers of funds from those basins with surplus power revenues to those with larger non-financial (public goods) components could be worked out to maintain the integrity of the water industry.


BILLION $
800
700
600
500
400
300
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100
15
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FIGURE 1
ANNUAL TOTAL FEDERAL OUTLAYS AND
TOTAL FEDERAL OUTLAYS FOR WATER RESOURCES 1957-1984
1982 = 100.
SOURCE: UNITED STATES FEDERAL BUDGETS.
TOTAL FEDERAL OUTLAYS
TOTAL FEDERAL OUTLAYS FOR WATER RESOURCES
57
60
65
70
75
80
84

Table 1. Gross Estimates of Annual Rates of Expenditures and Sources of Funds for Water Resources in Georgia, 1978-1980.

Agency	Range	Fund Sources
Corps	$30-50 mil.	Fed. Taxes & Fees
SCS	1-10 mil.	Fed. Taxes
Agriculture (ex. SCS)	30-35 mil.	Fed. Taxes*
Commerce	1-2 mil.	Fed. Taxes
EPA	100-130 mil.	Fed. Taxes
Interior	15-20 mil.	Fed. Taxes & Fees
State of Georgia	50-75 mil.	State Taxes & Fees
Local Governments (WS)	200-250 mil.	Revenues, Bonds and Loans#
Local Governments (WQ)	60-220 mil.	Taxes, Surcharges Bonds, Loans@
Public Utilities (Power)	20-40 mil.	Revenues, Bonds, Equities
Farmers (Irrigation)	30-50 mil.	Revenues, loans
Industry Self-Services	? - ?	
Personal and Other Water Services	? - ?	
Wild Guess Sum	637-882 mil.	

Notes: *Includes loans. #Does not include Federal loans, grants to avoid double counting. Annual operating expenses probably range from $15-20 mil. for water supply plants. In a selected sample of 8 small systems with good records in 1975; construction costs averaged $5.2 mil., annual OM&R was $1.8 mil. and revenues were $2.6 mil., leaving about $0.7 mil. for amortization, debt service, etc. For water supply only $793,000 or 15% of the funds for construction came from Federal sources for this sample. However, for the state as large as 18% of construction funds came from Federal sources. (See R. M. North Financing and Cost Sharing Municipal Water Supply Systems ERC 06-77. Institute of Natural Resources, University of Georgia. June 1977.) @ Does not include Federal or State loans and grants.

Table 2. Federal Budget Outlays for Natural Resources and Environment.

Function	1974	1975	1976	TQ[1]	1977	1978	1979	1980	1981	1982	1983*	1984*	1985*	1986*
Water resources	2.2	2.6	2.8	0.8	3.2	3.5	3.9	4.3	4.2	4.0	4.0	3.3	3.5	3.6
Conservation & land management	0.7	1.3	1.2	0.5	1.3	2.0	1.9	2.3	2.6	2.7	2.7	2.2	2.1	2.1
Recreational resources	0.7	0.8	0.9	0.3	1.0	1.4	1.5	1.7	1.6	1.5	1.7	1.5	1.4	1.3
Pollution control & abatement	2.0	2.5	3.1	1.1	4.3	4.0	4.7	5.5	5.2	5.0	4.3	4.1	4.0	3.8
Other natural resources	0.7	0.8	0.9	0.2	1.0	1.2	1.3	1.4	1.5	1.5	1.6	1.4	1.4	1.4
Gross outlays	6.3	8.0	8.9	2.9	10.8	12.1	13.3	15.2	15.1	14.7	14.3	12.5	12.4	12.2
Less receipts	-0.7	-0.7	-0.8	-0.3	-0.8	-1.1	-1.2	-1.4	-1.6	-1.9	-2.1	-2.6	-3.1	-3.5
Net outlays	5.6	7.3	8.1	2.6	10.0	11.0	12.1	13.8	13.5	12.8	12.2	9.9	9.3	8.7
Water transportation#	1.4	1.5	1.6	0.4	1.7	1.9	2.0	2.2	2.4	2.7	3.1	3.0	3.1	3.2

Source: The U.S. Budget in Brief Fiscal Year 1984. Office of Management and Budget. Washington, 1983. p. 73.
*Estimate. #Included in Transportation Budget.

Current Federal Initiatives

The Federal establishment is actively (more or less) pursuing several lines of discussion and proposals that will affect State and local interests in water resources. Some of these include:

(1) The Cabinet Council on Natural Resources (and Congressional) proposals to increase non-federal repayments on vendible water resource services (power and water supply) to 100 plus percent of cost with substantial hikes in the level of cost recovery for the less vendible services such as fish and wildlife enhancement;

(2) Administration efforts to increase front end financial contributions from local sponsors without sharing any of the revenues;

(3) Congressional efforts to change the funding system and priorities. These proposals range from setting up block grants to States, to putting the Corps into the water supply lending business, to insuring state and local borrowings for water projects, to substantial increases in some user fees such as navigation, to increasing Federal regulatory control over groundwater aquifers, to setting up a limited-function national water bank to finance State and local water projects. No one knows the likely outcomes of these proposals but their very existence tells us that Federal financing of water resources is in a state of turmoil sufficient to induce adverse effects on the water industry. The states must take a more active role in defining their needs and in setting up mechanisms to construct, operate and expand their water resource facilities.

Emerging State Roles

Most states have already moved away from the long discredited Federal style of laundry list (Section 308 type) water resources planning toward such ideas as management strategies, issue planning and administrative allocation of water resources. Most of these approaches recognize the nature of the hydrologic conditions such as the interfaces of quality and quantity as well as ground waters and surface waters in their operations. Georgia has already moved to the forefront in adopting a management strategy approach to developing and managing its waters.

If we wish to stay in the forefront, we need to consider the adoption of mechanisms to promote the financing of our water needs as Federal largesse declines. Some ideas that should be debated include:

(1) A state revolving fund for grants or loans to public and private projects that meet water supply, waste treatment, conservation and other needs;

(2) An institutional system to seek greater financial integrity of the State's water industry by matching revenue services (power, water supply) with public services (flood control, water quality) either statewide or by river basin. A large part of this effort should be devoted to insuring that revenues produced from existing Federal projects flow back to the State;

(3) An improved statewide inventory of program, project and facility needs, along with their costs and revenues. Such studies may be useful in generating more funds for both current and developing economic conditions.

Fortunately we have a great deal of momentum gathered over the past 10-12 years toward insuring that water resources do not become a limiting factor to our State's economic growth and environmental well-being. We have developed this momentum while doing an outstanding job, using a regulatory approach (e.g., wastewater, groundwater, surface water permits). Since the State, through EPD primarily, has done so well in establishing a management strategy from a regulatory approach, we should find it easy to move gradually into a mode of more aggressive state development of our waters by providing mechanisms or enabling authorities to capitalize more water projects at the State and local levels. We should all benefit if we don't wait too long.

WETLANDS AS VITAL COMPONENTS OF THE NATION'S WATER RESOURCES

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ABSTRACT

In general, large coastal wetlands are considered to be integral parts of estuaries and rivers and, therefore, receive the same measure of legal protection accorded the navigable waters public domain. In contrast, many interior wetlands have historically been considered private property real estate, subject to unrestricted conversion for agricultural or other development, often with the aid of federal "reclamation" pork-barrel money. The Corps of Engineers 404 permitting program often is the only barrier to wholesale conversion of some of the most biologically productive habitats such as riparian, floodplain and bottomland hardwood vegetation. In my opinion, recent wetland research adequately supports the contention that all wetlands are integral and valuable parts of the nation's water resources and should accordingly be valued and protected in the same manner as are rivers, lakes and estuaries to which wetlands are coupled. Evidence for this coupling is present in the following categories: nursery grounds for fish and wildlife, relation of productivity to water flow regimes, and waste assimilation capacity.

Wetlands are not isolated habitats, as many people seem to regard them. Rather, wetlands are extensions of estuaries, rivers and lakes, and, therefore, are vital components of the nation's water resources. Accordingly, wetlands that are closely coupled with water bodies should be considered a part of the public domain to be valued and legally protected just as are navigable and other large bodies of water.

In recent years large coastal wetlands have received a measure of legal protection at the state level. In 1968, for example, Georgia passed a coastal Marshland Protection Act which requires approval by a marshland commission for alterations or developments that would affect the structure and function of the extensive salt and brackish marshes that lie between the barrier islands and the mainland. Most coastal states have passed similar laws. In contrast, interior wetlands currently receive very little protection unless set aside as parks or wildlife refuges. Interior wetlands not only tend to be treated as private property real estate, to be developed without restriction, but conversion to agricultural, urban-industrial or other uses has often been subsidized by federal "pork barrel" reclamation projects. The Corps of Engineers 404 permitting program is often the only barrier to wholesale conversion of some of the most biologically productive habitats, such as bottomland hardwoods. A difficulty in administering this program is deciding where to draw the line between bottomland and upland since some parts of floodplains are flooded only at irregular intervals.

The southeast is rich in wetlands, as shown in Figure 1, especially estuarine and riverine types. According to a USDI survey, some 50% of Florida and 33% of Louisiana was wetland in the 1950's. The percentage for Georgia was 16%, which is about the average for the southeast as a whole. Current inventories now underway by the Fish and Wildlife Service indicate that the area in wetlands is rapidly being reduced by diking and drainage projects. Both federal and state governments are currently in conflict within themselves; some bureaus or departments are actively working to preserve wetlands while others are actively promoting their destruction through allocation of taxpayers money to reclamation projects.

The desirability of preserving wetlands has generally been argued on the basis of their value for fish and wildlife and for their capacity for waste assimilation

WETLANDS OF UNITED STATES (G. B. HUNT, 1967)

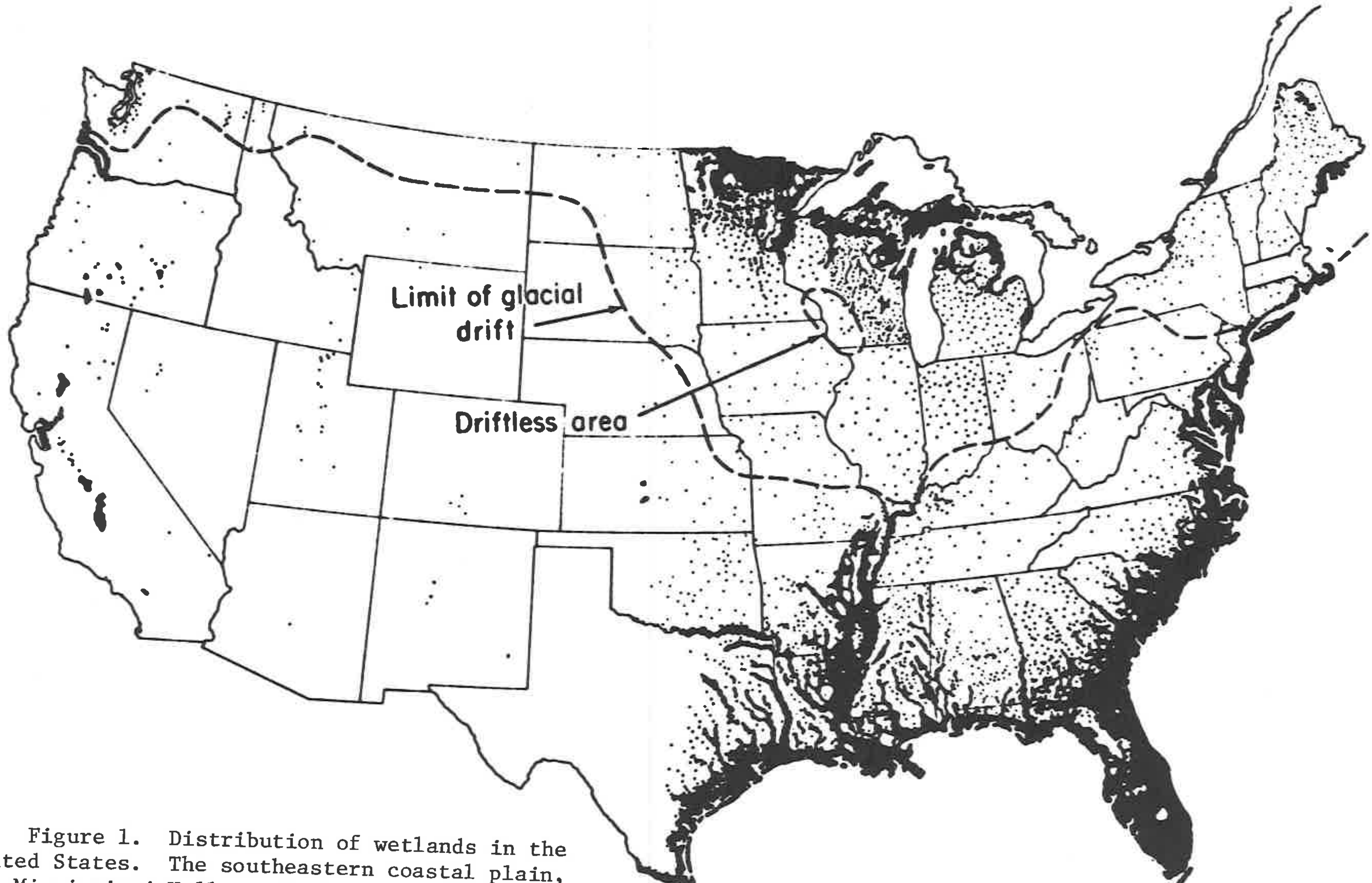

Figure 1. Distribution of wetlands in the United States. The southeastern coastal plain, the Mississippi Valley and the north central glaciated regions have the largest areas of wetlands.

and water conservation. These and other values can be readily documented (see symposium volume edited by Gleeson, Clark and Clark, 1979), but I believe that the best overall argument for wetland protection is that they are linked with groundwater, rivers, estuaries and lakes, all of which are vital components of the earth's life support system. Without water there can be no economy, and indeed no life.

The fact that the productivity and the biota of wetlands are more directly related to the nature of water exchanges with adjacent large water bodies than to soil or other terrestrial conditions provides a strong argument for considering wetlands as a part of, not apart from, the nation's water resources, and hence to have a greater public than private value. I shall cite four examples to document this close coupling of wetlands and navigable waters. Conner and Day (1974) found that Louisiana swamp forests, seasonally flooded from large rivers, are much more productive than dry land forests. Likewise, a 1967 study by the University of Florida Center for Wetlands reports that seasonal flooding or flowing water increases productivity of cypress stands several-fold, as compared to stands in and around stagnant ponds. A number of studies have demonstrated that productivity of coastal marshes is proportional to the frequency of tidal flooding (Steever et al. 1976). In a recent study of marshes on the lower Savannah River, we found that undiked tidal freshwater marshes produced 31% more dry matter than diked marshes that no longer received the tidal subsidy (Odum et al. 1983). In this paper we also discussed the feasibility of using such tidal marshes for tertiary treatment of degradable wastes.

Figure 2 summarizes still another study that demonstrates the close relationship between water flow and productivity. As shown, the best tree growth in bottomland hardwoods occurs where flooding is moderate and seasonal; the poorest growth occurs under conditions of continuous flooding or no flooding. In gum-cypress stands where water roots that are especially adapted to saturated soils develop, extensive or continuous flooding is less of a stress.

In summary, the closer the functional coupling with open water bodies, the greater the influence on productivity. Also, the fact that wetlands provide key nursery grounds for so many species of fish, shellfish and waterfowl is an additional indication of the close coupling of waterbodies and wetlands. Best of all, wetlands provide a protective buffer between land and water, reducing storm water damage to the land on the one hand and soil and other pollution to the water on the other hand. This function alone is enough to justify preservation.

When it comes to suggesting means to preserve wetlands, I tend to think in terms of the stick and carrot analogy. As of 1983, it seems to me that additional regulations (i.e., the "stick") may be less effective in preserving wetlands as compared to incentive approaches (i.e., the "carrot"). At least, the time has come to try to coordinate the two approaches. As already suggested, conversion of wetlands to agricultural and urban uses would be greatly slowed if federal and other governmental subsidies for drainage, diking, and filling were reduced. In truth, a great many projects for converting wetlands to other uses would not have a net economic benefit without government subsidy. A good example from the past is marshy Mattamusket Lake in coastal North Carolina, which was once drained for agriculture by a consortium of Dutch investors, and then restored as a waterfowl refuge when the agricultural project went backrupt. The cost of keeping the water out of the natural depression proved to be very much more costly than the developers had anticipated. It is especially significant that the Dutch who once prided themselves on their skill in diking and converting coastal marshes to agricultural land in their own country (the "polders") are now seriously debating whether to reclaim any more of their country's coastal wetlands. For one thing, it was discovered that the remaining marshes are the main nursery grounds for shrimp populations that are harvested in the North Sea by fishermen of several nations.

Recently, in an interview with the press, a reporter asked me why we should not use wetlands to raise crops if wetlands are as fertile as ecologists claimed.

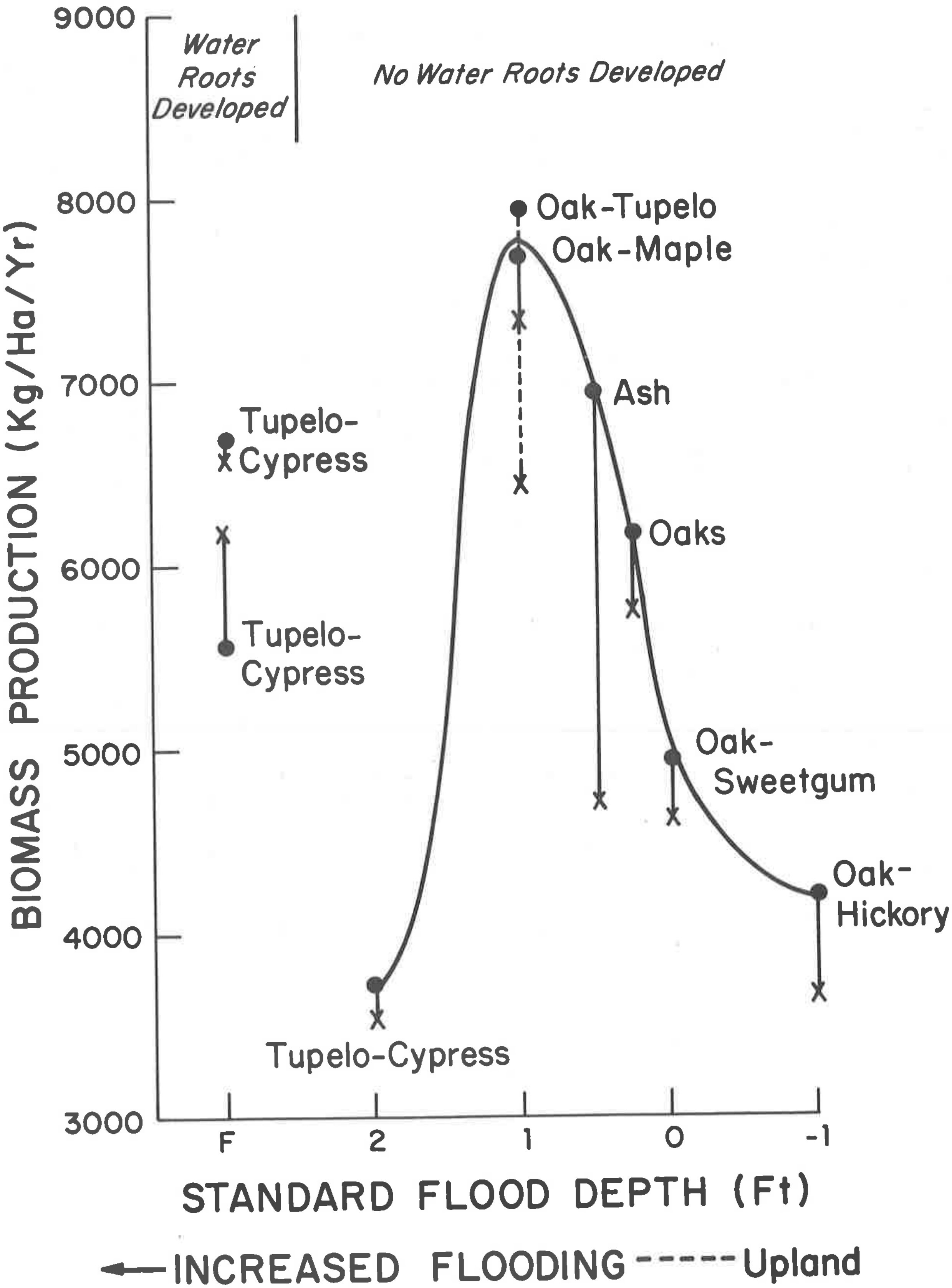

Figure 2. Forest production in a gradient from constant flooding (tupelo-cypress) to no flooding (upland oak-hickory) in the middle Savannah River Valley. (●) peak production potential; (x) mean annual (1970-1979) production. Highest timber growth is in region of moderate seasonal flooding. The oaks in the flood zones are different species (water oak, laurel oak, etc.) than those on the upland (graph based on unpublished data of James Cooley and J. B. Birch, used with permission).

My reply was that the bottom of the Mississippi River is also undoubtedly very fertile but that is no reason why we should divert the river at great cost in order to plant soybeans on the bottom. Again, we come back to the original position; wetlands are a part of rivers and other water systems, and like such resources are best left in a natural state, or managed in such a way as to enhance their natural qualities. Wetlands deserve the same common property protection accorded other parts of the public domain.

Preservation of privately owned wetlands would be greatly accelerated if the Internal Revenue Service would recognize the non-market as well as the market value of these unique and energetic ecosystems. Such recognition would permit a substantial tax deduction to owners, whether individuals or corporations, who wish to donate the property to state, federal, or private conservation agencies for preservation. We have been involved in making dollar evaluations of wetlands based on energy analysis procedures for several private owners and one large corporation who wish to take tax deductions for gifts in situations where market (i.e., real estate) values are very much smaller than non-market values. Despite the logic of using a public value for property that is for public use, the tax courts have yet to approve this method of evaluation. We believe that eventually a precedent will be established as the total long-term value of wetlands and other life-support environments are increasingly recognized.

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COMPARATIVE STUDY OF THE CAUSES AND EFFECTS OF RECENT SOUTHEASTERN DROUGHTS

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ABSTRACT

The effects of the 1980-81 drought in Georgia are compared to a drought in 1954-55 to determine whether the effects were more severe than precipitation amounts alone would have indicated. Local, regional and statewide precipitation data are examined and stream flows and lake levels are compared to statewide average precipitation. The location of high pressure centers in the Gulf of Mexico is also examined to determine whether common circulation patterns can be linked to drought conditions in Georgia. The effect of high pressure in the Gulf on Texas precipitation is also examined. The 1980-81 drought is found to be less severe in precipitation deficit than 1954-55 and the effects on stream flows and lake levels are found to be generally less severe than precipitation alone would have indicated, with the exception of one lake, when compared to 1954-55. A relationship is found between high pressure in the Gulf and lower-than-normal precipitation in the summer in Georgia. Some evidence is found that high pressure in the eastern Gulf may increase precipitation in Texas while high pressure in the western Gulf may decrease it.

INTRODUCTION

Georgia, a state with abundant rainfall and many lakes and rivers, has had little cause for concern about drought. Even in the worst drought year in the past three decades, most of Georgia received more rain than some midwestern agricultural states receive in a normal year.

However, public concern arose during the drought of 1980-81 when Lake Lanier, near Atlanta, fell far below its normal summer level in 1981. In some cases, docks and other recreational facilities were left aground (Holler, 1982) and large expanses of muddy flats and tree stumps were left exposed. This has raised the question of why the drought of 1980-81, which was not as severe in terms of precipitation deficit as the next most severe drought in 1954-55, produced such severe effects.

This study compares the relative effects of the two drought periods and their precipitation deficits and examines some meteorological conditions to determine whether certain circulation patterns can be associated with drought periods in Georgia and Gulf Central states.

In this study the term drought refers only to precipitation deficit rather than such drought effects as low soil moisture. The study concentrates on regional precipitation averages because large scale precipitation patterns determine stream flows and lake levels; however, records from some individual sites are examined.

Precipitation in Georgia is seasonal, with rainy periods in winter and summer, and precipitation levels vary widely from greater than 68 inches in the northeastern mountains to about 40 inches in east central Georgia. The state is divided into nine climatic regions of roughly equal size, with three tiers of three regions. The nine-region data are sometimes averaged to produce data comparable to the state's earlier three-region divisions.

In this study the seasonal precipitation patterns are not considered separately except in examining meteorological conditions associated with summer drought conditions. A reduction in summertime precipitation has popularly been attributed to a change in circulation patterns caused by shifting of the semipermanent high pressure center usually located near Bermuda. This change would not necessarily apply in the same manner to winter precipitation patterns.

The first part of this study examines statewide and regional average precipitation for 1954-55 and 1980-81, as well as some records as far back as 1930, to compare drought effects in the two periods.

The second part examines the effects of the two periods upon certain lake levels and stream flows.

The third part examines meteorological conditions during the two periods in summertime to determine whether shifting of the Bermuda High can be related to decreased precipitation in those months. In addition, the record is examined for 1980 and 1981 to determine whether placement of high pressure centers within the Gulf of Mexico can be related to increased or decreased precipitation in coastal and near-coastal Texas. More detailed results of this study can be found in Paris and Justus (1983).

DATA ANALYSIS

Data maintained by the National Oceanic and Atmospheric Administration are used. The reports include monthly regional average precipitation for 1954-55 and 1978-81 and annual site precipitation for six local recording sites. The six sites are Atlanta, Athens, Columbus, Macon, Savannah and Augusta.

Data for eight climatological regions on and near the coast of Texas for 1980 and 1981 are examined. The locations of Georgia and Texas climatological regions, streamflow gauging stations, and lakes in this study are identified in the full report (Paris and Justus, 1983).

Precipitation and Effects

Averaging regional data for 1954-55 and 1980-81 and finding the accumulated change from normal precipitation (Tables 1 and 2 and Fig. 1) indicates that the earlier drought period was more severe in terms or precipitation deficit than 1980-81. A similar plot for 1978-81 (Fig. 2) indicates that the state actually had two drought periods in that four-year period, with peak deficits centering around the winters of 1978-79 and 1980-81.

Regional differences are significant. In general, the northern part of the state suffered less severe drought in both 1954-55 and 1980-81. Figure 3 shows the differences between the northwestern and southeastern regions. There is a similar difference between the northern and southern thirds of the state in 1954-55, although the northern part of the state appeared to have suffered a more severe drought in 1954-55 than the northwestern region did in 1980-81.

Data from the six cities show similar regional differences. Only Athens appears to have suffered a severe drought in 1980-81 (Table 3), while the other five cities had their most severe drought in the last 52 years in the 1954-55 period. Dividing the ranking for each year into the years on record gives a recurrence interval, which indicates the time between occurences of similar precipitation amounts. By that method, 1954 was a 50-year drought in all but one city, where it was a 17-year drought. Using the driest of 1980 and 1981 shows a 26-year drought in Athens, a 4- to 7-year drought in four cities and about a 2-year drought in Columbus (in effect, no drought at all).

Stream Flow Analysis

Sixteen stream flow gauging stations were chosen from the many that the U.S. Geological Survey keeps records for. The choice was based mainly upon length and continuity of record at the site. Although nearly all large Georgia streams are downstream from dams and thus will be affected in some way by releases, the 16 sites chosen are far enough downstream not to be severely affected by dam releases.

Table 1. Georgia Mean Precipitation for July and August by Climatic Region

	NORTH WEST	NORTH CENT.	NORTH EAST	WEST CENT.	CENT.	EAST CENT.	SOUTH WEST	SOUTH CENT.	SOUTH EAST
JUL	4.76	5.26	5.37	5.56	5.23	4.98	6.16	6.07	7.16
AUG	3.86	3.93	4.32	3.98	4.01	4.43	4.68	5.30	6.39

Texas Mean Precipitation for July and August for Eight Climatic Regions

	L.ROLL PLAINS	NORTH CENT.	EAST TEX.	EDWARDS PLATEAU	SOUTH CENT.	UPPER COAST	SOUTH	LOWER VALLEY
JUL	2.14	2.22	3.42	2.26	2.68	4.70	1.79	1.65
AUG	1.85	1.93	2.91	1.98	2.57	4.48	2.14	2.56

(L.ROLL PLAINS = LOW ROLLING PLAINS)

Table 2. Georgia Mean Precipitation (Inches)

JAN	4.15	JUL	5.62
FEB	4.42	AUG	4.55
MAR	5.57	SEP	4.10
APR	4.26	OCT	2.72
MAY	3.87	NOV	2.91
JUN	4.31	DEC	4.28

Table 3. Ranking of Precipitation in 6 Cities for 52 Years. Lowest = 1.

City	1954	1955	1980	1981
Athens:	1	4	22	2
Atlanta:	1	5	25	10
Augusta:	3	7	12	36
Columbus:	1	11	26	22
Macon:	1	7	12	35
Savannah:	1	10	8	13

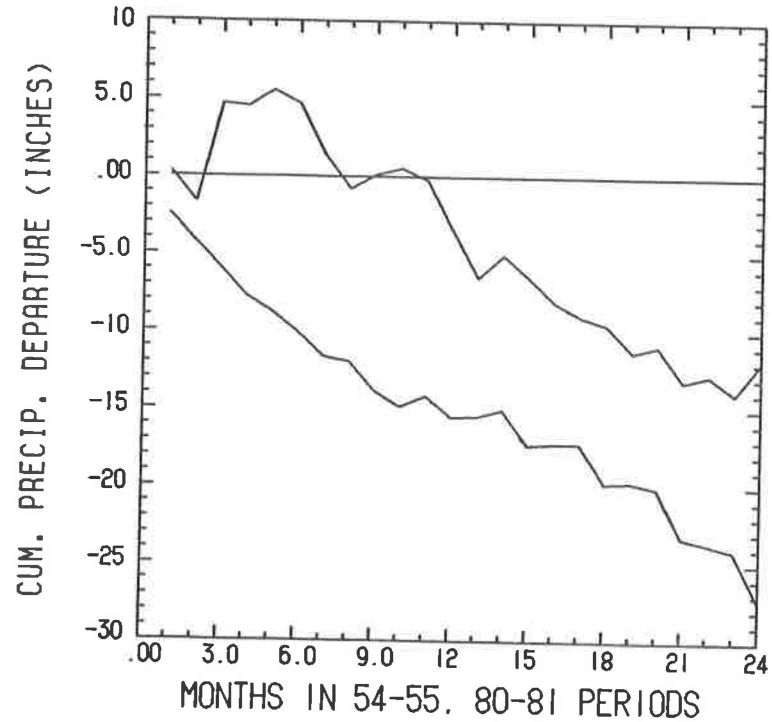


Figure 1. Cumulative departure from statewide monthly mean precipitation in inches for the periods 1954-55 and 1980-81. Lower line is 1954-55.

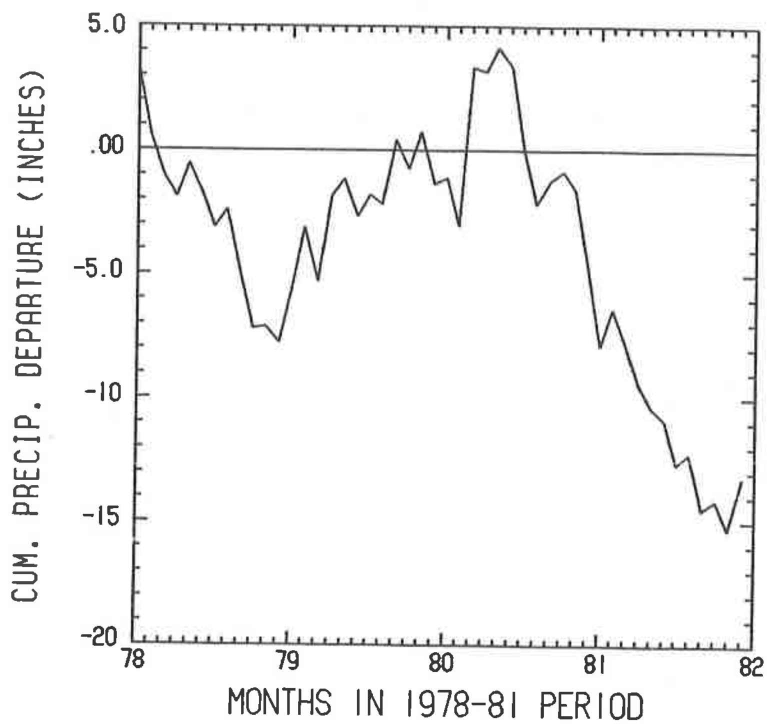


Figure 2. Cumulative departure from statewide monthly mean precipitation in inches for 1978-81.

Also, since release of water from an artificial impoundment is in part a function of water uses and priorities, flow downstream from a dam would be a legitimate measure of water supply and demand.

Of the 16 sites chosen, seven (Ichawaynochaway, Canoochee, Brier, Tobesofkee, Middle Oconee, Toccoa and Chattooga) are relatively short streams. The others (Broad, Ocmulgee at two sites, Oconee, Flint, Ohoopee, Ogeechee, Alapaha and Satilla) are longer. The Geological Survey ranks minimum flows during each water year (April 1 to March 31) for a number of time spans, from one day to 183 days, as well as for the entire year.

Carter (1982) had calculated recurrence intervals for various periods and plotted isopleths across the state. From his figures, the 1980-81 drought is up to a 100-year drought.

However, the 16 streams chosen for this study do not show the 1980-81 drought period to be that severe, and in all but a few cases, the 1954-55 drought was worse.

In the one-day, 183-consecutive-day and one-year minimum stream flows, 1955 is almost uniformly ranked lowest. The 183-day flow in 1982 for the Flint River was the lowest, and the one-day minimum flow in Ichawaynochaway was lowest in 1982. In some cases, the minimum flows for some periods were recorded in years other than 1954-55 and 1980-81.

For the intervals of 3, 7, 14, 30, 60, 90 and 120 days, 1955 is almost uniformly ranked lowest. Ichawaynochaway Creek has 1982 ranked lower than the earlier drought periods for all intervals except 60 and 90 days. In the Flint River, 1982 is ranked lowest for 30, 90 and 120 days.

Most large dams in Georgia have been built for several reasons, including flood control, power generation and navigation. Navigation means both downstream river use and to an increasingly large extent, recreational boating on the lake itself. One study of the effects of the 1980-81 drought on Georgia lakes (Holler, 1982) found that record low levels were experienced in four of eight lakes operated by the U.S. Army Corps of Engineers. Holler says that the 1980-81 drought produced drier conditions than the 1954-55 drought or an earlier drought in 1925-27. However, of the eight lakes Holler examined, only two, Clark Hill and Allatoona, existed as far back as the 1954-55 drought.

Of Georgia's large lakes, only seven have existed since before the 1954-55 period: Allatoona, Blue Ridge, Burton, Clark Hill, Lloyd Shoals, Nottley and Sinclair.

This study examines only year-end lake contents, while Holler considered contents through the year. All of Holler's old and new records were recorded around the year end, so year-end contents should reflect abnormally low contents earlier in the year.

Of the seven lakes considered, only Clark Hill had the lowest level in the 1980-81 drought period. At Lloyd Shoals, Nottley, Sinclair and Allatoona, the lowest year-end levels were recorded in years other than the two drought periods. In the case of Clark Hill, the 1954-55 year-end levels were only slightly higher than in 1980 and 1981.

The lake levels in the 1980-81 drought period may reflect decisions not to allow too low a level. According to Holler, the operators of Lake Lanier made a decision to conserve water and prevent the lake from falling an estimated 2.6 feet further than it actually did in the summer of 1981.

Circulation Patterns

A common perception is that movement of the semipermanent high pressure area known as the Bermuda High from its usual summertime position in the Atlantic to other locations is responsible for dry conditions in the Southeast (e.g., Cody, 1982). There are good reasons for assuming such a relationship. When the Bermuda High is in its normal position near Bermuda, its clockwise circulation would tend to bring moist air into the Southeast, providing the moisture necessary for the normal summertime precipitation processes. If high pressure were located in the Gulf of Mexico it would tend to bring drier continental air into the Southeast.

In this study, the Bermuda High, or as it will be known in its Gulf of Mexico location, the Gulf High, is examined only for July and August. Daily weather maps published by the National Oceanic and Atmospheric Administration for 7:00 a.m. EST were examined for 1954-55 and 1968-81. The location of high pressure centers in the Gulf of Mexico and Gulf Central U.S. was noted and tabulated for each month. An index, which is simply the number of days with a Gulf High divided by 31, the number of days in July and August, is compared to precipitation normalized by the maximum in the period. If high pressure in the Gulf is a cause of lower-than-normal precipitation, then some relationship should be expected.

Figure 4 is a representative example of a plot for the northwest region of Georgia. Other regions produce similar plots. Although there is little indication of a linear relationship, the points are almost all in the upper half of the plot above the diagonal. This indicates that lower-than-normal precipitation is generally experienced when the Gulf High occurs frequently in a month, but the absence of a Gulf High does not necessarily mean the possibility is eliminated. Low precipitation occurs at times when the Gulf High does not exist.

An attempt is also made to relate the location of a Gulf High within the Gulf to lower- or higher-than-normal precipitation in parts of coastal or near-coastal Texas. The Gulf is divided roughly at the Mississippi River and the position of high pressure in the eastern or western half is noted. High pressure in the eastern Gulf would tend to bring moist Gulf air into coastal Texas while high pressure in the western Gulf would bring in drier continental air.

When high pressure was in the Gulf in July and August, it was in an eastern position 16% of the time in July 1980, 0% in August 1980, 33.3% in July 1981 and 60% in August 1981. Figures 6a and 6b show normalized departure from monthly mean precipitation for seven regions in Texas plotted with departure from mean Gulf High index. Figure 6a shows the expected similar trends in rain and Gulf High index departure from the mean while Figure 6b shows no such similarity. Since a low Gulf High index is otherwise associated with low rain, the eastern position of the high in July and August 1981 might be at least partially responsible for wetter conditions in Texas. However, more data would have to be examined to draw stronger conclusions.

Comparison of Drought Effects

In order to determine whether the 1980-81 drought produced effects more severe than precipitation deficit alone would have indicated, the average annual stream flows of the 16 streams examined are averaged and compared to statewide average precipitation. Because stream flow figures use water years, monthly statewide average precipitation is used to give precipitation for water years. The water year is dated from the year in which it ends; thus water year 1980 began in April 1979 and ended in March 1980.

Using 32 years of data gives a near linear fit (Fig. 5). Comparing water years 1955 and 1981 indicates higher stream flows in 1981 than might have been expected. The 1955 data indicate a higher stream flow than the linear regression, but still closer to it than 1981.

When similar comparisons are done for year-end lake levels, there is not as good a relationship. However, it appears that Clark Hill had lower levels in 1980 and 1981 than precipitation alone would have indicated.

Clark Hill Dam is on the Savannah River, which is used for commercial navigation below Augusta. The operator of the dam, the U.S. Army Corps of Engineers, has in the past tried to maintain a certain channel depth. It is possible that management of the lake resulted in lower levels in order to maintain a greater flow downstream.

In other lakes, the levels in 1980 and 1981 do not appear to be lower than precipitation amounts alone would have indicated, when compared to the effects of

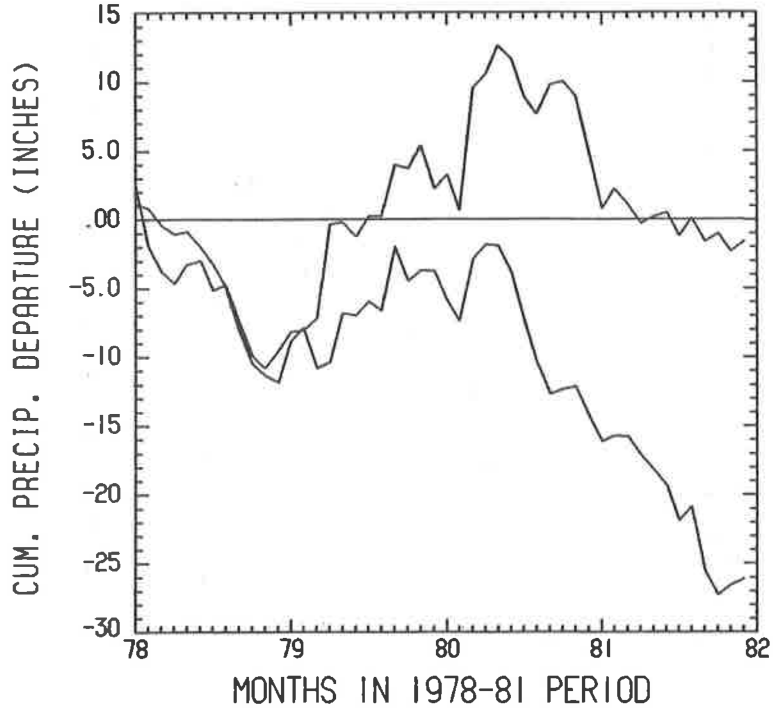


Figure 3. Cumulative departure from regional monthly mean precipitation in inches for the Northwest and Southeast regions for 1978-81. Lower line is Southeast region.

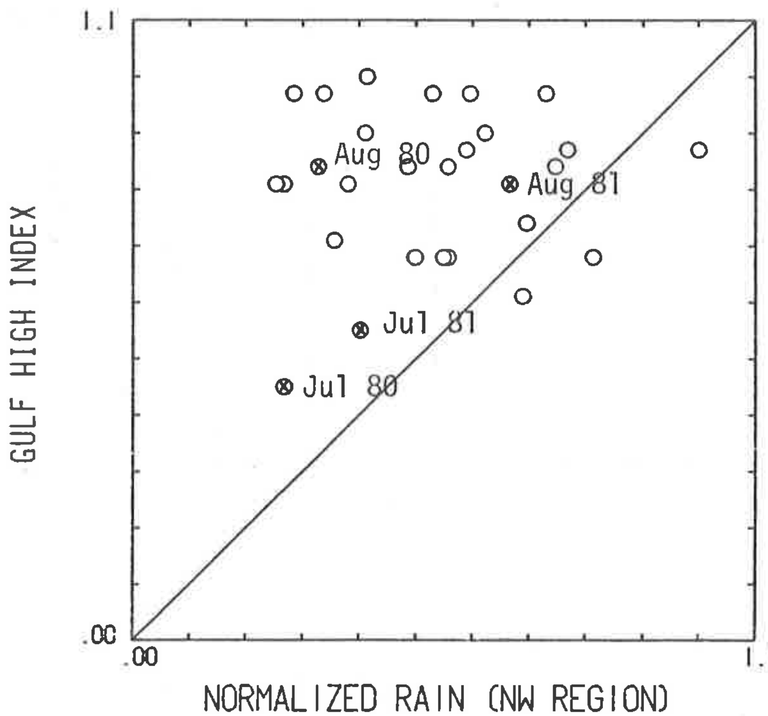


Figure 4. Gulf High Index (explained in text) versus normalized precipitation for July and August 1968-81 in Northwest region. Note preponderance of points above diagonal.

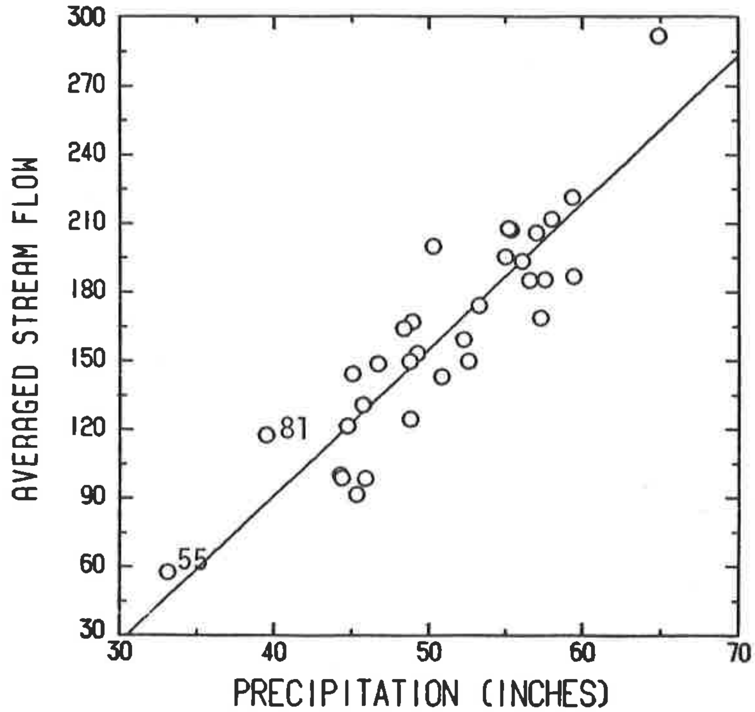
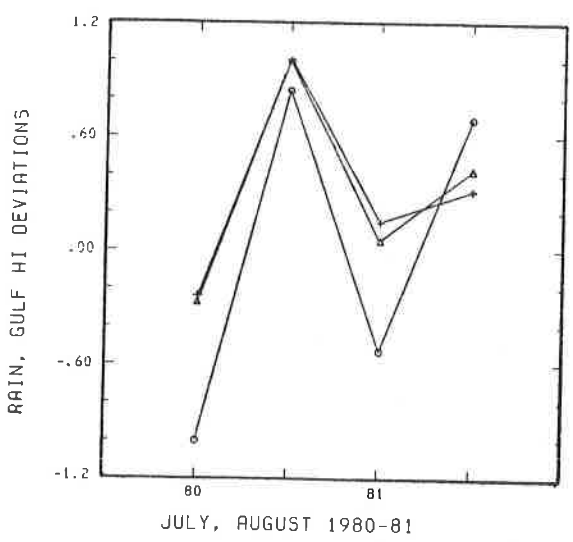
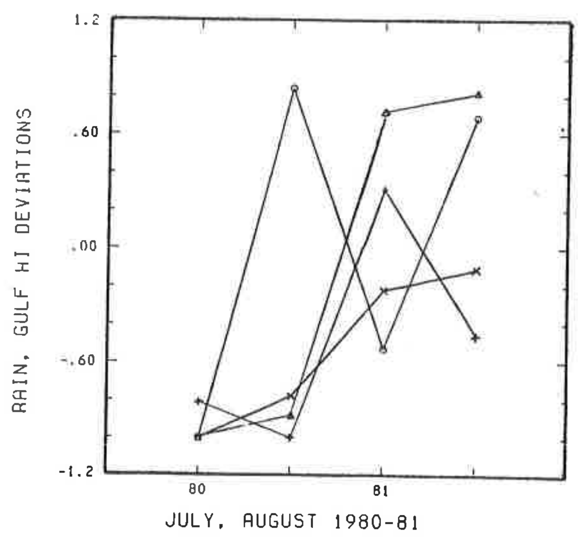


Figure 5. Averaged annual flow for 16 streams versus statewide annual precipitation for water years 1950-81, with linear regression.





Figures 6a, 6b. Gulf High Index departure from the mean (circles) and precipitation departure from monthly mean, normalized by maximum in the period for July and August 1980-81. In 6a, +'s are Lower Valley, triangles are Southern regions. In 6b, x's are North Central, triangles are Upper Coast, and +'s are East Texas regions of Texas.

1954 and 1955. Since at least one lake, Lake Lanier, was managed in such a way as to prevent extremely low levels, it is possible that these lakes, too, were intentionally kept at higher levels than if normal drawdown procedures had been followed.

CONCLUSIONS

Conclusions about the relative severity of the 1980-81 and 1954-55 droughts in Georgia are complicated by wide variability across the state and by the variation in effects which are caused by human actions rather than simply precipitation amounts. However, some generalizations can be made about large-scale effects. The data leave little doubt that the 1954-55 drought was more severe in precipitation deficit and that in general streams flowed lower and lakes were lower.

From this it would seem that if certain locations experienced water shortages during the 1980-81 drought, a likely explanation is that water usage has increased enough since 1954-55 that less severe droughts can make water supplies marginal.

There does appear to be a relationship between movement of the semipermanent high pressure center from Bermuda to the Gulf of Mexico and lower-than-normal summer precipitation in Georgia. However, reduced precipitation also occurs at times when there is no identifiable high pressure center in the Gulf of Mexico.

There is some indication that the position of high pressure within the eastern Gulf may be associated with increased precipitation in coastal Texas, while high pressure in the western Gulf may be associated with decreased precipitation in coastal Texas. However, a firm conclusion would require examination of more data.

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GROUND-WATER CONDITIONS IN THE TERTIARY AQUIFER SYSTEMS NEAR CHARLESTON, SOUTH CAROLINA

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ABSTRACT

The Paleocene-Eocene Black Mingo Formation, the Eocene Santee Limestone, and the Eocene-Oligocene Cooper Formation are the principle geohydrologic units in Charleston, Berkeley, and Dorchester Counties, South Carolina. The Cooper Formation is an impure, sandy limestone that locally yields small quantities of water but which more commonly acts as a confining bed. Consequently, most water is obtained from the underlying Santee Limestone and from sand within the upper 100 feet of the Black Mingo Formation.

The configuration of the potentiometric surface of the Santee Limestone is influenced by topographic features, areal differences in transmissivity, ground-water withdrawals, and the presence of faults. Ground-water movement generally is toward the southeast, and water elevations range from 100 feet, m.s.l., in western Berkeley County to -30 feet, m.s.l., at Charleston. A potentiometric trough identified at Charleston may be the result of ground-water withdrawals and low transmissivities combined with natural pre-development discharge through offshore springs.

Water quality ranges from a calcium bicarbonate type in the Santee Limestone to a sodium bicarbonate type in the Black Mingo. Water in both aquifer systems grades into the sodium chloride type or sodium chloride-bicarbonate type in areas near the coast. Open-hole wells that penetrate both systems produce water with quality typical of the deeper lying Black Mingo; and where the Black Mingo contains brackish water, overlying fresh-water-bearing aquifers may be contaminated as water flows up the well bore. Saltwater contamination has also occurred in the Charleston area, where ground-water withdrawals have caused saltwater intrusion.

INTRODUCTION

Charleston, Berkeley, and Dorchester Counties encompass an area of approximately 2,500 square miles in the central portion of South Carolina's Lower Coastal Plain Province (figure 1). During 1980, industry, agriculture, water utilities, and private home owners in the area used an average of 99 mgd (million gallons of water per day). About 20 percent of that water, or 19.1 mgd, was supplied by wells drawing ground water from the Middendorf, Black Creek, Peedee, Black Mingo, Santee, and Shallow Aquifer systems. The Middendorf, Black Creek, and Peedee Systems, of late Cretaceous age, occur at depths greater than 500 ft (feet) and, due to well-construction costs and water quality, are penetrated by fewer than 25 wells. Slightly more than half the ground water (about 11 mgd) is obtained from units of Tertiary age which include the Paleocene-Eocene Black Mingo Formation, the Eocene Santee Limestone, and the Eocene-Oligocene Cooper Formation.

GEOLOGIC SETTING

The Tertiary formations consist of fine-to medium-grained sand, dark organic clay, and both pure and impure limestone deposited in estuarine and shallow

THE STUDY AREA: BERKELEY, CHARLESTON & DORCHESTER COUNTIES, SOUTH CAROLINA

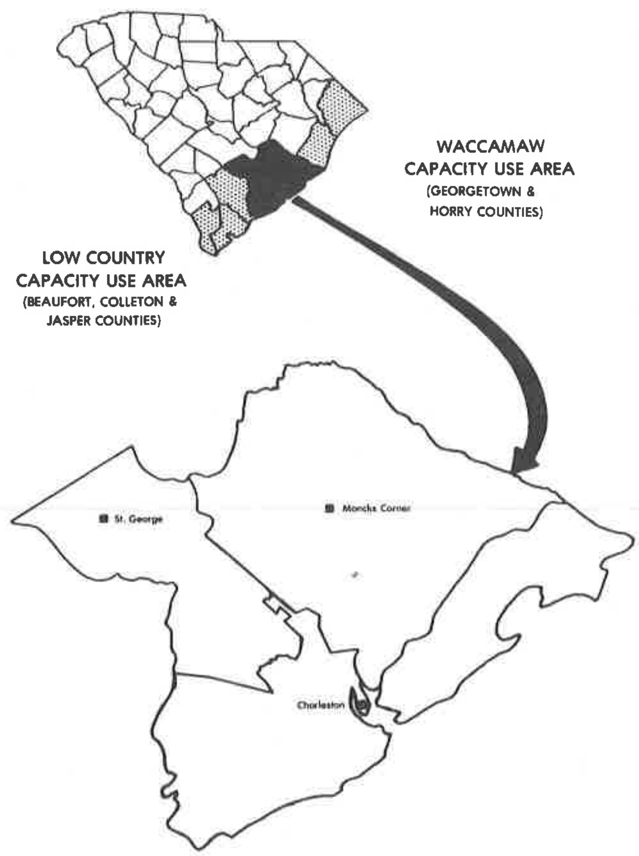


Figure 1.

marine environments. Their lithologies and geophysical characteristics are illustrated in the stratigraphic column in figure 2. All three formations crop out within the confines of the study area, but for the most part they are covered by 20 to 60 ft of Miocene to Pleistocene sand, clay, and shell.

Black Mingo: The Black Mingo is a heterogeneous, fossiliferous sequence of white to pale-gray limestones, green to gray argillaceous sand, carbonate- and silica-cemented sandstone, and dark-gray to black clay. In the outcrop areas of northern Berkeley County, the lower part of the formation is predominantly shale and clay, whereas the upper part consists chiefly of sand and limestone and is the principal water-bearing segment.

The downdip section in central Dorchester County is composed of a yellowish-gray to greenish-gray, somewhat calcareous or sandy clay in the lower part and gray-green silty clay and muddy sand, interbedded sand and clay, and quartzose shelly limestone in the upper part (Gohn, et. al., 1970).

The formation crops out north of Moncks Corner in Berkeley County and throughout much of adjacent Georgetown and Williamsburg Counties. Its surface dips south-southwest beneath the Santee Limestone at a rate of about 11 ft/mile, lying at sea level in the vicinity of Bonneau, Berkeley County, and dipping to more than -600 ft m.s.l. in southern Charleston County. The formation thickens from approximately 400 ft at Moncks Corner to 650 ft at Seabrook Island.

Santee Limestone: The Santee Limestone is a creamy white to gray, fossiliferous and slightly glauconitic calcilutite to calcirudite. In the outcrop areas it usually is greater than 80 percent calcium carbonate, and it locally contains 90 to 96 percent calcium carbonate (Heron, 1962). The base of the limestone becomes increasingly glauconitic and arenaceous at the northern edge of the outcrop where it intertongues with underlying limestone of the Wharley Hill Formation (Poozer, 1965). Downdip, the calcium carbonate content decreases to between 40 and 80 percent, and quartz sand, glauconite, and phosphate percentages increase (Gohn, et. al., 1977).

The Santee Limestone underlies all of the study area except the northernmost corner of Berkeley County, and it subcrops in a belt extending westward from Charleston County into southern Orangeburg County. The surface of the Santee dips southward at an average rate of 8.3 ft/mile and thickens from a few feet at the north edge to more than 300 ft at Edisto Island.

Cooper Formation: The Cooper Formation is a sandy, phosphatic limestone that is rather uniform in color and texture and has no obvious signs of bedding. Malde (1959) described surface exposures as 25-75 percent carbonate, 10-45 percent sand, 2-3 percent clay, and 5-20 percent phosphate. Descriptions of cores taken near Summerville indicate somewhat greater carbonate and clay content; 60-75 percent and 10-30 percent, respectively (Gohn, et. al., 1977). The carbonate compound consists principally of foraminiferal shell, and color typically ranges from pale green or yellowish gray to olive brown.

The Cooper underlies most of the study area and occurs near land surface in a 12-to 20-mile wide east-west trending belt through upper Charleston, Berkeley, and Dorchester Counties. As its thickness increases southward from a few feet at Moncks Corner to about 300 ft in southern Charleston County, its surface dips south-southeast at about 3 ft/mile.

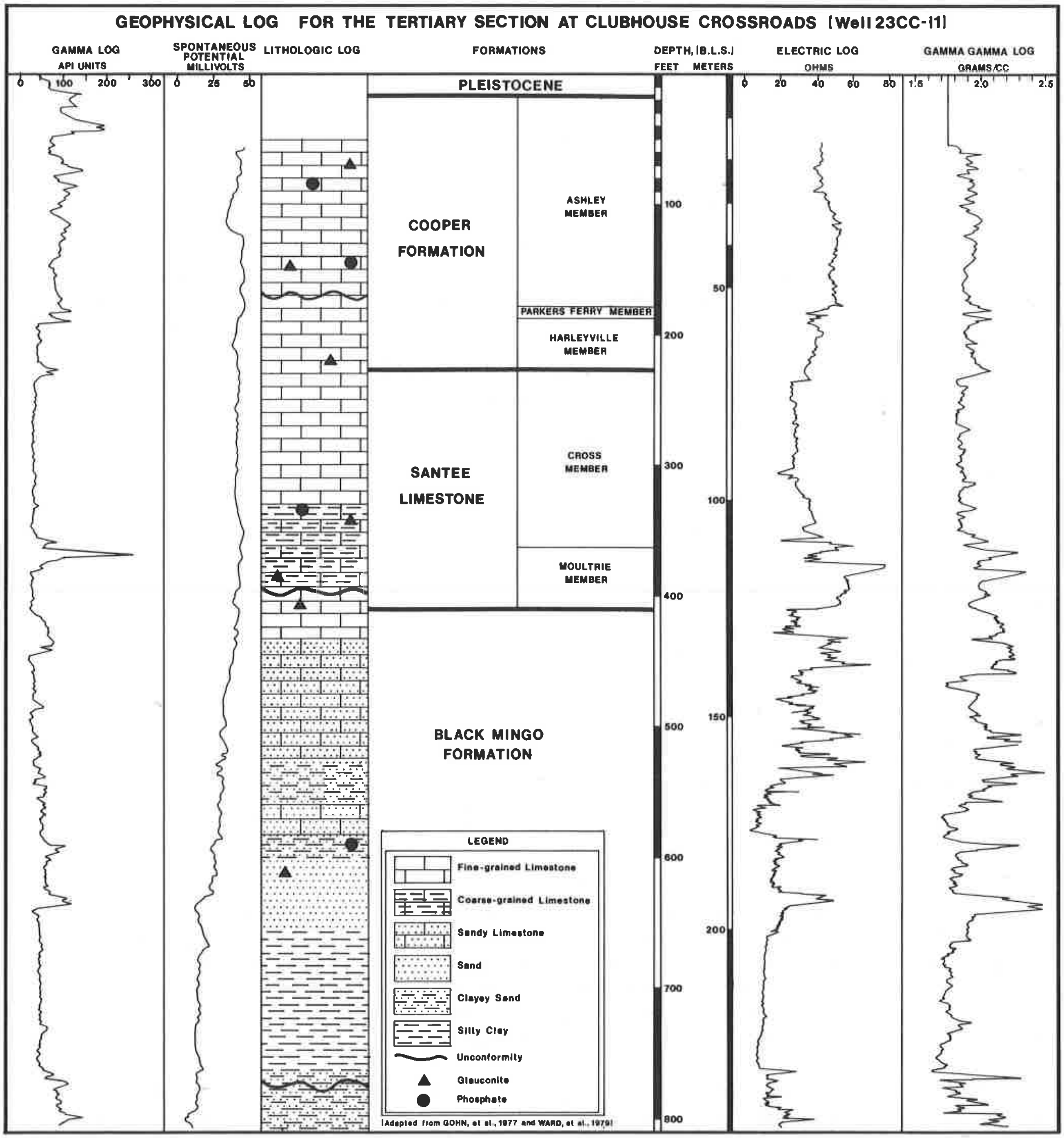


Figure 2. Stratigraphic section for the Tertiary units at Clubhouse Crossroads, Dorchester County.

WELL YIELDS

The Black Mingo is the most productive of the Tertiary units. Its upper 100 feet consist of fine-to medium-grained sand and silty sand, interbedded with clay, dark-colored limestone, and carbonate-cemented sandstone. The sand beds predominate and form the principal water-bearing units.

In northern Berkeley County, wells open to the Black Mingo are reported to produce up to 320 gpm (gallons per minute) with specific capacities of 6 gpm/ft or less. Yields of up to 600 gpm with specific capacities of 8 to 14 gpm/ft are reported in southern Berkeley County and in western Dorchester County. In general, it is possible to obtain 300 to 500 gpm in most parts of the study area, so long as the amount of drawdown and the quality of the water need not be considered.

The yields obtained from the overlying Santee Limestone are usually modest and vary greatly from one area to another. Wells in the outcrop area and in central Charleston County produce up to 300 gpm with specific capacities on the order of 4 gpm/ft.

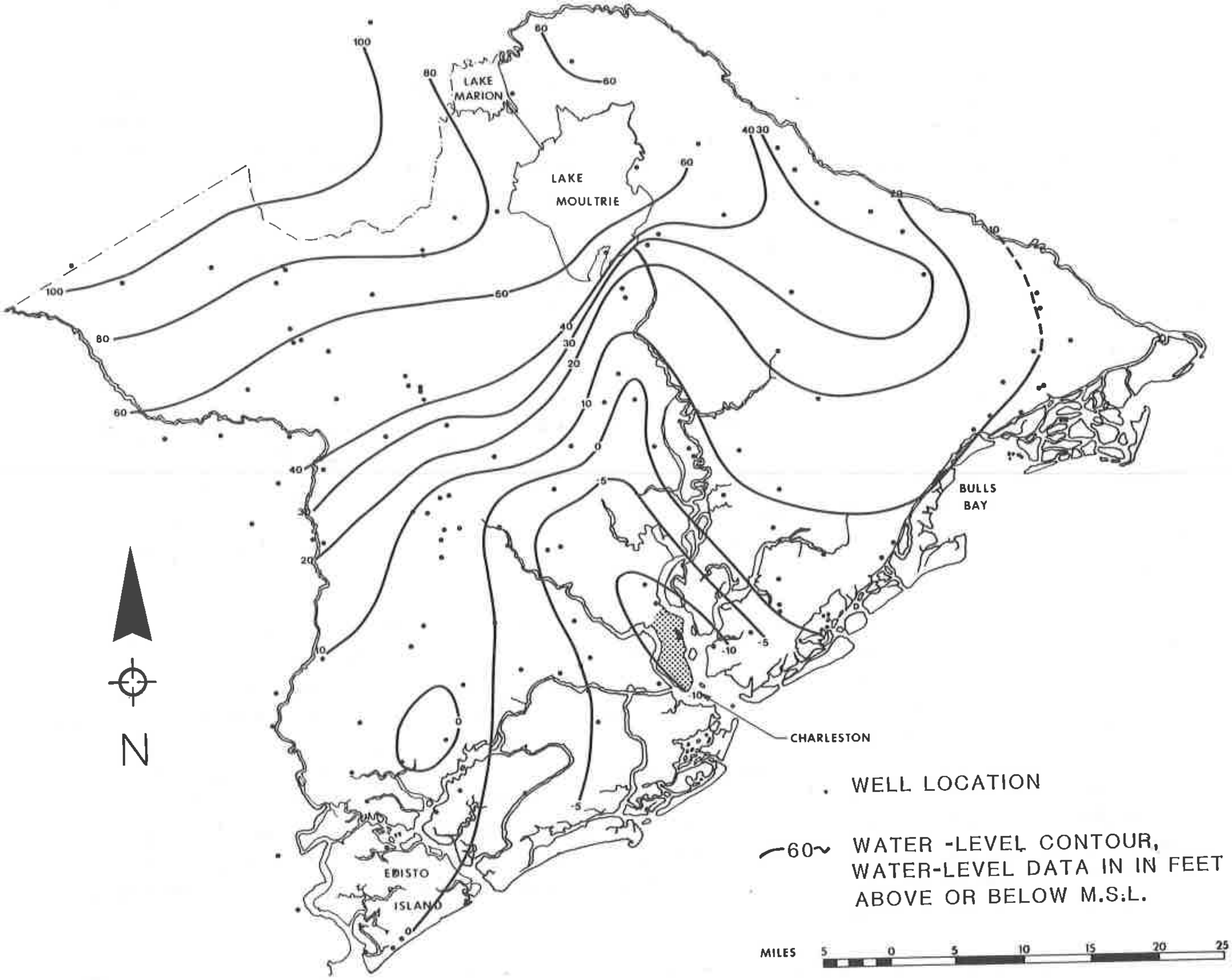
The greatest yields from wells open to the Santee Limestone are obtained in western Dorchester County where individual wells produce up to 500 gpm with specific capacities of 8 to 13 gpm/ft. By contrast, wells in central Dorchester County commonly produce less than 50 gpm with specific capacities of less than 1 gpm/ft, and "dry holes" are reported locally. These extremely poor yields are associated with the presence of the Cooke fault (Gohn, 1983) just southeast of Summerville; the basin that occurs on the northwest side of the fault is filled with impure, sandy limestone in which permeability development is poor.

The Cooper Formation is significant as a hydrologic unit mainly by virtue of its impermeability. In most localities, its sandy, finely granular limestone produces little or no water but, instead, acts as a confining unit. Only a few feet of the formation need be present to effectively retard the vertical movement of ground water. Except for a 20-to 40-ft thick bryozoan limestone occurring in a small area of southern Dorchester County, and brackish water-bearing zones reported in southern Charleston County, the Cooper Formation is not known to yield significant amounts of water.

WATER LEVELS

Water levels in the Santee Limestone range from about 100 ft above m.s.l. in western Dorchester County to more than 10 ft below sea level at Charleston (figure 3.) Ground-water movement is generally southward, away from the major recharge areas of Orangeburg, Clarendon, and Berkeley Counties. Local variations in transmissivity, topographic features, and pumping effect the hydraulic gradient and the direction of flow.

The hydraulic gradient averages about 2 ft per mile, but the presence of relatively low transmissivity zones in central Dorchester and Berkeley Counties causes steeper gradients in the northern half of the study area (3.0 to 3.5 ft/mi) than in the southern half (0.6 to 1.5 ft/mi). Some recharge takes place in the subcrop areas of northeastern Berkeley County, and ground water flows toward the southeast and south under a gradient of about 1 ft/mi; but the gradient steepens and flow becomes more southwesterly as relatively lower transmissivities are encountered.



WATER LEVELS, SANTEE LIMESTONE, NOVEMBER, 1982

Figure 3.

Topographic features such as Lake Moultrie and the Santee River exert an influence on the direction of flow and on water-level fluctuations. Lake Moultrie serves as a source of recharge and influences water levels through the effects of loading. The Santee River Valley acts as a line sink for discharge, and ground water in the vicinity of the valley moves northeastwardly where it discharges through small sinks and springs. River levels exert a short-term influence on local ground-water levels by means of loading and bank storage effects (figure 4).

Ground-water withdrawals have also affected water levels and movement. The concentration of public-supply, industrial, and domestic wells along a corridor paralleling the Cooper River from Charleston to Goose Creek and Moncks Corner has resulted in the formation of a potentiometric trough that extends northwest from Charleston toward Summerville and Goose Creek, and northward between Goose Creek and Moncks Corner. Water levels are declining throughout the area, except in the vicinity of Charleston, and where transmissivities are very low the declines can be extreme (figure 5). By contrast, water levels at Charleston have been recovering as industrial users have switched to surface water and as wells have been abandoned because of saltwater contamination (figure 4). The trough, which still exists at Charleston, appears to be the result of pre-development discharge through offshore springs (no longer in evidence) associated with the St. Helena Banks fault combined with low aquifer transmissivities and modern ground-water development.

WATER QUALITY

The chemical quality of ground water from the Black Mingo Formation and Santee Limestone is generally good but varies both with locality and depth. Chemical quality is best in the upgradient areas of Berkeley and Dorchester Counties and deteriorates down gradient, resulting in water that is only marginally potable or is nonpotable throughout much of coastal Charleston County.

Water from the Black Mingo Formation is typically an alkaline sodium bicarbonate type characterized by high concentrations of fluoride and dissolved silica and low concentrations of iron. Fluoride concentrations range between 0.1 mg/L (milligrams per liter) and 5 mg/L, increasing toward the south and southeast, and exceeding 1.5 mg/L in most of the area south of Summerville (figure 6). Silica occurs in concentrations of 25 mg/L to 45 mg/L and appears to be derived from the microcrystalline silicates, opal, clinoptilolite, and cristobalite that are reported to be abundant in much of the formation (Heron, 1969; Gohn, et. al. 1977). Near the coast in central and southern Charleston County, the Black Mingo contains brackish water and is of the sodium chloride bicarbonate or sodium-chloride type.

Water from the Santee Limestone is of the calcium bicarbonate type in most parts of the study area. However, in southern Charleston County, water at the base of the aquifer is high in fluoride, silica, and sodium bicarbonate, which may be the result of recharge from the underlying Black Mingo. Farther east, the chloride concentration increases (figure 7) and water in the Santee is brackish.

Many wells in the area are of open-hole construction, and the chemical quality of samples obtained from such wells generally reflects the quality of water in the lowermost formation penetrated by the well. Because water in the Black Mingo is more brackish than that in the overlying Santee Limestone, wells

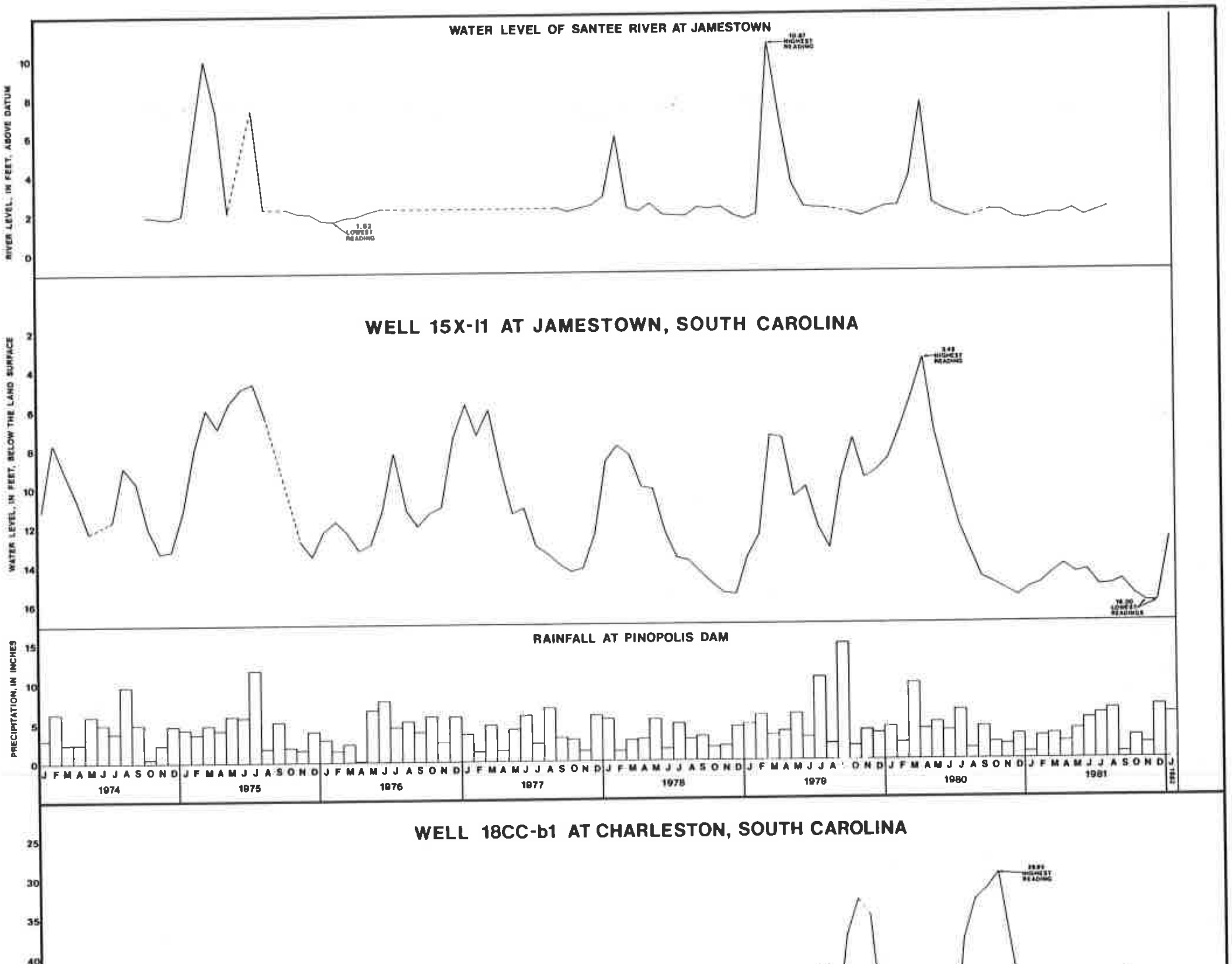


Figure 4. Hydrographs for Well 15X-L1, near the Santee River, and Well 18CC-b1, at Charleston.

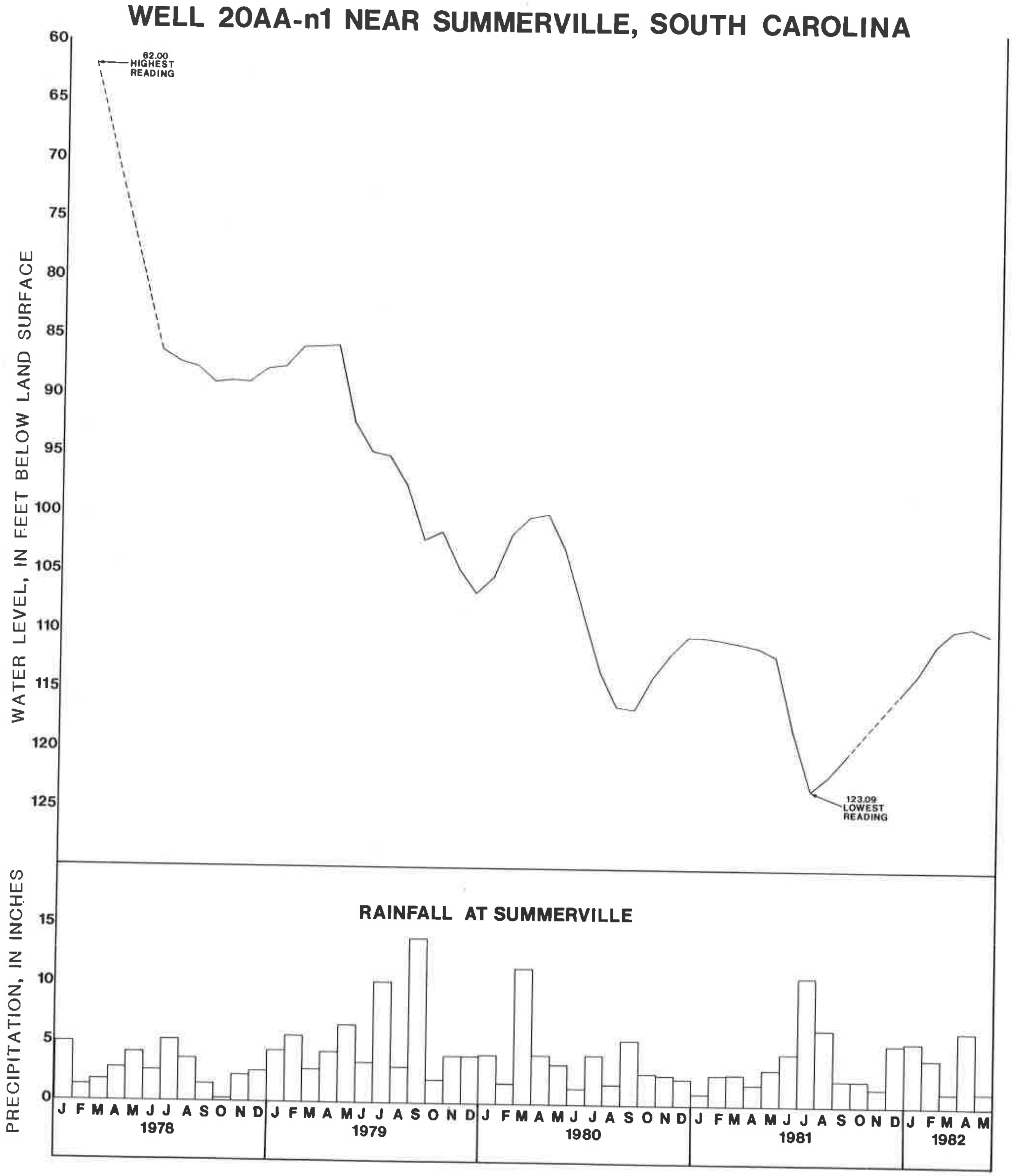


Figure 5. Hydrograph for Well 20AA-n1, near Summerville, Dorchester County.

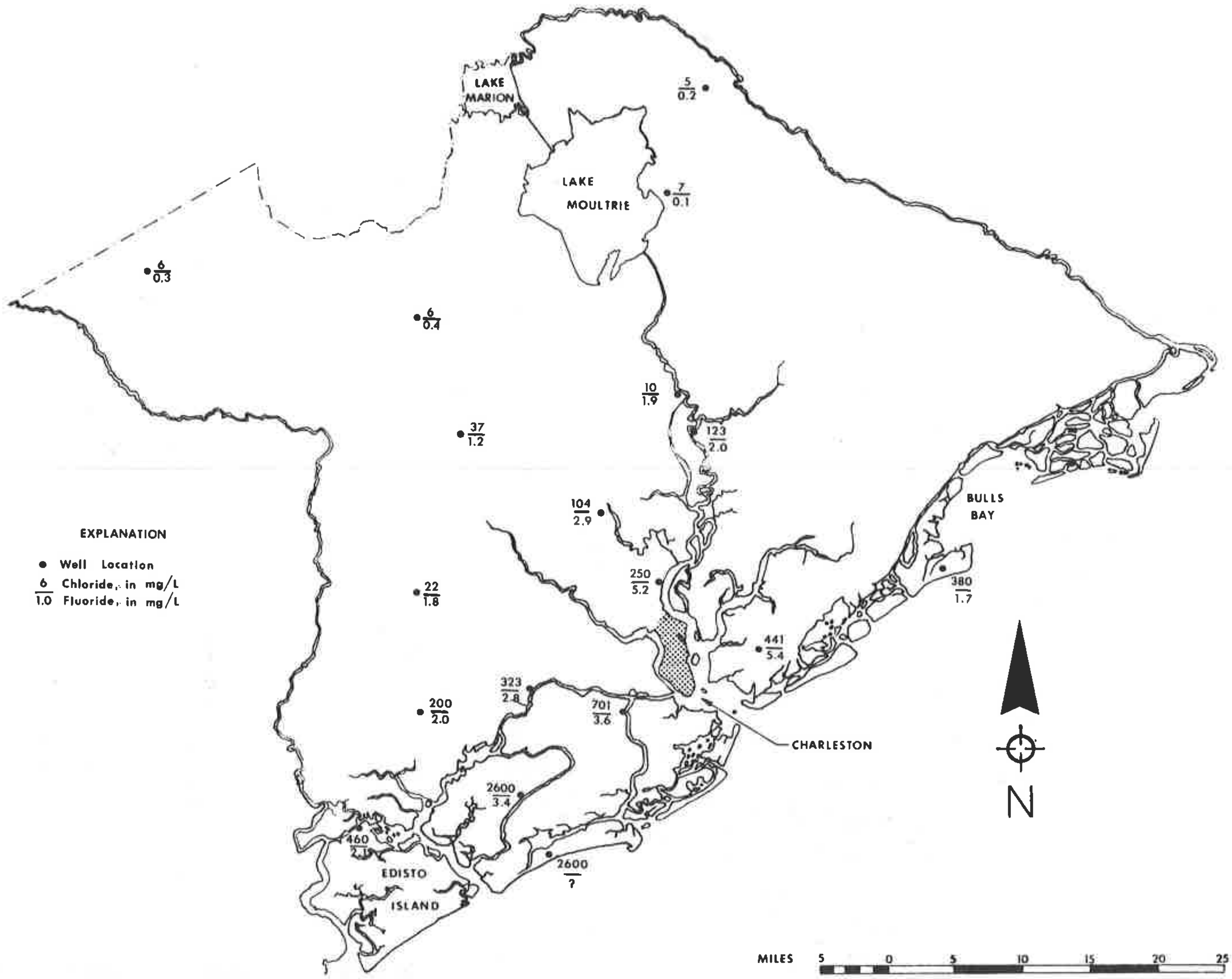


Figure 6. Distribution of fluoride and chloride in the Black Mingo Formation.

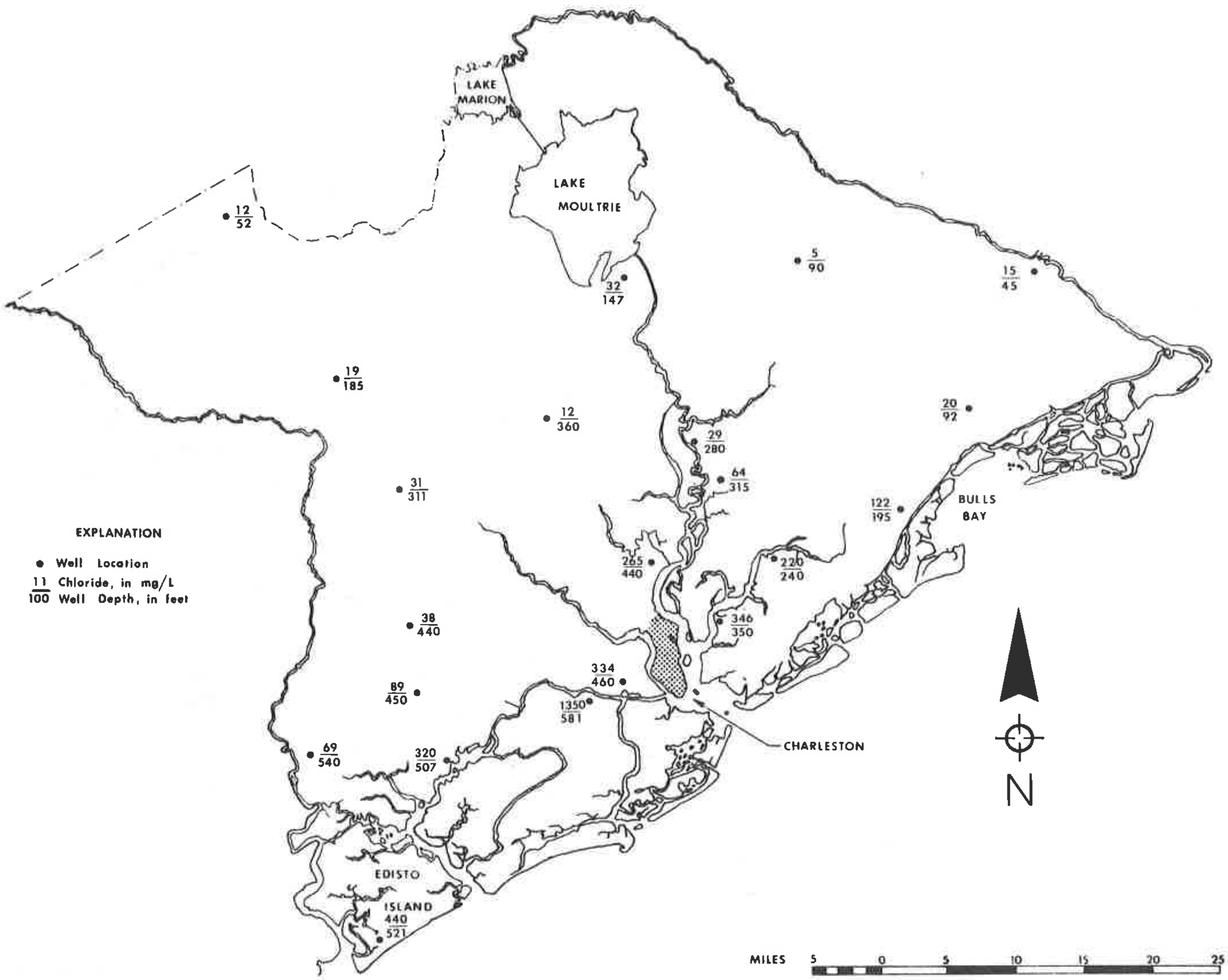


Figure 7. Distribution of chloride in the Santee Limestone.

that interconnect the two systems are commonly contaminated as saltwater flows up the well bore and into the relatively fresh water in the overlying limestone. As well depths increase, so does the degree of saltwater contamination (figure 8). The problem is common in the southernmost section of the study area where the Black Mingo has a somewhat greater head and has affected many of the wells inventoried during the course of the study.

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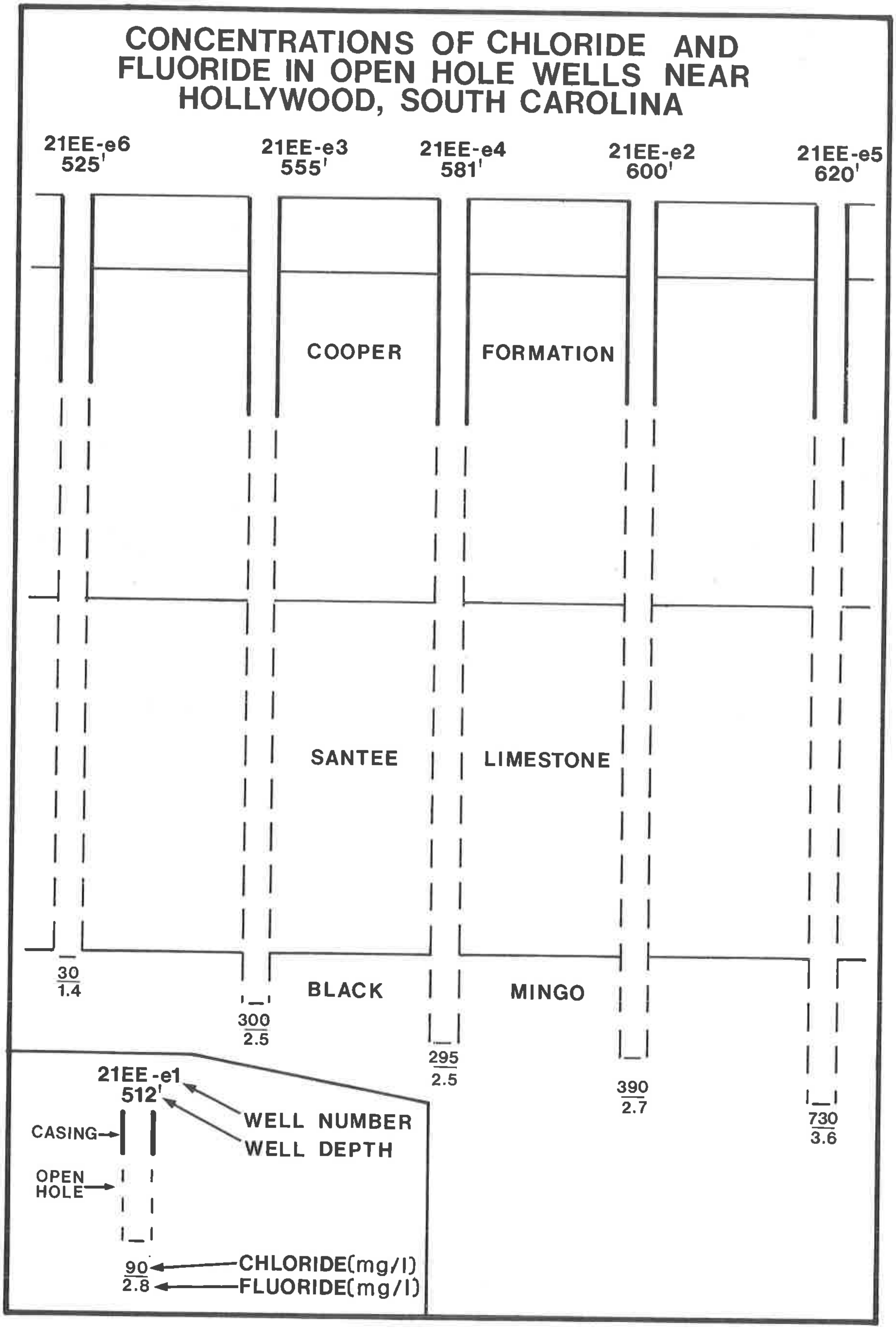

CONCENTRATIONS OF CHLORIDE AND FLUORIDE IN OPEN HOLE WELLS NEAR HOLLYWOOD, SOUTH CAROLINA
21EE-e6
525'
21EE-e3
555'
21EE-e4
581'
21EE-e2
600'
21EE-e5
620'
COOPER
FORMATION
SANTEE
LIMESTONE
BLACK
MINGO
30
1.4
300
2.5
295
2.5
390
2.7
730
3.6
21EE-e1
512'
WELL NUMBER
WELL DEPTH
CASING
OPEN HOLE
90
2.8
CHLORIDE(mg/l)
FLUORIDE(mg/l)

Figure 8.

GROUNDWATER CONTAMINATION

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ABSTRACT

Groundwater is water that is utilized by plants, soil water which is held on the surfaces of soil particles, and water which percolates through the soil to an aquifer. It is the latter which furnishes 50% of the water for domestic use in the United States. Seventy-five percent of the cities rely on groundwater for part if not all of their supply of fresh water.

Naturally groundwater varies greatly in its chemical composition and may be brine, hard water or very low conductivity water. Groundwater near the surface of the earth is easily contaminated by man's activities. The contaminants may be biological and/or chemical. The biological contaminants are bacteria, protozoa and, more rarely, other organisms. The chemical contaminants may be inorganic or organic.

Contamination of aquifers is widespread throughout the United States and caused by many different substances. It is estimated that about 10% of the aquifer water may be contaminated. This number may be greatly increased when the method of monitoring is improved. The incidences of acute diseases caused by groundwater contamination are relatively few, and chronic incidences of disease are very few.

There is no federal program whose specific aim is groundwater protection. There are a group of statutes designed primarily for other environmental problems that focus indirectly on groundwater and offer some measure of protection.

At the state level there is a broad mixture of regulations that can protect groundwater from contamination. They are diverse because different regions have different types of problems. There are three main types of controls. They are source controls, groundwater quality standards, and regulations on land use.

PRESENTATION

Groundwater is of three types: water utilized by plants, water that adheres to soil particles and is very difficult to dislodge, and water that percolates through the soil to the aquifer, a pervious stratum through which water flows. These aquifers are subtended by an aquitard which is relatively impervious.

It is the water in the aquifer that is most important as a freshwater resource. Approximately 50% of the people of the United States use groundwater for domestic purposes and 75% of the cities utilize groundwater as part of their supply. Groundwater is often referred to as well water. It may be pumped or it may be under pressure and form artesian water.

This underground source of water is very large and comprises 96% of all fresh water in the United States. Only 4% of the fresh water is the surface water of lakes and streams. Most of these aquifers are within 2,500 feet of the land surface. They are of two types: unconfined aquifers which are easily recharged and easily contaminated, and confined aquifers which are very difficult to recharge and not very often contaminated (see Figure 1). One of the best examples of a confined aquifer is the Ogalla in the western part of our country. Most of the water in this aquifer was laid down in Pleistocene times. Little, if any, recharge takes place.

Aquifers vary greatly in their natural chemical quality. They may be very soft with very few dissolved solids or they may be from low hardness to very hard. This is dependent upon the amount of calcium and the magnesium in the water. Some aquifers have large amounts of dissolved solids of sodium, potassium, calcium and magnesium. These waters are similar to seawater in chemical quality.

The movement of groundwater is very slow compared to surface water, and the flow is usually laminar rather than turbulent as in surface streams. Estimates of rate of flow vary from 5 ft/yr to 50 ft/yr.

Toxic substances that enter groundwater may precipitate by interaction with the natural water or co-precipitate because of the presence of other chemicals. The pH and/or redox potential of the water may greatly influence these processes. High temperature and pressure may also affect the solubility of toxics.

Some substances are lighter than water and float at or near the surface of the water. Other substances are heavier than water and sink to intermingle with the sediments in the aquifer. These substances often remain in place over long periods of time. They may leach soluble substances into the water. The amount of leaching is greatly influenced by the pH and redox potential of the water. The water-soluble substances usually move with the water and, hence, are diluted. In streams this is mainly by turbulent flow, whereas, in groundwater it is mainly by advection and dispersion.

Some substances coat particulates and move with them. They may settle out if conditions favor the settling out of the particulates on which they are sorbed. In aquifers their movement is much slower, and the specific gravity of the particle which they coat could be very important in determining the conditions under which they settle out.

Attenuation results in changes occurring in toxic substances after they are released. In the ground the attenuation starts when the chemical enters the ground or the leachate leaves the lagoon or disposal pond, the dump or the burial ground. Physical sorption of toxicants onto the colloidal fraction of clays is very common in many soils. Those substances that sorb are metals and some organic compounds. Oily toxicants may adhere to sand grains and larger particles. Organic colloids are present in some soils and are very effective in chelating metals and some organic compounds. These types of attenuation may continue into the subsoil.

Biological attenuation of groundwater is mainly accomplished by activity in the soil, but recent investigations indicate such activity exists in subsoil strata and even in aquifers. This attenuation is accomplished mainly by bacteria and fungi. The organic radical of a toxic substance may be utilized as an energy source or as a nutrient for building protoplasm. This breakdown of toxic compounds may occur in several stages, with different organisms utilizing the products produced by other organisms. Depending on the type of toxic chemical, the products may be recyclable material as is the case of methylated mercury which is metabolized by yeast. The methyl radical is metabolized and the mercury is split off in a metallic form. Some molecules are relatively easily metabolized while others are only metabolized after considerable time when the molecule has had time to interact by physical and chemical processes.

Many of these biological processes are aerobic and usually produce nontoxic end products. The product produced by anaerobic activities, such as hydrogen sulphide, may be toxic to many organisms. The characteristics of the water in the aquifer greatly influence the type of attenuation that may take place. If the water contains considerable amounts of alkaline metals, precipitation is more likely to occur than in water of low conductivity. The presence of sulphides or high salinity may retard attenuation by biological processes. The pH of the water is also important because bacteria and other microorganisms are often more active in waters with a circumneutral pH. The temperature and pressure of the water may also affect attenuation.

Contamination of groundwater is from many sources. Natural contamination is the shift in chemical composition of water as it percolates through the soil or as it flows through the matrix of the aquifer. Manmade sources of contamination are from the disposal of wastes in septic and storage tanks, lagoons, and solid waste dumps and from other activities, such as spills and leaks, agricultural activities, mining, highway de-icing salts. Contamination may also occur when pumping rates exceed the replacement rates of fresh water. In such cases infiltration of saltwater may occur. This most often happens near the seacoast.

Sources of disposal that have caused the greatest amount of groundwater problems are septic tanks, solid and liquid wastes from municipal treatment plants, industrial solid wastes and impounded wastewater, mine wastes, feedlot waste, and radioactive wastes. Leachate from these sources often, over time, contaminates freshwater aquifers. Since the plume of contamination moves very slowly, it may be several years before the source of contamination is recognized.

An increasing cause of contamination is overpumping. This results from the greatly increased use of groundwater, particularly, groundwater in more or less confined aquifers. Irrigation water which has high salt and pesticide concentrations is becoming a problem in some parts of the country where the aquifers are unconfined and close to the surface.

The number of chemicals now being used and distributed through the environment is estimated to be about 30,000. Relatively few instances of contamination have been found. The general estimate is that about 1% of the groundwater in the United States is contaminated. This estimate may not be correct, for no systemic effort has been made to determine the frequency of contamination. The amount of groundwater used and the incidents of contamination are given in the accompanying Table 1. One can see that compared to the total amount of water used, the incidents of contamination are relatively few.

The chief sources of contamination rank differently in importance in various parts of the country. For example, in the Southwest natural leaching is most important; second is irrigation return flow and third is seawater encroachment. In the south central states, natural pollution is first in importance; oil field brine is second; and well construction, third. In the northeastern part of the country, septic tanks and cesspools are most important; second are leaks from pipelines and storage tanks; and, third, highway de-icing salts. In the Northwest, septic tanks are first; sewage treatment plant discharges, second; and irrigation return flow, third. In the Southeast, septic tanks are first; urban and industrial landfills are second and surface impoundments are third.

The contaminants that cause illness may be biological or chemical. The biological contaminants that cause disease may be bacteria, viruses, protozoa, worms or fungi. The EPA reports that between 1945 and 1980, bacteria caused 94 outbreaks of disease with a total of 26,041 cases of illness. Viruses caused 55 outbreaks with 3,291 cases of illness. Parasites caused 9 outbreaks and 2,093 cases of illness. On a yearly average these figures would be much less. For example, there would be 2.7 outbreaks of bacterial diseases and 744 cases of illness and for viruses there would be 1.6 outbreaks and 94 cases of illness (Page et al. 1983).

Acute health effects caused by chemical contamination of water are fewer. Between 1959 and 1980 - 21 years - there were 303 reported cases of illness caused by copper, selenium, fluorides, nitrates, arsenic and sodium hydroxide (Page et al. 1983). Six outbreaks were caused by toxic organic chemicals and resulted in 52 cases of illness. The organics included oil wastes, phenols and pesticides. These incidents may be considerably more frequent because methemoglobinemia, which causes blue babies, is not a reportable disease.

Recent investigation has shown widespread contamination of groundwater by toxic synthetic organic chemicals; C.E.Q., (1981) states that serious contamination has resulted in 34 states (Page et al. 1983). Few cases of illness are reported from such contamination, possibly due to lack of records or recognition of the causes of illness, or because the contamination did not affect human health.

There is no federal program aimed specifically at the problem of groundwater contamination. However, there are some programs that provide a measure of protection. The most important federal statutes affecting groundwater are the Resource Conservation and Recovery Act (RCRA) of 1976, the Safe Drinking Water Act (SDWA) of 1974, the Clean Water Act (CWA) of 1977, the Toxic Substances Control Act (TSCA) of 1976, the Surface Mining Control and Reclamation Act (SMCRA) of 1976, and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980. At the state and local level, the main types of regulation affecting groundwater quality are (1) those dealing with particular sources of pollution, such as septic systems and waste disposal systems, (2) those establishing and implementing water quality standards for aquifer water in which aquifers may be classified according to current or projected uses, and (3) those which regulate the use of land in areas overlying critical aquifer recharge zones.

The cleaning up of aquifers, once they have become contaminated, is very expensive and sometimes not feasible. The best way to protect groundwater is (1) to eliminate the contaminants at their source; (2) to protect the recharge areas of unconfined aquifers by regional planning; (3) to develop an effective monitoring system so that contamination of groundwater is quickly spotted.

To date, one of our greatest problems in assessing groundwater contamination is the lack of effective monitoring systems. Because of this lack, we do not know how widespread contamination is, nor do we know the health effects and other environmental effects produced by groundwater contamination.

REFERENCE

Page, Veronica I., Patrick, Ruth, and Quarles, John, 1983, Groundwater Contamination in the United States, University of Pennsylvania Press, Phiadelphia, Pennsylvania

Table 1. Groundwater Use and Incidences of Contamination

State	Groundwater use	Incidences of Contamination
Arizona	4,800 mgd	23
California	4,000 mgd	--
Connecticut	116 mgd	64
Florida	3,000 mgd	58
Idaho	5,600 mgd	29
Illinois	1,000 mgd	58
Nebraska	5,900 mgd	35
New Jersey	652 mgd	374
New Mexico	1,000 mgd	105
South Carolina	200 mgd	89

GROUND-WATER CONDITIONS IN THE BLACK CREEK AQUIFER SYSTEM OF NORTHEASTERN COASTAL SOUTH CAROLINA

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ABSTRACT

The Waccamaw Capacity Use Area lies in the easternmost corner of South Carolina, incorporating all of Horry and Georgetown Counties and the Brittons Neck portion of Marion County. The public water supply for the area comes almost entirely from wells completed in the Black Creek Aquifer System, a sand formation of Late Cretaceous age.

Between 1974 and 1982, water use from this aquifer system increased by 113 percent in Horry County and 13 percent in Georgetown County. As a result, water levels in wells tapping the aquifer have dropped by almost 100 feet in some places and are continuing to fall at rates ranging from zero at Georgetown to 9.5 feet per year at Myrtle Beach. At the prevailing rates of decline, the water levels will reach the top of the formation in the Myrtle Beach vicinity in 8 to 10 years and will begin to dewater the topmost screens in another 5 to 10 years.

The water in the aquifer often contains excessive levels of fluoride, total solids, and, on a more limited basis, chloride. Otherwise the water is soft, low in iron, has a high pH, and represents the best supply of large volumes of drinking water to satisfy local demands. The concentration of the objectionable constituents is not uniform but it attains a maximum along the coast at the state line, and diminishes with distance inland and southward, toward Georgetown.

Two guidelines have been established to assist in the development of a master management program:

- no drawdowns shall be allowed to reach the top of the water-bearing zones,
- no salt water encroachment into the producing zones will be tolerated.

With these guidelines established, water supply alternatives are proposed that will supplement and perhaps replace the Black Creek Aquifer System. These alternatives are:

- develop alternative inland Black Creek Aquifer well fields to decentralize withdrawals,
- develop well fields along the Pee Dee River to utilize the shallow flood-plain deposits,
- construct a facility to treat water from either the Pee Dee River or the Intracoastal Waterway.

INTRODUCTION

Horry and Georgetown Counties largely compose the Waccamaw Capacity Use Area in South Carolina (Figure 1). The area is experiencing sufficient ground-water problems to warrant coordination and limited regulation of the withdrawals from the Black Creek Aquifer System, the principal source of water.

The population of the area is heavily affected by tourism. During the summer months the population along the coastline swells with the influx of tourists, and the water use expands similarly to meet the demand. The economy, in addition to the tourism, is largely agricultural with a small concentration of industry in Georgetown and a small fishing fleet operating out of Georgetown, Murrells Inlet, and Little River.

GEOLOGIC SETTING

There are four principal aquifer systems beneath the area. In descending order, these are the shallow Tertiary-age formations and the Peedee, Black Creek, and Middendorf Formations of late Cretateous age. In the areas of heaviest water use, along the coast, the Middendorf is too salty, and the Peedee and shallower aquifers generally yield limited amounts of water or they yield water containing objectionable levels of iron or hydrogen sulfide. As a consequence, the Black Creek Aquifer System has become the principal source of water for the area. The Peedee and shallow formations are used by only a few small-scale irrigation, commercial, and industrial water users.

The Black Creek Aquifer System is largely composed of dark gray clay interbedded with medium- to fine-grained, light- and dark-gray sand. Calcium carbonate cemented sandstone beds are common especially in the top half of the formation. The top of the Black Creek dips to the south and strikes almost due east-west. The formation thickens from about 500 feet at the western edge of the area to 750 feet at the coast.

HYDROLOGIC CONDITIONS

The transmissivity of the aquifers in the Black Creek System tends to decline from Horry into Georgetown County. This decline can be attributed to both a decrease in the total thickness of the sand beds and to a reduction in grain size of the aquifer material. Figure 2 shows the theoretical distance-drawdown plots for two similarly constructed and pumped wells. It can be readily seen that in order to yield the same amount of water in Horry County, the well at Litchfield Beach in Georgetown County must have more drawdown than similar wells in Conway or Myrtle Beach.

The water use has increased tremendously from 1974 to 1982, and it is expected to continue at similar rates through the year 2000. The increase in water use is primarily due to urban development concentrated along the coast, whereas the inland areas of the counties have experienced only moderate increases.

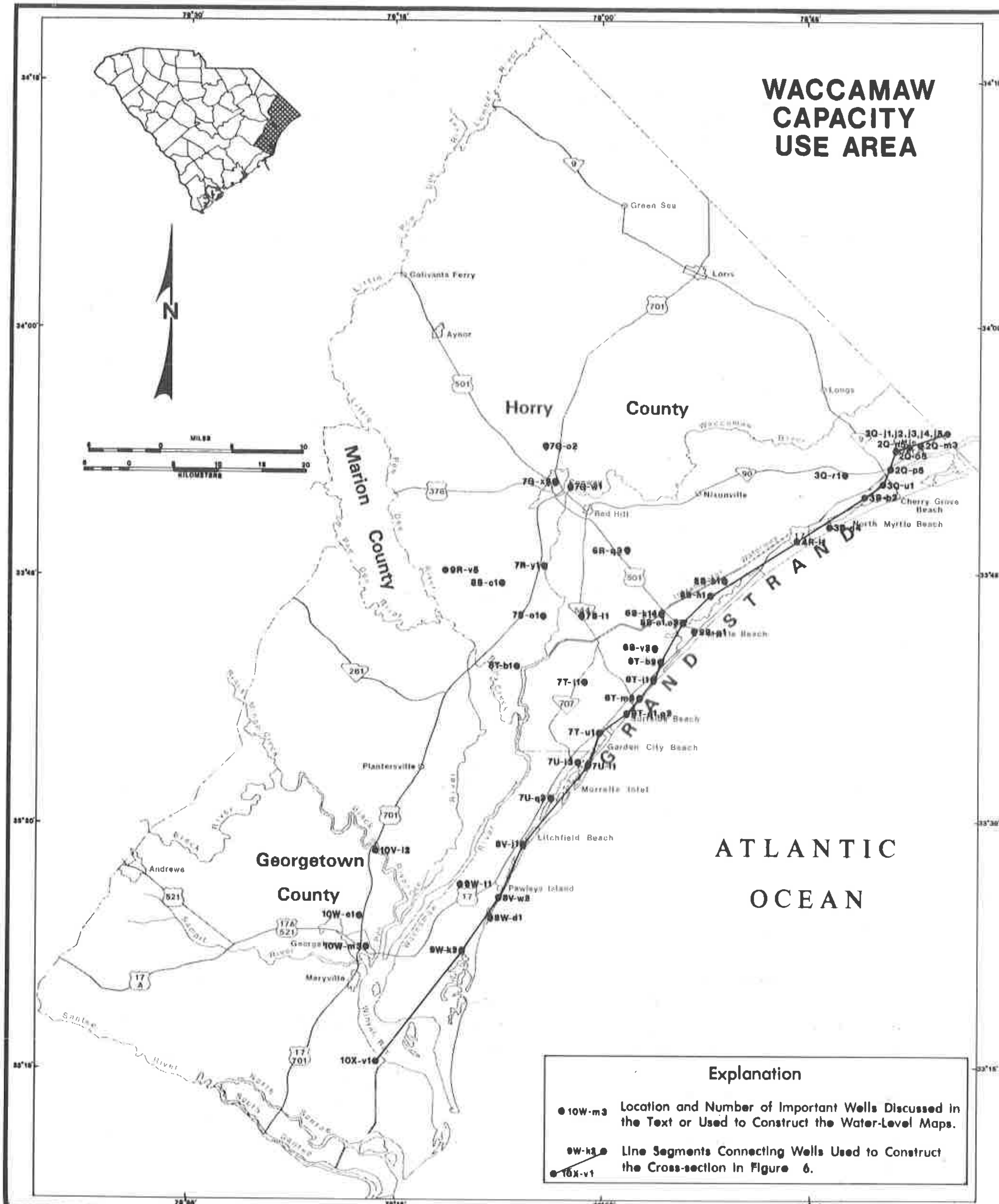

Figure 1. Map showing the study area, and the locations of wells used in the text, and in the construction of the potentiometric map and the cross section.

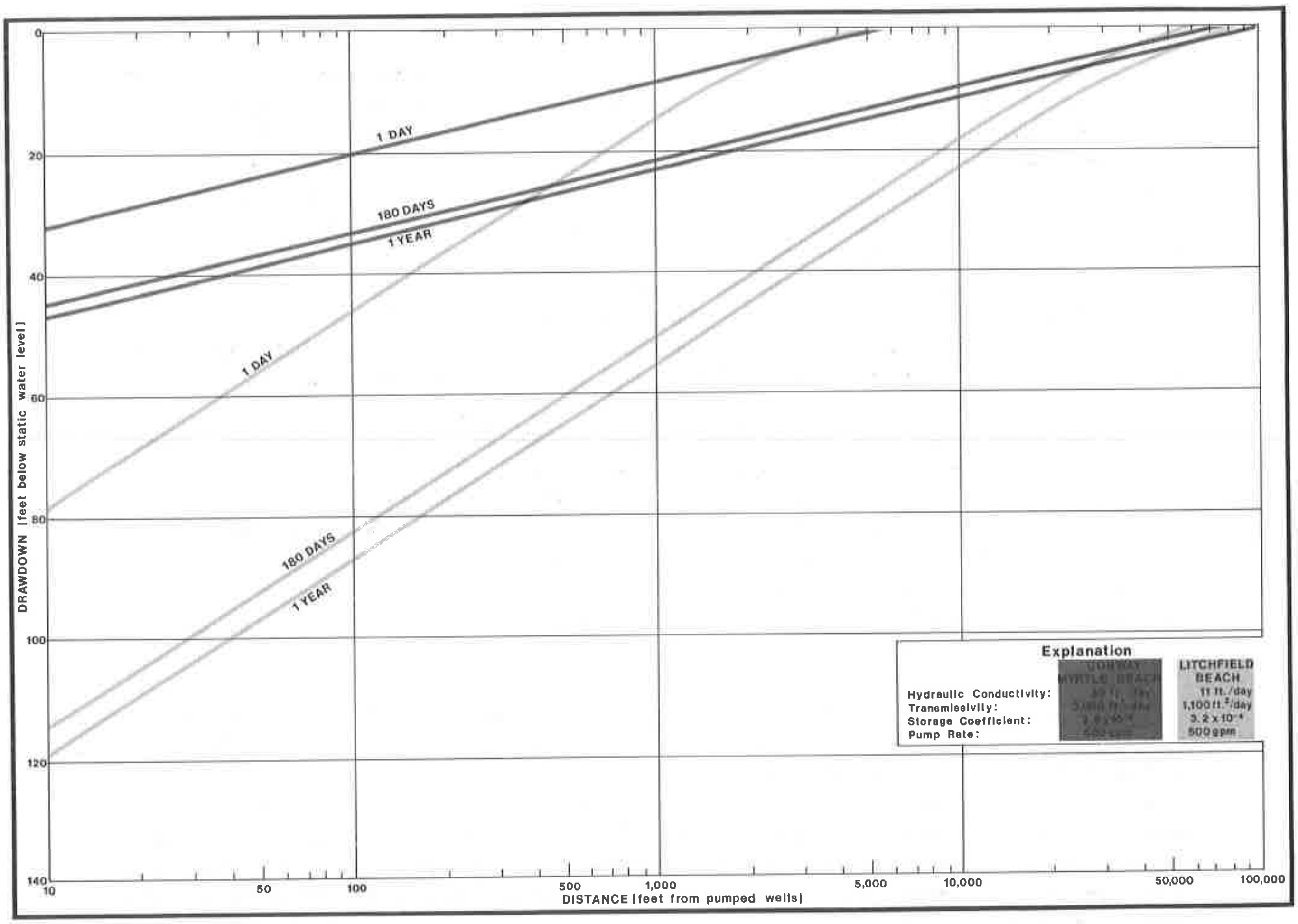

Figure 2. Theoretical distance-drawn plots for two similarly constructed wells.

The water levels in the Black Creek Aquifer System exhibit an annual fluctuation from a March high to a September low. This pattern closely reflects the annual water-use cycle created by the summer tourist population influx (Figure 3). The one- or two-month lag time between water-use changes and the water-level response may be the result of the four-mile distance to the center of the Myrtle Beach cone of depression from the two wells. The annual fluctuation pattern is superimposed on a larger scale declining trend evidenced, to a greater or lesser degree, on the hydrographs from all the Black Creek Aquifer monitoring wells. Rates of decline range from near zero at Georgetown to 9.5 feet per year at Myrtle Beach. Four of those hydrographs (figure 4) are compared to the cumulative rainfall departures from normal. Unfortunately, local pumping effects and overall declining trends tend to mask any relationship between these two families of plots.

Two cones of depression can be seen on the potentiometric map, one centered at Georgetown and one centered at Myrtle Beach (Figure 5). The Georgetown cone is relatively stable and has not expanded or deepened appreciably in seven years. The Myrtle Beach cone, on the other hand, has deepened by approximately 80 to 90 feet and has expanded by 6 miles between 1975 and 1982. Most of the water-use increase in Horry County shown in Table 1 has occurred in the coastal area. Georgetown County has not experienced large-scale water-use increases. The small increase shown on Table 1 has been widely distributed across the county, except for the small area just south of the Horry County line between Pawley's Island and Garden City.

A section down the coastline, from Calabash, North Carolina (Well No. 2Q-j2) to Esterville Plantation (Well No. 10X-v1) in Georgetown County, has been constructed to show the chloride distribution in the Black Creek and Middendorf aquifers. To this date there has been no measurable increase in the chloride levels in the monitoring wells which indicates that salt-water intrusion is not occurring at the present time. However, monitoring efforts continue in order to detect intrusion if and when it does occur.

The water in the Black Creek Aquifer System is soft and low in iron, but it contains elevated levels of chloride, fluoride, and dissolved solids. The concentrations of these three species occur at their maximum along the coast at the North Carolina line. The concentration distributions reflect the controlling influence of the Cape Fear Arch, which has deflected the recharge flow around this area and has not allowed the connate seawater to be fully flushed out. The water quality improves to the south and to the west, away from the effects of the arch.

The only major problems with the water quality in addition to the chloride, are the fluoride level, which ranges from approximately 0.5 to 6 mg/L, and the total dissolved-solids content, which ranges from 300 to 1500 mg/L. The South Carolina Department of Health and Environmental Control (DHEC) has petitioned the EPA to review the interim standard for fluoride in order to eliminate the need for treatment of the ground water. A new standard of 6 or 8 mg/L would allow almost every well to operate within the limits. The main result

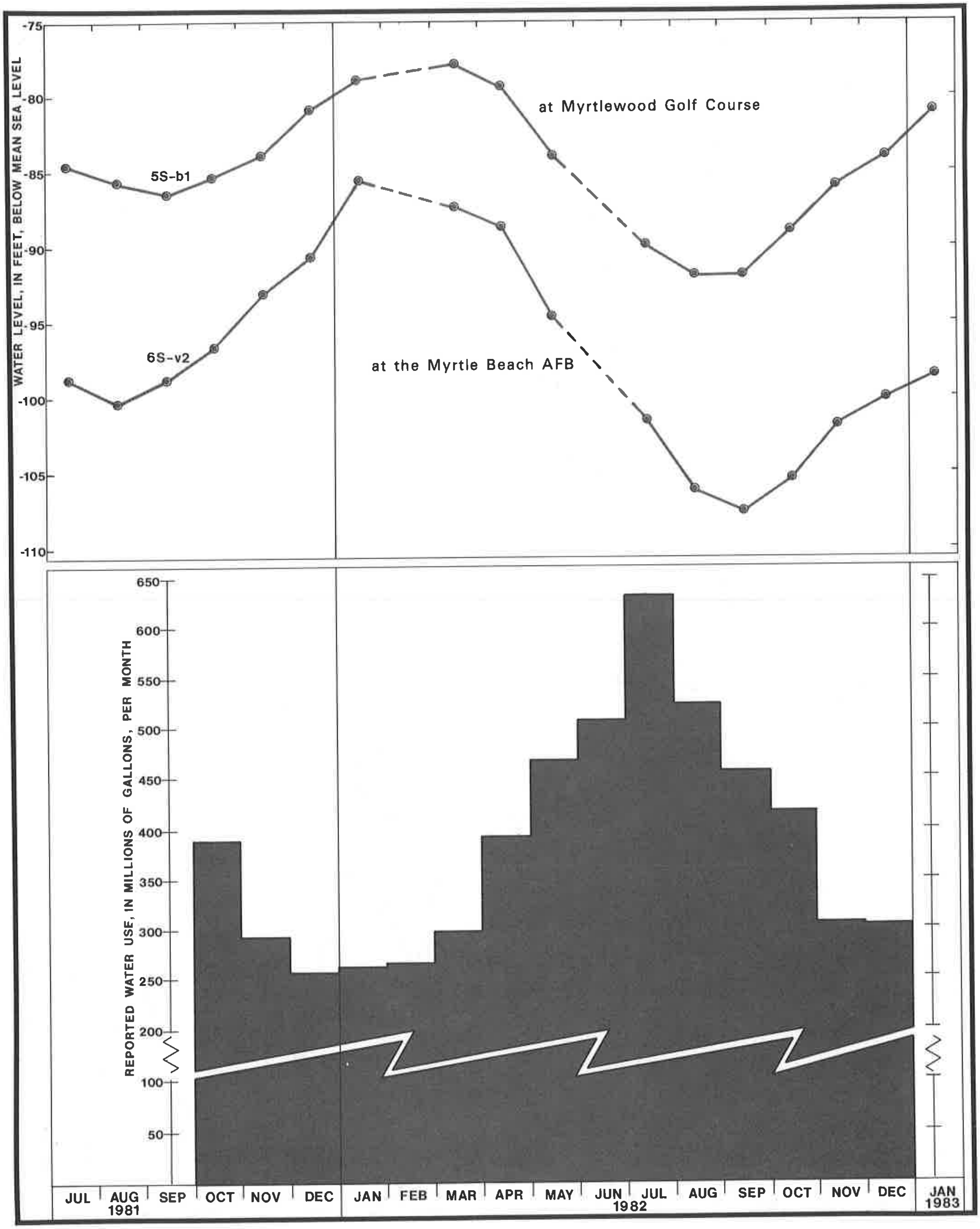

Figure 3. Annual water levels compared to annual water use.

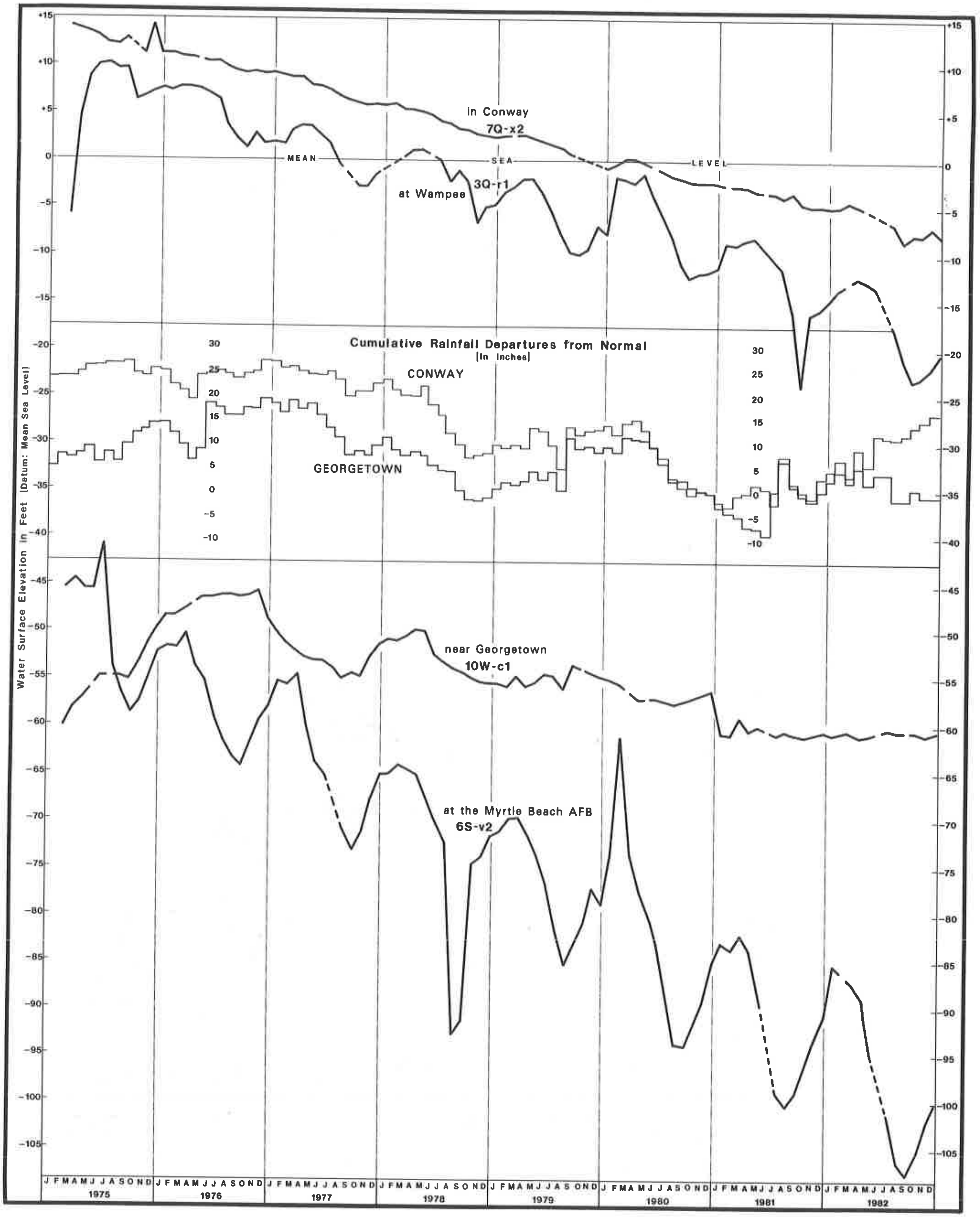

Figure 4. Water levels, Black Creek aquifer system, 1975-1982.

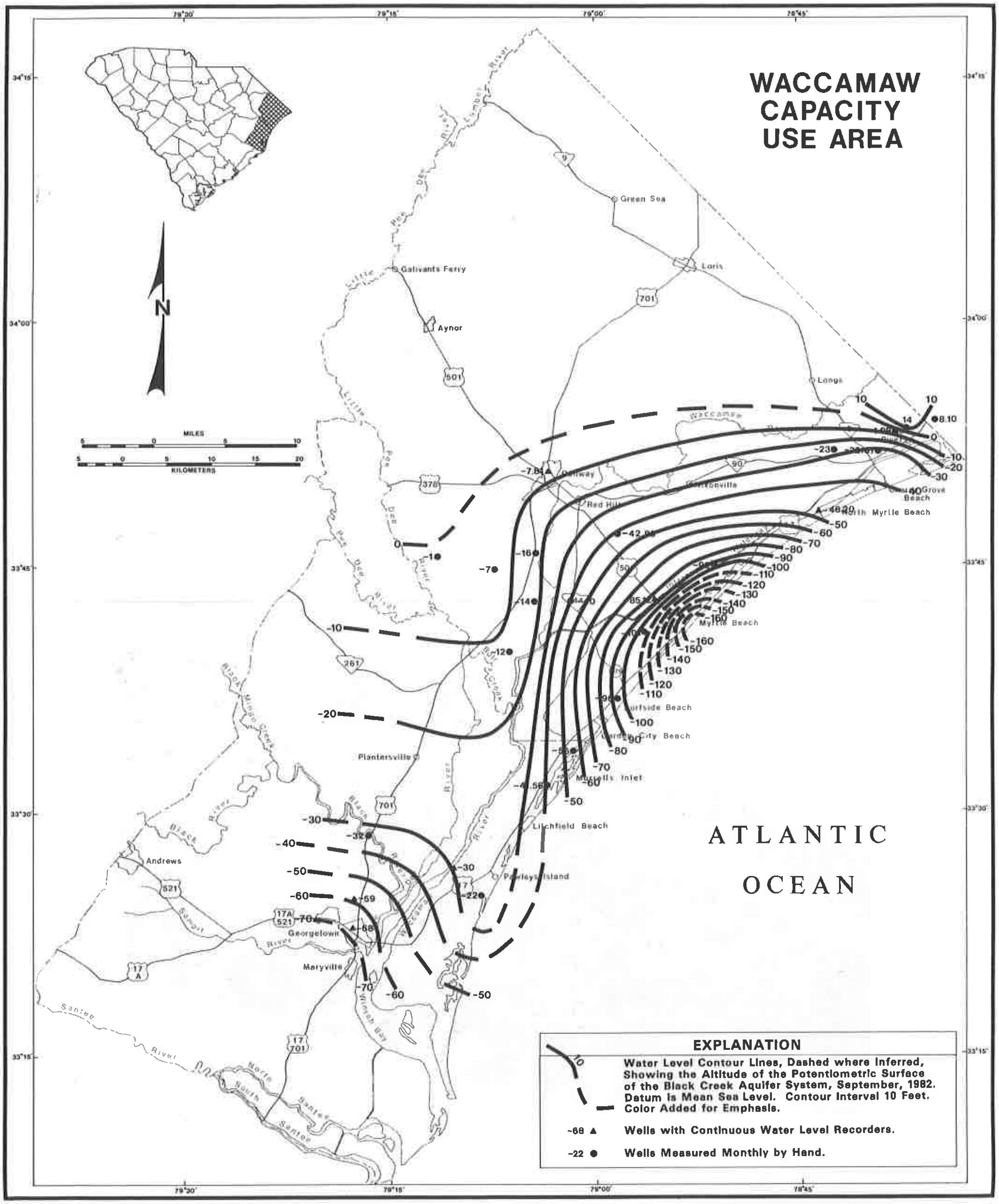

Figure 5. Potentiometric map of the Black Creek aquifer system, September 1982.

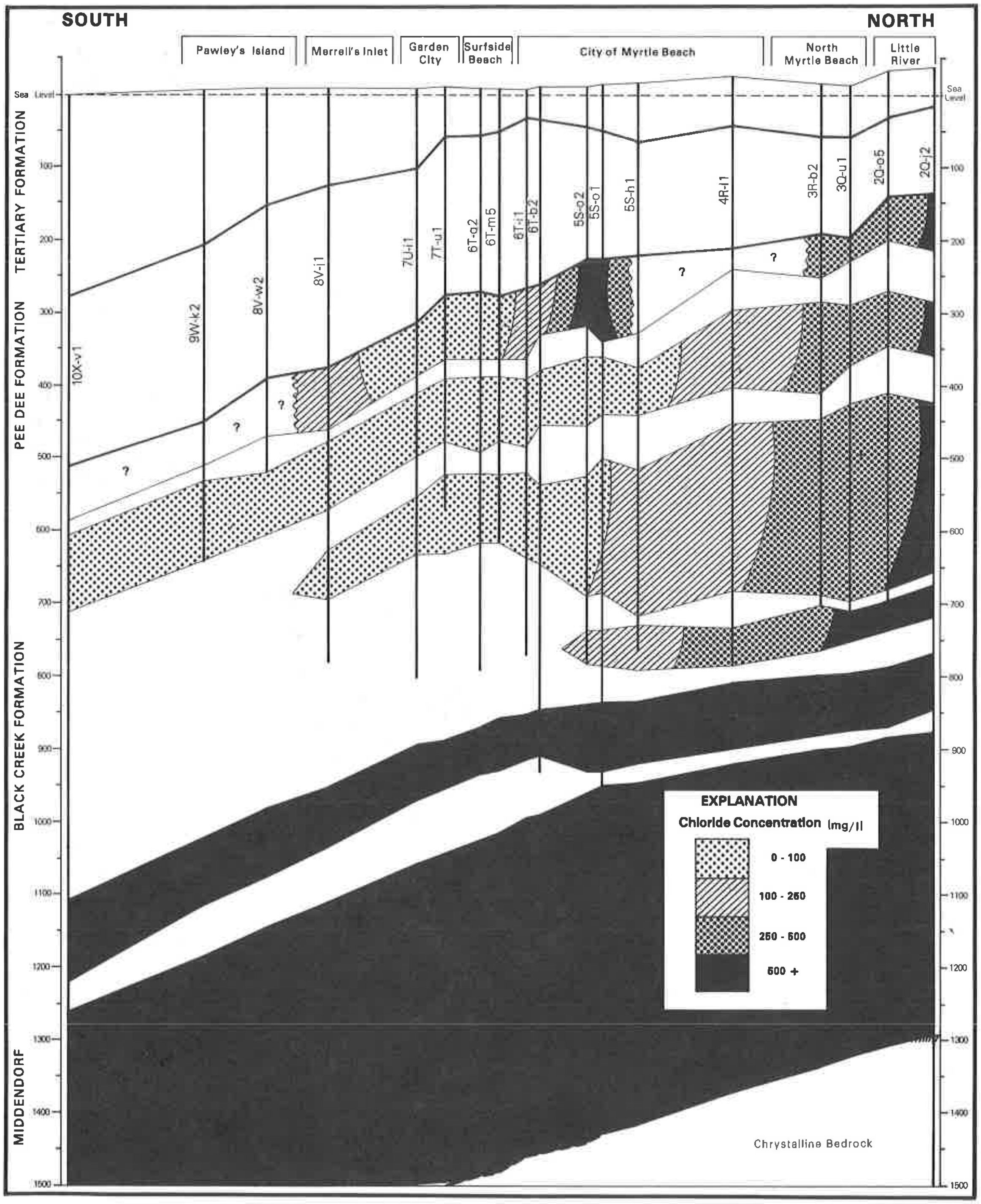

Figure 6. Generalized cross section showing chloride distribution.

TABLE 1. Gross annual water use, in millions of gallons, from the Black Creek Aquifer System.

YEAR	HORRY COUNTY	GEORGETOWN COUNTY	TOTAL
1974[1]	2,780	960	3,740
1982	5,950	1,080	7,020
2000[2]	15,500	1,500	17,000

Source: [1]Zack, 1977,
[2]CH_2M Hill Engineers, verbal communcation.

TABLE 2. Water demand, in millions of gallons per day (Mgd), from the Black Creek Aquifer System.

YEAR		HORRY COUNTY	GEORGETOWN COUNTY	TOTAL
1974[1]	Average	7.6	2.6	10.2
	Peak	12.7	4.4	17.1
1982	Average	16.3	3.0	19.3
	Peak	27.2	5.0	32.2
2000	Average	35-40[2]	4.0[3]	40
	Peak	60-70[2]	7.0[3]	70

Source: [1]Zack, 1977
[2] CH_2M Hill Engineers, vebal communication.
[3] Extrapolation of 1974 and 1982 data.

of the high dissolved-solids content is a characteristic "beach-water" taste that most residents ignore, but which most visitors find objectionable.

MANAGEMENT OPTIONS

For future expansion of the water supply to meet the projected demands, several guidelines have been developed to protect the water supply and to maximize the production from the aquifer.

1. No drawdown will be allowed into the water-bearing zones. This will be enforced by restricting pump intakes to above the topmost screen.

2. No chloride encroachment will be allowed. This will be accomplished by reduction of pumpage in areas where increasing chloride concentrations have been detected.

The cone of depression around Myrtle Beach, if left unchecked, will reach the top of the aquifer in 8 to 10 years. In order to avoid this, and in order to avoid hindering the development of the area, it will be necessary to either develop alternate water supplies or decentralize the current pumpage centers and develop the aquifer in other areas.

The Water Resources Commission is reviewing an alternative involving development of a second Black Creek Aquifer well field west of Conway, outside of the current cones of depression. This well field must be able to deliver up to 40 mgd by the year 2000, without adversely affecting the drawdowns in the existing cones of depression. An investigation will be required to determine the characteristics of the aquifer in the area and to predict the effects of a well field of this magnitude.

A second alternative would be on the western margin of the area, along the Little Pee Dee River. At this location, water could be obtained from shallow infiltration wells drilled into the sand-and-gravel flood-plain deposits, as well as drilling into the Black Creek and Middendorf aquifer systems, in order to diffuse the water withdrawals vertically as well as horizontally.

The City of Myrtle Beach is evaluating the feasibility of producing a water supply from the Intracoastal Waterway. All indications at present are positive, and work on an engineering report is under way. If the Waterway source proves to be feasible, and Myrtle Beach abandons its wells, a great stress will be removed from the aquifer, and the expected life span of the aquifer will be lengthened.

SUMMARY

In summary, the Black Creek aquifer system in this area is the principal source of large quantities of good-quality water. The aquifer system, however, is experiencing water-quality and water-level problems that require management and coordination of ground-water pumpage. The main concerns for the system are elevated levels of fluoride, chloride, and dissolved solids; rapidly declining water levels; and the potential for future saltwater intrusion or encroachment.

There are currently several alternatives available to the local water users to address these problems. The watchwords will be care, planning, and foresight; but a water supply can be developed which will be safe, sufficient, and sound within the time frame dictated by the rate of water-level decline.

PRECIPITATION ESTIMATES FROM VISIBLE AND INFRARED SATELLITE DATA

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1. INTRODUCTION

Precipitation information is a primary requirement of hydrologists and agriculturalists around the world. Also, of utmost importance is the need to make estimates of areas of heavy precipitation prior to the issuance of flash flood warnings and to evaluate or predict flood potential. The conventional method of acquiring precipitation data by rain gauges is quite limited on a global basis; as a result, on many occasions precipitation analyses derived from conventional methods do not represent the true volume of water accumulated over an area of interest during a particular period of time. Satellite-derived precipitation estimates supplement these data or even, in some important cases, may be the only data available.

Methods are being developed for both geostationary and polar-orbiter data. The geostationary spacecraft, which provides observations at 30-minute intervals of North and South America, are the primary source of precipitation data for these regions. However, for those areas where geostationary satellite data are not available, techniques using polar-orbiter data alone are used. Visible and infrared observations are the principal data sources. However, there is a limited technique development effort which uses microwave data. Other data sources to be used in estimating precipitation include NMC (National Meteorological Center) analyses and forecasts, conventional atmospheric soundings, radar data (where available), satellite-derived soundings, and rainfall climatologies.

There are two basic types of precipitation-estimation techniques: cloud history and cloud indexing. Cloud history works best where geostationary satellite data are available. The frequent looks from geostationary satellites allow the life cycle of a cloud to be followed and precipitation estimates to be computed for each stage of the cloud's development. In contrast, cloud indexing is the principal method where only polar-orbiter satellite data are available. Only two pictures a day can be obtained from one polar-orbiting satellite. Cloud indexing involves characterizing a cloud by an index number according to its appearance in imagery and then using a look-up table or regression equation to estimate the precipitation from the cloud. Both the cloud history and cloud indexing methods have procedures for modifying the estimates for different climates and environments.

This paper presents geostationary satellite data techniques for analyzing three basic types of precipitation systems: convective, tropical cyclone, and extratropical cyclone.

2. CONVECTIVE RAINFALL TECHNIQUES

Scofield and Oliver (1976, 1977, 1978, 1980 and 1981a) have developed a technique which gives half-hourly or hourly rainfall estimates for convective systems by using GOES IR and high resolution visible pictures. The Scofield/

Oliver technique is presented in the form of a decision tree which an analyst uses to determine rainfall estimates. The technique was designed for deep convective systems that occur in tropical air masses with high tropopauses, and it is applied using IR pictures displayed according to the digital enhancement curve (Mb curve) designed to help detect convective storm intensity.

An example of a flash flood producing thunderstorm system displayed with such a curve is shown in Fig. 1. The picture shows the temperatures associated with each of the contours in the Mb curve: medium-gray (-32 - -41°C) represents the warmest tops; white (below -80°C), the coldest.

Estimates of convective rainfall are computed by comparing the changes in two consecutive pictures, using both IR and high resolution visible. The technique is shown in Fig. 2 and is divided into two main parts:

(a) The active portion of the convective system is identified; clues are presented for helping to make this decision.

(b) The half-hourly convective rainfall estimate is computed for the active portion from the following meteorological factors: (1) cloud-top temperature and cloud growth factor or divergence aloft factor, (2) overshooting top factor, (3) thunderstorm cluster or convective cloud line merger factor, (4) saturated environment factor for stationary and slow moving thunderstorms, and (5) precipitable water factor for modifying estimates for thunderstorms in dry environments or with high bases. Detailed explanations of these meteorological factors are found in the previously mentioned references.

The thunderstorm system in Figs. 1 and 3 produced over 15 inches of rain in a 6-hour period near F. Operational estimates of over 10 inches were computed for the same area and during the same 6-hour period. The flash flood rainfall at F (Figs 1 and 3) was produced by stationary thunderstorms which grew rapidly and possessed overshooting tops; a merger (between 0800 and 0900 GMT) also occurred between the cluster at F and the one at M.

As mentioned above, the Scofield/Oliver technique using the IR enhancement curve (Mb) was designed for estimating rainfall from deep convective systems with a high tropical tropopause. As shown in a previous paper by Scofield, Oliver and Spayd (1980), the strength of the convection is at times best estimated by a comparison of the temperature of the convective tops with the computations from the soundings determining at what height the anvil will spread out. This occurs at the stable layer near the top of the area of free convection, not at the tropopause. When this occurs, the Mb curve is not the best to use because at temperatures warmer than -62°C the Mb curve does not show the details clearly.

The Scofield/Oliver technique is being modified (see Scofield, 1981b) so that when soundings are available the temperature of the convection computed from a sounding is compared with the observed cloud-top temperature. This computed temperature is the best measure of the expected anvil temperature and should be used for examining the anvil growth rates. Temperatures equal to or colder than the computed temperature would indicate heavier rainfall rates than warmer ones.

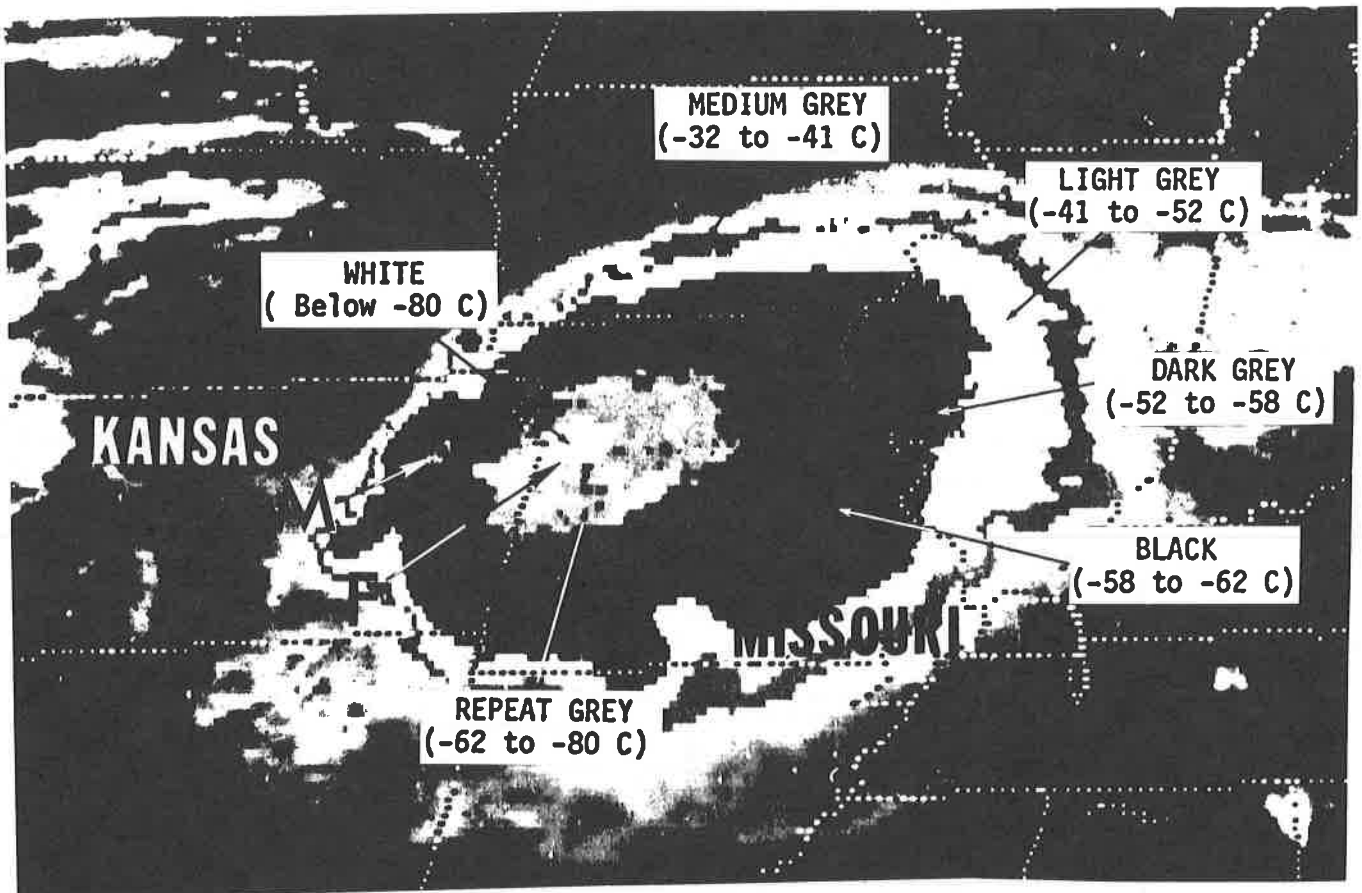


Figure 1. Enhanced infrared imagery (Mb Curve), 0800 GMT, August 13, 1982.

CONVECTIVE RAINFALL TECHNIQUE

(A) RAINFALL IS COMPUTED ONLY FOR THE <u>ACTIVE</u> PORTION OF THE THUNDERSTORM SYSTEM.

The following are clues for helping to make this decision.

- IR temperature gradient is tightest around station end of anvil for a thunderstorm system with vertical wind shear (IR).
- Station is located near the center of the anvil with a tight, uniform IR temperature gradient around entire anvil for a thunderstorm system with no vertical wind shear (IR).
- An overshooting top is over the station (VIS and IR).
- Anvil is brighter and/or more textured (VIS).
- From comparing last two pictures: Station is under half of anvil bounded by edge which moves least (IR).
- Station is near 300-mb upwind end of anvil (IR, skip this clue if no upper air data available).
- Station is near the area of low-level inflow (VIS).
- Station is located under a radar echo.

(B) HALF-HOURLY RAINFALL ESTIMATES IN INCHES ARE COMPUTED FROM THE FOLLOWING FACTORS:

1.
CLOUD-TOP TEMPERATURE AND CLOUD GROWTH FACTOR [*IR*].
Determine amount that the coldest cloud tops increased within half-hour.

	>2/3° LAT	>1/3° ≤2/3° LAT	≤1/3° LAT or same	Areal decrease of shade or warming from white to rpt gray or within the rpt gray	Coldest tops 1 or more shades warmer
Med Gray (-32 to -41°C)	0.25	0.15	0.10	0.05	T
Lt Gray (-41 to -52°C)	0.50	0.30	0.15	0.10	
Dk Gray (-52 to -58°C)	0.75	0.40	0.20	0.15	
Black (-58 to -62°C)	1.00	0.60	0.30	0.20	
Rpt Gray* (-62 to -80°C)	1-2.00	0.60-1.00	0.30-0.60	0.30	
White (below -80°C)	2.00	1.00	0.60	0.40	0.10

**Colder repeat gray shades should be given higher rainfall estimates.*

OR

DIVERGENCE ALOFT FACTOR* [*IR and 200-mb Analysis*].

Med Gray	Lt Gray	Dk Gray	Black	Rpt Gray	White
0.15	0.30	0.40	0.60	0.60-1.00	1.00

**IR imagery shows edges of thunderstorm anvil along the upwind end forming a large angle of between 50-90 degrees pointing into the wind; 200-mb analysis often shows these storms just downwind from where the polar jet and subtropical jet separate.*

2. **OVERSHOOTING TOP FACTOR** [*VIS*, *IR*]. Add to the Overshooting Tops*:

Med Gray	Lt Gray	Dk Gray	Black	Rpt Gray	White
0.50	0.45	0.40	0.30	0.30	0.30

**High-resolution visible imagery is the best data for determining this factor.*

3. **THUNDERSTORM OR CONVECTIVE CLOUD LINE MERGER FACTOR** [*IR*, *VIS*]. Add 0.50 to the colder tops in the area of the merger.

4. **SATURATED ENVIRONMENT FACTOR** [*IR*, *VIS*]. Add to the colder tops stationary for a given amount of time:

	Med Gray	Lt Gray	Dk Gray	Black	Rpt Gray	White
≥1 Hour but <2 Hours	0.20	0.20	0.20	0.20	0.30	0.30
≥2 Hours	0.40	0.40	0.40	0.40	0.50	0.50

5. **PRECIPITABLE WATER FACTOR** [*Surface to 500-mb Precipitable Water Analysis*]. At this time only used to modify the estimate computed for thunderstorms in dry environments or with high bases.

TOTAL HALF-HOURLY CONVECTIVE RAINFALL ESTIMATES (in inches) =

$$\left(\text{Cloud-Top Temperature and Cloud Growth Factor or Divergence Aloft Factor})^{1} + \text{Overshooting Top Factor}^{2} + \text{Merger Factor}^{3} + \text{Saturated Environment Factor}^{4}\right) \bullet \left(\frac{\text{Observed Surface to 500-mb Precipitable Water}}{{}^{*}1.5\ (\text{Standard Surface to 500-mb Precipitable Water for the Technique})}\right)^{5}$$

**This ratio is only used when the observed surface to 500-mb precipitable water is less than 1.3 inches.*

[Scofield:4-1981]

Figure 2. Convective rainfall technique.

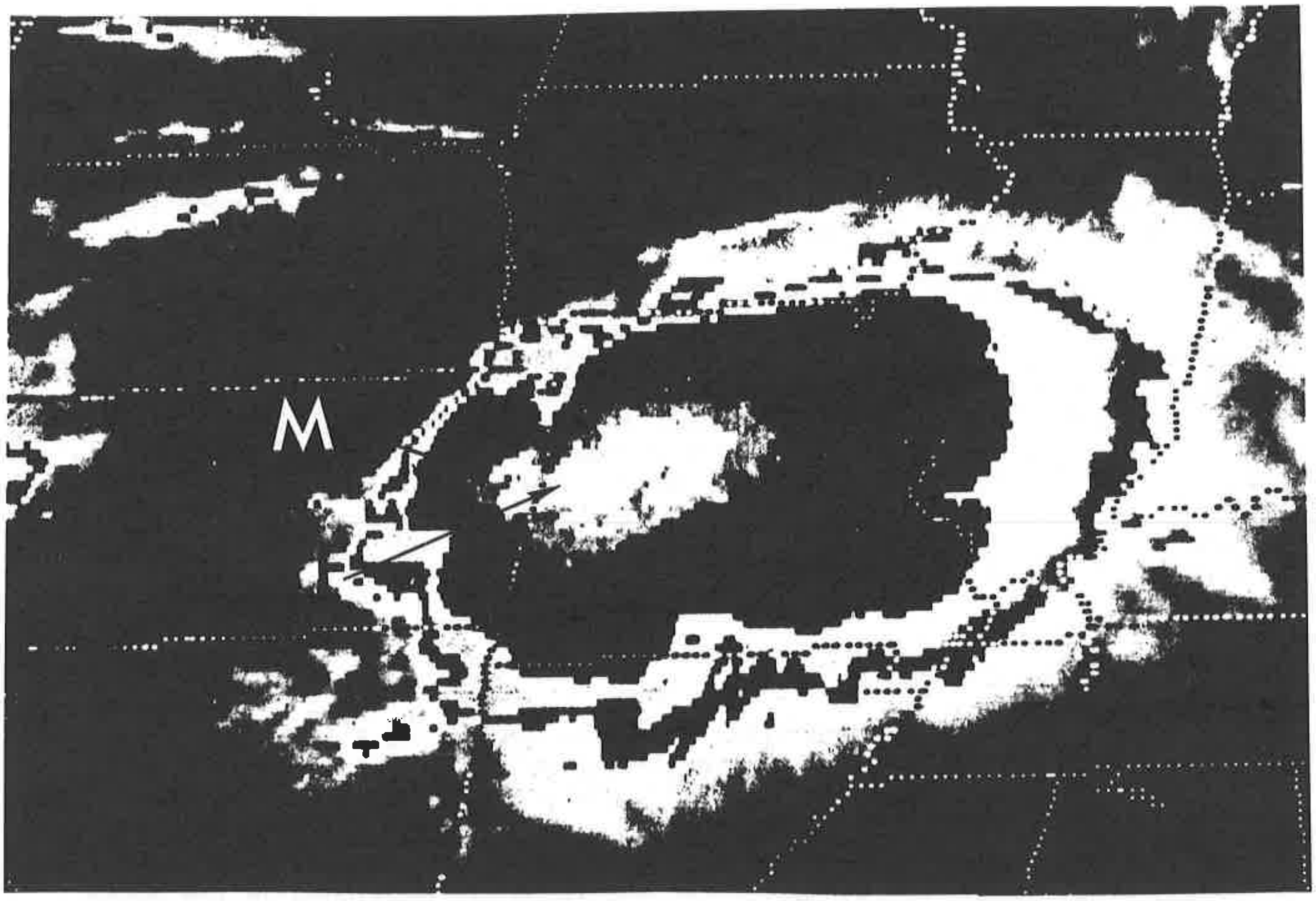


Figure 3. Enhanced infrared imagery (Mb Curve), 0900 GMT, August 13, 1982.

3. TROPICAL CYCLONE TECHNIQUE

In an unpublished manuscript, Spayd and Scofield (1982) presented a technique for estimating precipitation amounts from tropical cyclones using IR and visible data. This technique could be modified for use every 3 to 6 hours for those areas not receiving hourly imagery. Unenhanced IR data could also be used in this technique, but using enhanced imagery yields a more detailed analysis. The tropical cyclone technique is presented in Figure 4 and is divided into four steps:

1. The following cloud features are located in the tropical cyclone: eye or cloud system center, wall cloud, central dense overcast area, outer banding area and area of cold convective cloud tops embedded in the outer banding.

2. Isolines are drawn around the above-mentioned cloud features.

3. Rainfall estimates are computed for the cloud features.

4. A total estimated rainfall potential is computed for the tropical cyclone before landfall.

On September 12-13, 1979, Hurricane Frederic crossed Cuba and travelled northwesterly until the eye made landfall near Mobile, Alabama, at 0300 GMT (September 13). An enhanced IR image of the hurricane during landfall is shown in Fig. 5. The total estimated rainfall potential of Hurricane Frederic was calculated to be 12.9 inches at 2200 GMT, 5-hours before landfall of the eye near Mobile. The observed 24-hour rainfall analysis is shown in Fig. 6; estimates for the tropical cyclone technique are shown in Fig. 7. In this case study, the total estimated rainfall potential of the cyclone and the hourly tropical cyclone technique estimates corresponded accurately to the magnitude and placement of the heaviest rainfall.

4. EXTRATROPICAL CYCLONE TECHNIQUE

Scofield, Oliver and Spayd (1982) are also developing a technique for estimating hourly extratropical cyclone precipitation by analyzing features in the satellite and radar data and surface and upper air observations. The methodology is being developed in the form of a flow diagram or decision tree and will be easy to apply manually or be placed on a man-machine interactive system. The principal steps in the extratropical cyclone technique mentioned in the above reference are shown in Fig. 8. In Step 1, areas of precipitation and the heaviest precipitation are identified and analyzed in the satellite pictures. The following categories of clues are used in making these decisions: observed precipitation in the surface and radar data, signatures in the imagery associated with precipitation and precipitation mechanisms in the atmosphere. In Step 2, estimates are computed based on the analyses in Step 1; in Step 3, the estimates are modified by the available moisture. This technique is being revised as we gain more experience and understanding in the satellite interpretation of extratropical cyclones.

5. SUMMARY AND OUTLOOK

This paper presented techniques for estimating rainfall from thunderstorms, tropical cyclones, and extratropical cyclones. For those countries receiving

Locate the following cloud features in the tropical cyclone:

- Eye or cloud system center.
- Wall cloud.
- Central Dense Overcast (CDO) area.
- Outer Banding Area (OBA).
- Area of cold convective cloud tops embedded in the OBA area.

↓

From comparing two consecutive pictures, draw isolines in the second picture around the following:

- Wall cloud (approximately 20 n miles either side of the eye or the cloud system center).
- A 50 n mile radius either side of the cloud system center within the CDO; heavy rain often occurs within this radius. Use IR and VIS to help modify the size and location of the isoline. Within this isoline, coldest and brightest areas should also be analyzed; these areas often locate the heaviest rainfall within the CDO.
- Bands in the OBA that are convective.
- Within the OBA, areas of cold convective cloud tops embedded in the convective cloud bands.

↓

From comparing two consecutive pictures, compute rainfall estimates for the isolines drawn above; the underlined rainfall accumulation is normally the value used in the estimate.

↓

A. Estimates for the CDO Area and Wall Cloud	Rainfall Accumulations[1] (inches per hour)
CDO (a 50 n mile radius either side of the cyclone center; this radius can be modified by the IR and VIS).	[3]0.50-$\underline{1.00}$-2.00[2]
Outer edge of the CDO.	0.01-$\underline{0.05}$-0.10
Wall cloud (20 n miles either side of the cyclone center(,	[3]1.00-$\underline{2.00}$-3.00

1. The colder the canopy temperature in the IR and the brighter and more textured the canopy is in the VIS, the higher the rainfall estimate.
2. Colder and brighter features analyzed within the CDO should be given higher rainfall estimates.
3. Cloud tops that are becoming warmer should have lower rainfall estimates.

B. Estimates for the OBA	Rainfall Accumulations[1] (inches per hour)
Outer Banding Area.	0.10-$\underline{0.30}$-0.50
The first band from the CDO located in the onshore flow.[2]	0.50-$\underline{1.00}$-2.00
Area of cold convective cloud tops embedded in the convective cloud bands.[3]	
Growing, becoming colder, or remaining the same.[4]	0.25-$\underline{1.00}$-4.00[5]
Decreasing in area.[4]	0.10-$\underline{0.50}$-1.00
Becoming warmer.[4]	0.05-$\underline{0.20}$-0.50

1. The colder the canopy temperatures in the IR, the higher the rainfall estimate.
2. Only considered when the OBA is moving onshore.
3. These estimates are obtained from the convective rainfall technique for estimating rainfall from convective systems.
4. These categories are determined from the changes observed in the thunderstorm anvil in two consecutive pictures.
5. The more rapid the convective cloud tops grow and/or become colder, the higher the estimate.

↓

Total Estimated Rainfall Potential:

$$\frac{R_{CDO}\,D_{CDO} + R_{WC}\,D_{WC}}{V} + \frac{R_{OBA}\,D_{OBA} + R_{ECT}\,D_{ECT}}{V}$$

Where,

R_{CDO}, R_{WC}, R_{OBA}, and R_{ECT} = Rainfall rates of the CDO, wall cloud (WC) area, significant bands in the OBA, and embedded cold convective tops (ECT), respectively.

D_{CDO}, D_{WC}, D_{OBA}, and D_{ECT} = Cross sections of the cloud features in the direction of motion.

= Speed of tropical cyclone.

[Scofield:12-81]

Figure 4. Tropical Cyclone Technique.

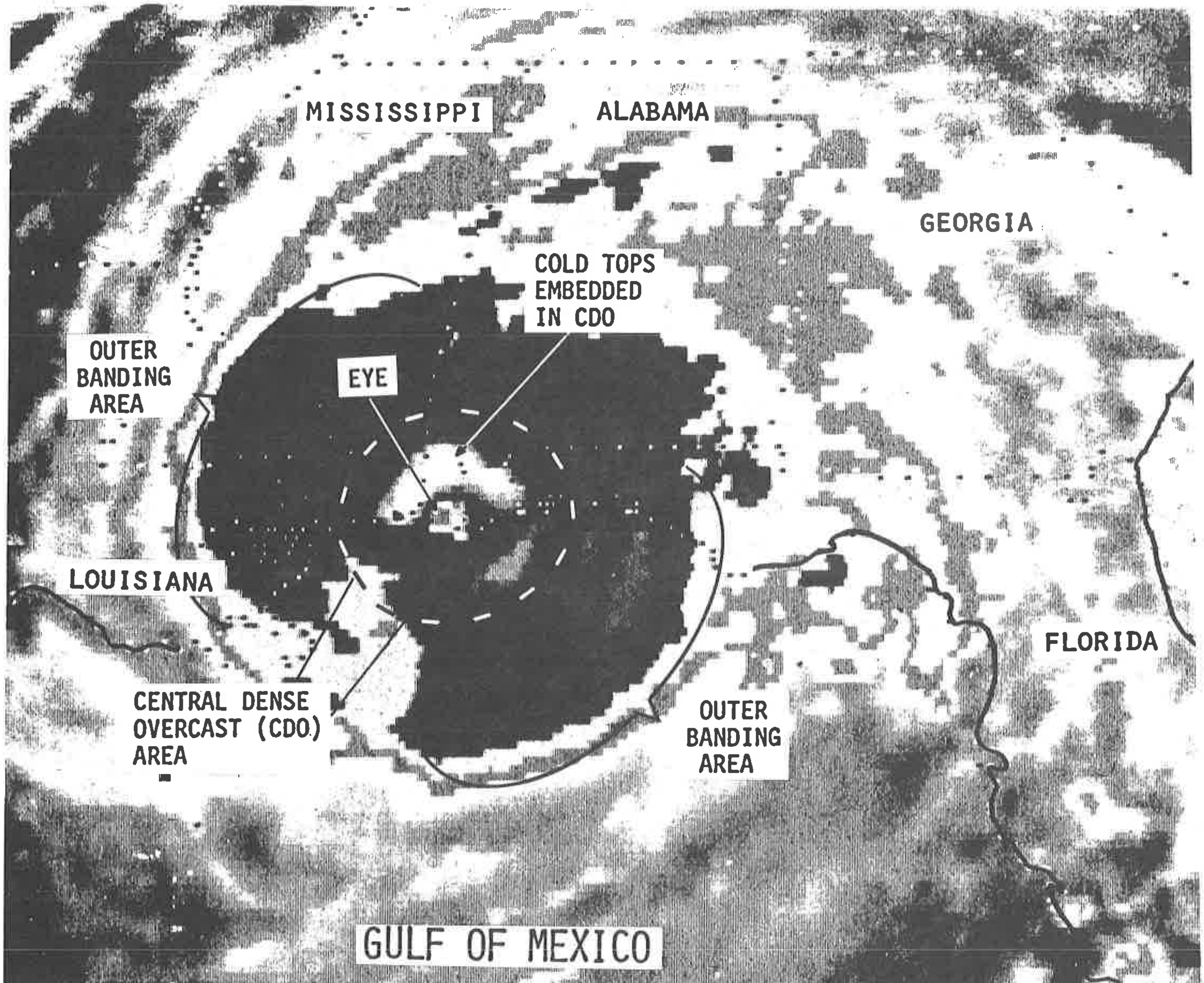


Figure 5. Enhanced infrared imagery (Mb Curve) of Hurricane Frederic, 0300 GMT, September 13, 1979.

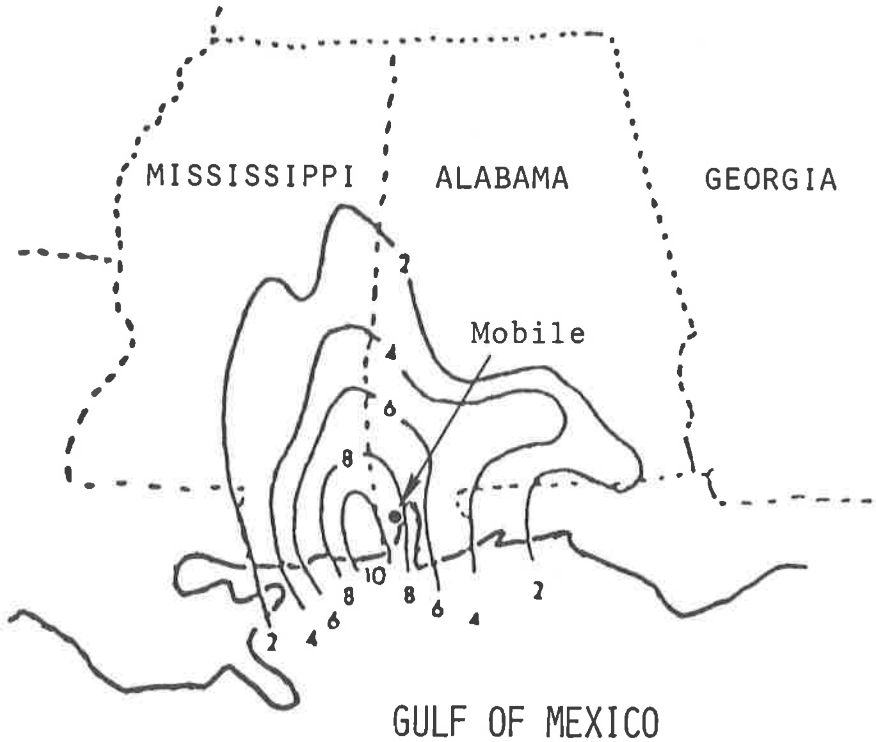


Figure 6. Observed 24-hour rainfall 1200 GMT, September 12 to 1200 GMT, September 13, 1979.

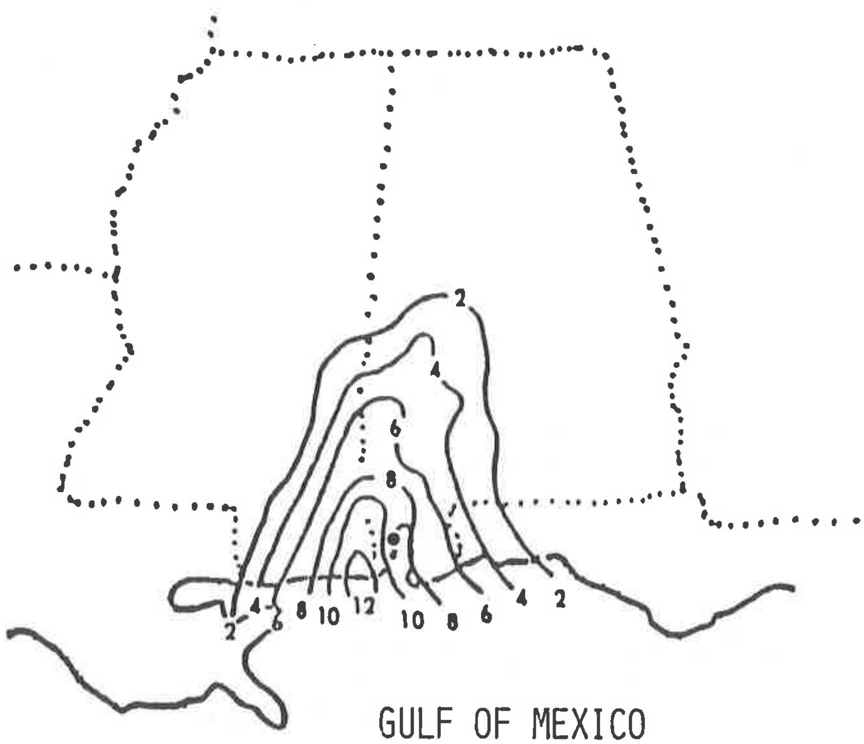


Figure 7. Tropical rainfall estimates, 2100 GMT, September 12 to 1130 GMT, September 13, 1979.

EXTRATROPICAL CYCLONE TECHNIQUE

I

Clues / Categories	Area of Precipitation Versus NO Precipitation	Area of Moderate to Heavy Precipitation
Observed precipitation.	• The occurrence of precipitation in the surface data and the radar data. • Precipitation occurring in one portion of the cloud may also be occurring in the remainder of the cloud that has similar appearance.	• Occurrence of moderate or heavy precipitation in the surface data. • Occurrence of VIP Level 2 or higher in the radar data. • Moderate-to-heavy precipitation in one portion of the cloud may also be occurring in the remainder of the cloud that has similar appearance.
Signatures in the imagery associated with precipitation.	• The comma head and comma tail in a synoptic-scale comma cloud. • A baroclinic leaf. • Middle-level clouds--will often move in a different direction and speed from upper-level cirrus clouds.	• Convective cloud bands or elements. This includes the comma tail associated with the synoptic-scale comma cloud. • Subsynoptic-scale waves. • Bright textured clouds in VIS; cold tops in the IR. • Consecutive IR pictures showing middle-level clouds becoming colder. • Inflection points. • Deformation zones.
Precipitation mechanisms in the atmosphere.	• Warm air advection with high moisture content. • Positive vorticity advection. • Upper-level jet axis. • Frontal boundaries. • Upslope flow. • Vertical instability. • Frictional effects.	• To the north of the jet max at the exit zone where it crosses the comma or baroclinic leaf cloud (often applies to West Coast storms). • To the south of the jet max at the entrance zone where it crosses the comma, baroclinic leaf, or middle-level cloud system (often applies to storms east of the Rockies). • Location of maximum warm air advection, low-level moisture convergence, and/or positive vorticity advection within a comma, baroclinic leaf, or middle-level cloud system. • Upslope flow. • Combination of two or more of the above mechanisms.

II

PART A

OBSERVED RAINFALL INTENSITY IN SURFACE DATA

Observed Intensity	Rainfall Accumulations (inches/hour)
Moderate	0.10 to 0.30
Heavy	>0.30

OR

ESTIMATED RAINFALL INTENSITY* FROM THE RADAR DATA

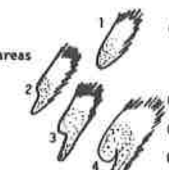
Code Number (VIP Level)	Echo Intensity	Rainfall Accumulations (inches/hour)
2	Moderate	0.1-0.3
3	Heavy	0.3-0.5
4	Very Heavy	0.5-1.0
5	Intense	1.0-2.0
6	Extreme	>2.0

*Take into account frozen precipitation conversion factor of rain/frozen precipitation ratio (radar reflectivity).

PART B

ESTIMATED RAINFALL FROM SATELLITE SIGNATURES

Observed Satellite Signature	Rainfall Accumulations[1] (inches/hour) Level Terrain
SIGNATURES ASSOCIATED WITH SUBSYNOPTIC-SCALE SYSTEMS	
Convective cloud bands or elements. (If convective clouds are deep--colder than -32°C--use the Scofield/Oliver technique for estimating convective rainfall.)	
• Cloud bands. (This includes the comma tail associated with the synoptic-scale comma cloud.)	0.20-0.30
• Cloud band merger with synoptic-scale fronts or other cloud bands.	Add 0.20-0.40 to the above.
Subsynoptic-scale waves and those with developing circulation centers.	
• Category 1	0.10-0.20
Heavy precipitation areas are stippled.	
• Category 2	0.20-0.30
• Category 3	0.30-0.40
• Category 4	0.40-0.50
Subsynoptic-scale wave merging with a convective cloud band.	Add 0.20-0.40 to the above.
SIGNATURES ASSOCIATED WITH CLOUD APPEARANCE AND TEMPERATURE	
• Bright textured clouds in VIS and cold tops in the IR.	0.05-0.30
• Consecutive IR pictures showing middle-level clouds becoming colder.	0.10-0.40
SIGNATURES ASSOCIATED WITH SYNOPTIC-SCALE SYSTEMS	
• Inflection points in a synoptic-scale comma cloud.	0.05-0.30
• A developing synoptic-scale comma or leaf-shaped cloud.	0.05-0.30
• Mid-level deformation zones.	0.05-0.30



1. If one or more of the moderate to heavy precipitation mechanisms at top of page accompany the satellite signature, give the signature the higher precipitation estimate.

UPSLOPE FLOW — Add 0.20-0.40 inches/hour to the above signature.

PART C

ESTIMATED RAINFALL FROM PRECIPITATION MECHANISMS IN THE ATMOSPHERE

Observed Precipitation Mechanisms	Rainfall Accumulations (inches/hour)
• To the north of the jet max at the exit zone where it crosses the comma or baroclinic leaf cloud (West Coast storms).	0.05-0.30
• To the south of the jet max at the entrance zone where it crosses the comma or baroclinic leaf cloud (east of Rockies).	0.05-0.30
• Location of the maximum warm air advection, low-level moisture convergence, and/or positive vorticity advection within a comma, baroclinic leaf, or middle-level cloud system.	0.05-0.30
• Upslope flow.	≥0.30
• Combinations of two or more of the above mechanisms.	≥0.30

III

Estimate obtained from Part A, B, or C) X * ($\frac{\text{Observed surface to 500-mb precipitable water}}{\text{Standard surface to 500-mb precipitable water}}$)

*As a first guess, only use this precipitable water (PW) factor when the observed surface to 500-mb PW is ≤0.75 inch and use a value of 1.0 inch as a standard surface to 500-mb PW.

[Scofield:10-81]

Figure 8. Extratropical cyclone technique.

GOES imagery, the three techniques offer meteorologists and hydrologists a simple tool for monitoring precipitation with existing resources. Results from operational applications of these techniques and case studies are being used to verify and to improve (when needed) the convective rainfall, tropical cyclone, and extratropical cyclone methodologies.

ACKNOWLEDGEMENTS

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GROUND WATER RESOURCES OF THE CENTRAL SAVANNAH RIVER AREA, SOUTH CAROLINA - REEVALUATED

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South Carolina Water Resources Commission

ABSTRACT

The Geology and hydrology of the Savannah River Plant and its environs on the South Carolina side of the Central Savannah River was initially evaluated by the U.S. Geological Survey during the period 1950-1965. The stratigraphic section overlying a basement complex of metamorphic rock and sediments of Triassic age (Dunbarton Basin) include mostly unconsolidated sediments of Late Cretaceous, Tertiary, and Quaternary age. The principal aquifers consist of sand and gravel within the Tuscaloosa (and/or Middendorf) Formations of Late Cretaceous age, the overlying Ellenton Formation of Paleocene (?) age, and the Congaree and McBean Formations of Claiborne age. Each aquifer is confined by clay or saprolite and has different poteniometric heads. The most permeable aquifers are the sand and gravel of Cretaceous age and the coarse sands of the Congaree Formation. Extremely low hydraulic conductivities in the basement crystalline and Triassic rocks provide very low yields of non-potable water to wells. The potentiometric surface of the Cretaceous sand aquifer indicates that the outcrop areas function primarily as discharge areas. While some recharge occurs in the interfluve areas, the bulk of recharge is from leakage across overlying Tertiary sediments in up dip areas. A depression in the potentiometric surface along the Savannah River downstream from Augusta reflects an atypical gradient reversal.

After 30 years of pumping substantial quantities of water from the Cretaceous aquifer and lesser quantities from the Claiborne aquifer, the stress on both systems appears to have resulted in only normal strain.

Subsequent to the original hydrogeologic studies (1954-1960), the area has been subjected to intensive reevaluation of its geology and hydrology. Nonetheless, to date, the principal parameters of the reported model appears to be reaffirmed as originally defined.

INTRODUCTION

In accordance with the conference objective, this paper refers to one of Georgia's adjacent areas, the central Savannah River area, specifically the South Carolina side of the river. Its purpose is to review the original conceptual model of the hydrology and geology of the Savannah River Plant (SRP) and its environs, as evaluated by the U.S. Geological Survey from the original siting of the plant in 1950 up to the early seventies; and to evaluate this with the results of subsequent studies. The area of interest is located almost midway between the Fall Line and the Citronella Escarpment, on the left bank of the Savannah River.

This area is underlain by a sequence of unconsolidated and partly consolidated sediments of Late Cretaceous, Tertiary and Quaternary age, deposited unconformably on a basement complex comprised of rocks of Precambrian (?) to Paleozoic age and sedimentary rocks of Triassic age. The oldest and lower-most unconsolidated sediment, the Tuscaloosa (or Middendorf) Formation of

Late Cretaceous age is overlain in the subsurface by the Ellenton Formation of Paleocene to Cretaceous (?) age and in turn by the Congaree, McBean, and Barnwell Formation of Eocene age, the Hawthorne Formation of Miocene age and alluvial deposits of Pliocene and Pleistocene age (Figure 1).

Cooke (1936) recognized seven marine terrace deposits of Pleistocene age on the Atlantic Coastal Plain of South Carolina, five of which he indicated as present in the Savannah River valley, extending from an altitude of 270 msl (mean sea level, in feet) to 100 msl. However these terraces are not represented on Figure 1.

The lithology, thickness, distribution, structure and history of these Cenezoic and Mesozoic sediments, as recognized in the original studies, have been described in a number of reports including those of Cooke (1936), Siple (1957, 1964, 1967), Marine and Siple (1964)(1974) and others and will not be repeated here, except for a brief description of their lithology and faunal content. The sediments form a wedge, about 1000 feet thick at SRP, thickening towards the southeast with the uppermost beds dipping about 8 feet per mile and the basal ones 36 feet per mile. Some differences of opinion exist regarding the nomenclature of stratigraphic units on opposite sides of the Savannah River but essentially the lithologic sections are similar. A table showing the comparision and equivalency of these units is shown in Du Pont (1983) and Bechtel (1982).

MIOCENE DEPOSITS

Hawthorne Formation

The surficial sediment in the upland areas, the Hawthorne Formation, consists mainly of tan, red, purple and gray sandy clay containing coarse gravel and limonitic nodules with intensive weathering of the deep red and purple clays into polygonal shapes. A common characteristic of the Hawthorne Formation is the presence of numerous sediment-filled fissures or clastic dikes criss-crossing the clayey sands. The fissures extend to considerable depth and are filled by different types of material. Some of this material consists of yellow tan to brown sand but in other dikes it may also consist of a stratified or laminated greenish gray, silty to sandy clay. The walls of the dikes are usually lined with a sheath of iron and/or manganese cemented quartz sand. Whereas many dikes have a random orientation, a significant number appear to have a preferred orientation of either N5°E or N85°E.

The Hawthorne Formation is also characterized by the presence of the fossil tube *Halymenites major* Lesquereux, (or Callianassa or *Ophiomorplia nodosa*) which occurs quite commonly in the sandy clay of this unit.

EOCENE DEPOSITS

Barnwell Formation

The Barnwell Formation includes those sandy deposits of late Eocene age that unconformably overlie the McBean Formation in Aiken and Barnwell counties. It consists mainly of deep red, fine to coarse clayey sand and sandy clay. Other parts of the formation contain beds of mottley gray, sandy clay and layers of cemented ferruginous sandstone. The deep-red materials are generally semi-consolidated and exposed in steep-walled cliffs or bluffs and is similar in appearance to loess deposits.

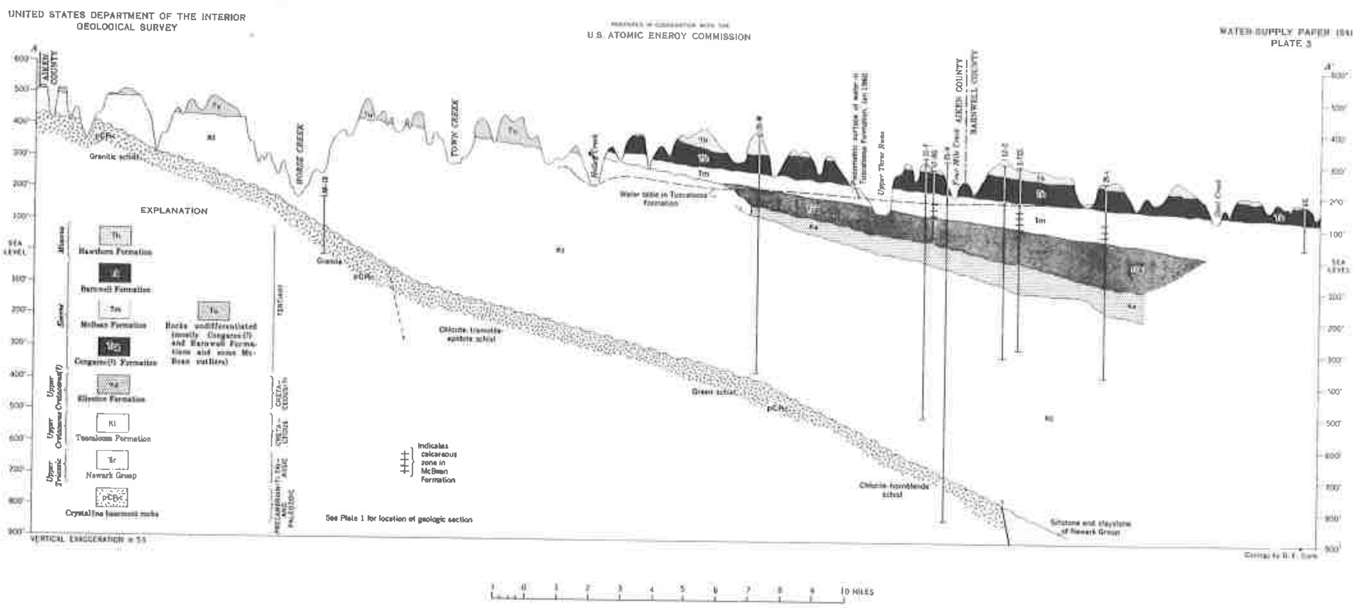

Figure 1. General geologic profile along line A - A', Savanah River Plant area, South Carolina (after Siple, 1967).

On the South Carolina side of the Savannah River only a very limited number of fauna have been recognized in the Barnwell Formation. Our studies revealed only a few samples of Ostrea gigantissima Finch which is also found at Shell Bluff and Griffin Landing on the Georgia side.

McBean and Congaree Formations

The McBean and Congaree Formations represent equivalents of the Claiborne Group of middle Eocene age in the Gulf Coastal Plain. Originally Cooke (1936, p. 55) considered the McBean Formation to include all deposits of Claiborne age in South Carolina. Later, Cooke and MacNeil (1952, p. 24) restricted the McBean to deposits of late middle Claiborne age, equivalent to the Cook Mountain Formation of Mississippi. Thus, as restricted, it may be considered in South Carolina as a clastic facies of the Santee Limestone, which crops out several miles to the southeast. Older Claiborne deposits were raised to formational rank by Cooke and MacNeil (1952) and designated the Congaree and Wharley Hill Formations.

In South Carolina the Claiborne deposits consist of fine- to medium-grained, clean, highly-polished quartz sand; green glauconitic marl and clayey sand; laminated beds of red, brown, yellow and ochre colored clay (generally of the montmorillonite group); impure beds of soft, fossiliferous limestone or marl; and lenses of silicified limestone. The McBean Formation is the most fossiliferous unit in the entire stratigraphic section, containing a variety of gastpropods and pelecypods along with a suite of Foraminifera and Ostracoda (Siple, 1967, Figure 17).

A bed of calcareous, sandy clay or marl about 15 to 30 ft thick occurs at the base of the McBean overlying the Congaree Formation. This deposit has been subjected to subsurface solution resulting in the subsidence of overlying beds and the formation of sink holes. It may also be associated with a number of Carolina bays which occur primarily in the southeastern part of the area. Either the calcerous zone near the base of the McBean or a greenish-gray clay in the upper part of the Congaree Formation functions as a confining layer in separating water in the McBean from that in the Congaree, producing a head differential of over 60 to 80 feet in some areas.

The Congaree Formation in many respects is lithologically similar to the McBean but consists of more well-sorted coarser sands, fuller's earth, brittle siltstone, and light gray to green shale alternating with thin-bedded, fine-grained sandstone.

PALEOCNE DEPOSITS

Ellenton Formation

The dark lignitic clay and associated coarse sand that occurs in the subsurface above the Tuscaloosa/Middendorf Formation and beneath the formations of Claiborne age constitute the Ellenton Formation. Selenite crystals are distributed sparsely throughout the quartz sands. In some areas the medium to coarse sand is replaced by very coarse sand and gravel. Lignite and decomposed pyrite or marcasite fragments, muscovite and kaolin aggregates are fairly common. The tentative age assignment of the Ellenton Formation was originally interpreted as late Cretaceous, based on the similarity of its lithology and stratigraphic position to the Black Creek Formation occurring several miles to the southeast and to the Blufftown Formation in western Georgia. The Ellenton Formation also resembles, but less definitely, deposits of Wilcox age elsewhere in the state. In 1982 Dave Prowell advised the writer (oral communication) that on the basis of their pollen analyses the unit is more probably Paleocene in age than Late Cretaceous. The permeable water-bearing sands of the Ellenton in some areas are not separated by confining beds from sands in the underlying Tuscaloosa Formation. The two units may have mutual hydraulic connection in these areas.

CREATACEOUS (LATE) DEPOSITS

Tuscaloosa (Middendorf) Formation

In the SRP area the Tuscaloosa Formation consists of fluvial and estuarine deposits of light-gray to white, tan and buff cross-bedded quartzitic to arkosic sand and gravel interbedded with lenses of white, pink, red, brown and purple silt and clay. Ferruginous sandstone concretions are commonly found in nodular or lenticular deposits at the contact between a permeable bed and an underlying less permeable bed and nodules of siderite are scattered throughout some of the silt and clay. Extensive lenses of kaolin ranging up to 50 feet in thickness are present in the Tuscaloosa and are particularly abundant immediately southeast of the Fall Line where they are mined extensively. However, these lenses pinch out rather quickly and are absent farther down dip.

Basement Rocks

The basement rocks range in age from Triassic to Precambrian. The older rocks consist of a granite-diorite injection complex characteristic of the Charlotte Belt (King, 1955) and metamorphosed sedimentary rocks and associated volcanics of the Carolina Slate Belt. The Triassic rocks include sandstone, siltstone and graywacke.

Well #35-H located near the Aiken-Barnwell county line was cored into basement rock at an altitude of -696 feet. The rock section can be described in general terms as consisting of dark green to greenish gray, fine-grained chlorite-hornblende schist containing numerous healed fractures filled with secondary calcite and zeolite.

The upper surface of the pre-Cretaceous basement rock has been eroded, tilted to the southeast, and buried (Figure 2). The general plane of this surface strikes N62°E and has a dip to the southeast of about 36 feet per mile. Beginning in late 1959 an intensive study was begun at SRP to determine the feasibility of storing high-level radioactive waste in caverns built in the basement rock at depths between 500 to 1000 feet below the rock surface or roughly 1500 to 2000 feet below ground surface.

In connection with this study a series of Deep Rock Borings (DRB) were drilled to penetrate 1000 feet of basement rock. Limited test and water well data had indicated the presence of a weathered mantle of saprolite approximately 40 to 60 feet thick, present on the surface of the buried crystalline rock. This occurrence was corroborated by the core data obtained in the DRB test holes and was found to extend over the entire area. One of these test borings, well

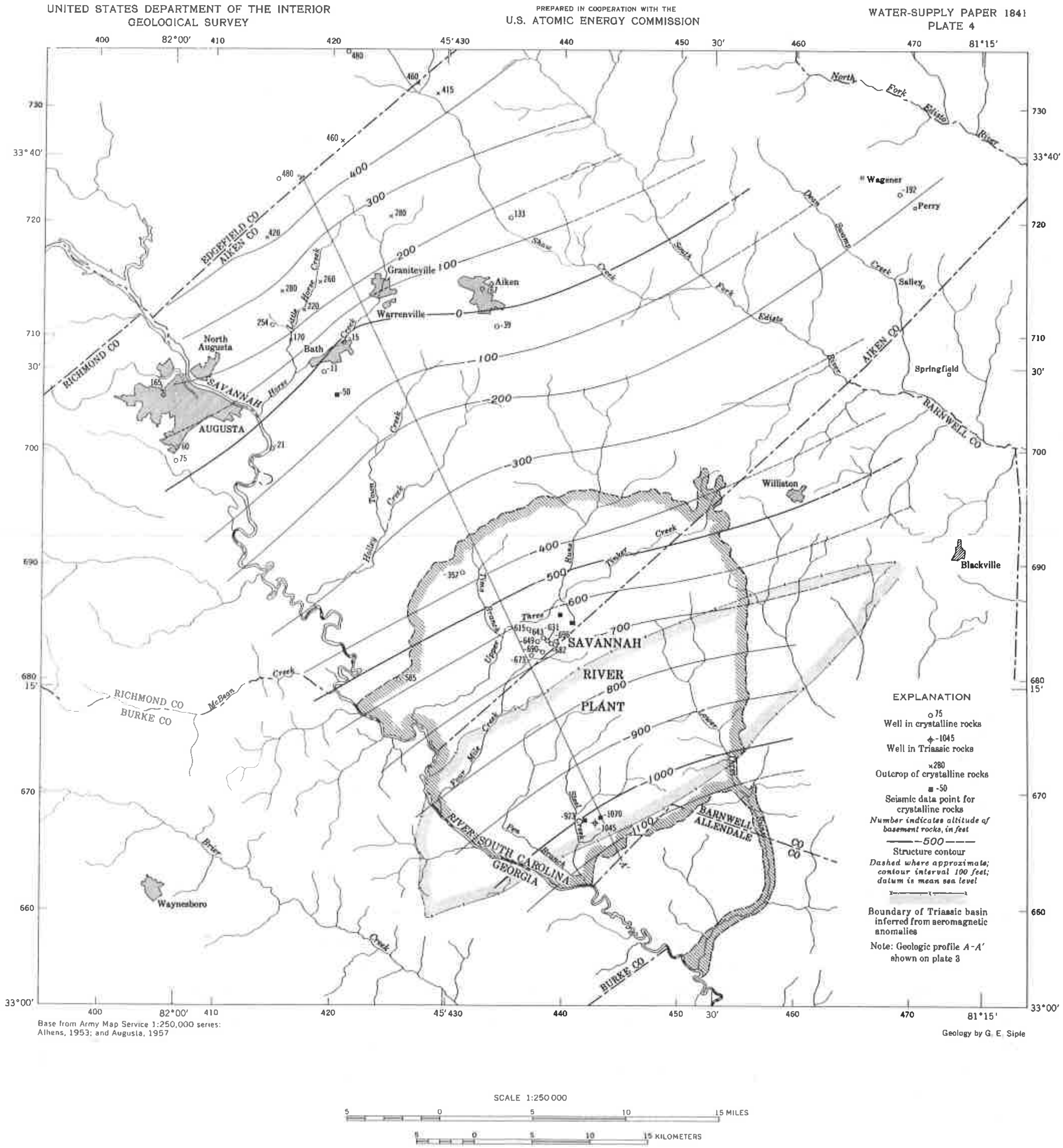

Figure 2. Map showing configuration of surface of basement (Pre-Cretaceous) rocks. Savanah River Plant area, South Carolina (after Siple, 1967).

P-5-R, located near the southern boundary of SRP and in proximity to the site of a seismic refraction survey made in 1953, penetrated 14 feet of brick red siltstone and claystone with included dark gray calcareous pebbles, similar to the fanglomeratic or conglomeritic facies of the Newark Group of Late Triassic age. On the basis of this core, together with the lower seismic velocities and the configuration of low-gamma intensities as shown by a 1958 aeromagnetic survey, the boundaries of a Triassic basin in the southern part of the SRP were identified (Siple and Marine, 1966; Siple, 1967). The basin, subsequently named Dunbarton, (Marine and Siple, 1974) was interpreted to extend about 25 miles to the northeast and about 5 miles to the southwest, into Georgia. Its axis was aligned roughly N63°E, very close to the strike of the schistosity in the host basement rock (Figure 2). Seismic reflection traverses were made to define the boundaries (in particular that of the northwest) of the basin. Additional borings drilled in the Triassic rock to 4,200 feet below land surface (or more than 3000 feet of Triassic) failed to penetrate the bottom of the basin.

Ground Water Hydrology

The two most important aquifers in the area consist of the Congaree Formation of Claiborne age and the Tuscaloosa/Middendorf-Ellenton formation of Cretaceous to Paleocene age. The McBean and Barnwell formations constitute less important aquifers. Sands in the McBean and Congaree Formations are considered good aquifers but the coarser sands in the Congaree have higher permeability and yield considerably more water to wells (over 600 gpm). The buried crystalline or Triassic rocks are of no significance as aquifers and their waters are too poor in quality to use for most purposes. Water in the crystalline rocks is a sodium-sulfate type with over 5,000 mg/L (milligrams per liter) total dissolved solids. The water in the Trassic rocks is a sodium-chloride type with dissolved solids in excess of 18,000 mg/L and chloride in excess if 11,000 mg/L.

The coarse sands and gravels of the Tuscaloosa Formation constitute the most permeable beds in the stratigraphic section and provide the highest yields (to 2000 gpm) to wells. From aquifer tests within the area, transmissivity values were calculated to range from 105,000 to 400,000 gpd per ft. (or an average 200,000 gpd per ft.) and the storage coefficient, from 2×10^{-4} to 8×10^{-4}. The water in this aquifer is of excellent quality, generally soft, acidic and low in dissolved solids (Median = 19 mg/L). However, the last two characteristics give it a tendency to be corrosive to metal surfaces.

The potentiometric surface of the Tuscaloosa Formation indicates that discharge occurs in the outcrop areas. (Figure 3). Some recharge occurs in the interfluve areas and discharges along the streams. Thus, little water moves down-dip from the outcrop area. Moreover, there is a depression in the potentometric surface along the Savannah River downstream from Augusta and along lower Horse Creek. In the northern part of this depression, where the river crosses the outcrop of the Tuscaloosa, ground water discharges into the river very readily. Near the south end of the depression the confining clay above the Tuscaloosa appears to have been breached by erosion during Pleistocene time, and the resultant erosional scar subsequently filled with permeable material. Sands in the McBean and Congaree Formations are considered good aquifers but the coarser sands in the Congaree have higher permeability and yield considerably more water to wells (over 600 gpm).

Subsequent Studies in the Central Savannah River Area

The conditions described above represent the conceptual model of this area's hydrogeology as developed by studies conducted by the USGS in contracts with the U.S. Atomic Energy Commission. Subsequently, a number of investigations

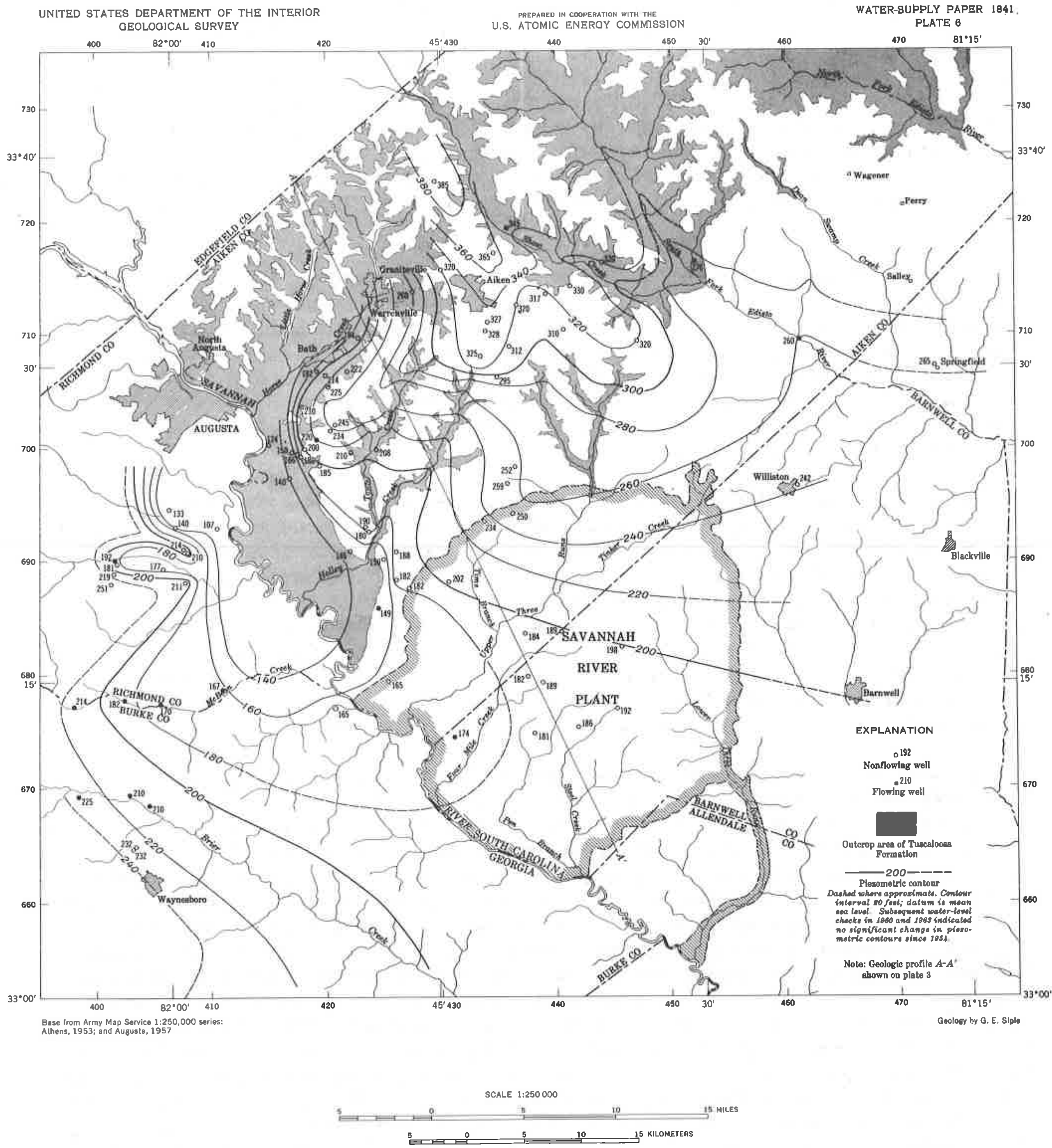

Figure 3. Piezometric map of the Principle Artesian Aquifer of Late Cretaceous age, October 1954, Savanah River Plant area, South Carolina (after Siple,1967).

involving a wide range of the most sophisticated techniques of modern hydrology, have been applied to the same or adjacent areas. It is of interest then, to compare these results and the degree to which they affect the original model.

One of the first subsequent projects to be initiated was the investigation of the eastern boundary of the SRP for the location of the Barnwell Nuclear Fuel Plant BNFP. These results were reported by Bechtel and others (1969) and their conclusions were in line with those of the original model. The same applies to further studies in this area for Chem Nuclear Wastes Inc. located almost immediately east of the BNFP (Cahill, 1982). However, at the latter site the investigations were concentrated mainly on the Tertiary section and its geohydrologic relationships, including both the saturated and unsaturated zones as potential avenues of waste movement. A number of studies were carried out in the location of several industrial sites to the southeast, in Allendale County. None of these studies reported any findings differing from the original SRP model.

Geologists and engineers of the Du Pont Co. Laboratory, (Marine and Routt, 1975, Marine and Root, 1978) and others conducted intensive studies and developed model programs concerning the hydrology of basement, Triassic, and unconsolidated sediments throughout the SRP area. Their conclusions have been released in a number of reports (the latest being the EIS report for the reactiviation of the L-Reactor, DOE-EIS-0108D (1983) and DP-ST-83-829 (1983). These reports appear to substantiate the findings of the original model in those elements that are comparable.

Faye and Prowell (1982) deviated somewhat from the model in suggesting that the fault of Siple (1967) and Marine and Siple (1974), named the Millett fault, had 30 to 700 ft. of displacement from the Tertiary strata down to the basal Triassic- crystalline contacts (Figure 4). They also suggested a second fault, named the Statesboro, extending NE-SW across the Savannah River about 26 miles downstream, in lower Allendale County, South Carolina (Figure 3). While the report did not indicate these faults were capable (i.e., had moved once in the past 35,000 years, or more than once in the last 500,000 years) it did not exclude this possibility.The report also referred to previous stratigraphic, ground water and surface water data in support of the postulated fault.

A fault with displacement of such magnitude, particularly if capable, would have very serious consequences on the construction on a nuclear power plant at the Georgia Power Company's Vogtle site located 7 miles to the northwest of the fault. Geologists for this company and their consultants, the Bechtel Corporation, conducted extensive studies to verify the existence and capability of the Millett fault and secondarily of the Statesboro fault. These studies included a wide range of scientific techniques including surface and subsurface mapping, mineralogic and petrographic analyses, downhole geophysical logging, surface geophysical methods, remote sensing imagery and photography, lineament analysis, potentiometric data, numerical model analysis and the distribution of historic seismicity of the area. Their report (Bechtel, 1982) based in part on the results of two lines of test wells extending across the proposed fault on both sides of the river, concluded that: 1-Core drilling and geophysical logging demonstrated the subsurface continuity of beds 40 to 80 m.y.B.P. (Tertiary to Late Cretaceous) across the trace of the postulated Millett fault (Figure 4); 2- Accustic reflection surveys prepared in the Savannah River demonstrated continuity of sub-surface strata deposited across the strike of both the Millett and Statesboro faults during the last 80 million years (Late Cretaceous): 3- There is no historic siesmicity which can be associated with either fault and that surface and subsurface hydrologic data do not support the presence of the fault in this time frame. In summary they concluded that no capable fault exists in the vicinity of the postulated Millett and Statesboro faults

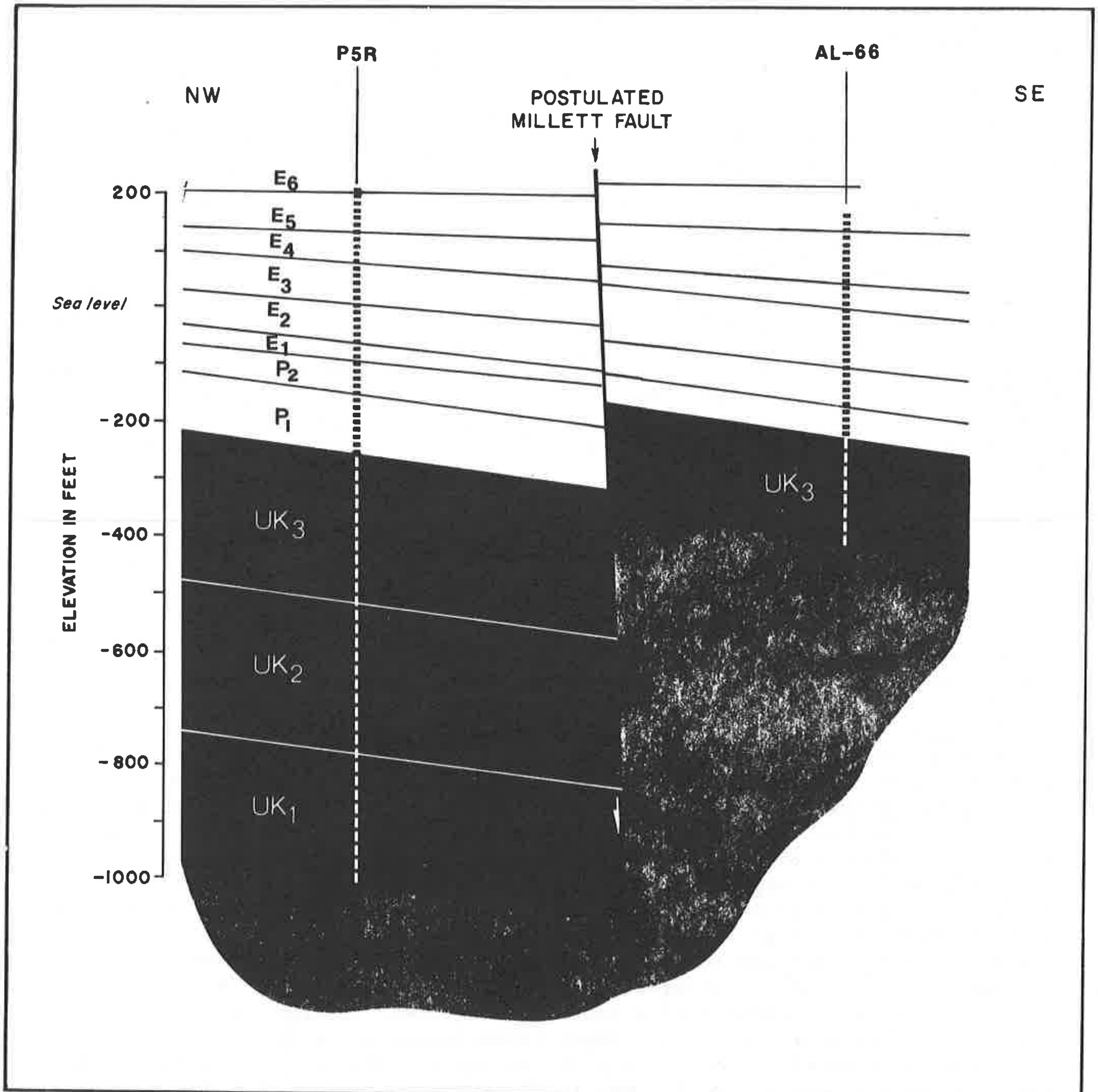

Figure 4. Cross-section from SRP to Allendale County, S.C. showing position and displacement of strata associated with Millett fault (after Faye and Prowell, 1982).

(Figure 5). However the results of the acoustic reflection studies did show the possibility of an approximate offset of about 50 feet at an elevation of -1,100 ft. (msl), believed to represent the surface of the Triassic rocks in the Dunbarton basin. But this contrasts with the 700 foot offset (more than one order of magnitude greater) proposed by Faye and Prowell (1982). Further there was no displacement in any of the Tertiary strata (Figure 4; 4A).

Whereas the several reports prepared by the Du Pont geologists do adhere to the stratigraphic terminology of Siple (1967), the Bechtel report (1982, Fig. 4-3) does substitute alternate terminology for some of the stratigraphic units. Whereas an adequate discussion of these is beyond the scope of this report, it might be noted that some of the differences are affected by two factors: (1) some paleontologists, including Prowell (oral communication, 1983), have observed that the dating of formational units on the basis of their pollen and dinoflagellate analysis has tended to result in younger age designation for the same units dated earlier on the basis of their included macrofauna, ostracoda and foraminifera, and (2) facies changes along the strike along with erosion by the Savannah River, have resulted in a higher carbonate content of similar units in Georgia than those in South Carolina. Thus the southwesterly erosion by the Savannah River (as a result of the Coriolis force) has produced a cuesta (such as Shell Bluff) on the Georgia side. But the material removed by erosion from the South Carolina side produced a slip-off slope. In this instance the river was the responsible agent, albeit it was subsequently designated as a political boundary. The writer believes that the application of the Georgia terminology (Jackson-Claiborne) to the section in South Carolina would make the latter more difficult to understand and interpret.

Recent (1982) measurement and analysis of the potentiometric surface in the Tuscaloosa aquifer, made both by the Du Pont Company and by Georgia Power and Bechtel, confirmed the major flow components of this surface as defined in the original 1967 model. Some minor adjustments were necessitated because of a lower overall head in the aquifer, from about 9 feet in area near the Savannah River to more than 12 feet in the upland areas. The 180 ft contour, instead of being closed, follows a direction more parallel with the river. But the 1982 map is essentially the same today as originally defined.

The loss in head is a comparatively recent development as is indicated by the hydrographs of several monitoring wells. During the period 1951-1961 there was about a 10-foot drop in head in these wells due primarily to heavy pumpage and a severe drought in the middle 1950's. From 1961-77, water levels recovered and remained stable. But since that time there has been an increase in pumpage both within and peripheral to the SRP and this has resulted in a lower water level (Figure 7). A significant amount of this increase has been for irrigation, particularly in Allendale and Barnwell counties. Since about 1978 this increase in pumpage has caused the water levels in the Tuscaloosa-Middendorf and the Ellenton aquifers to decline to or beyond the maximum low levels of the drought year of 1955. Although, this decline is still within the margin of safe utilization of the aquifer, it might be an indication that overpumpage could result if proper conservation proceedures are not followed. Pumpage within SRP during the period of 1963 to 1977 was about 5000 gpm (gallons per minute), or 7.2 mgd (million gallons per day). At the present time it amounts to about 6500 gpm (9.4 mgd). Projected pumpage when the L-Reactor is reactivated in November will be 9400 gpm (13.5 mgd) within SRP and 11,800 gpm (17.0 mgd) in contiguous areas, making a total of 21,200 gpm (30.5 mgd). Siple (1967) concluded that a withdrawal of 37.8 m3/m (cubic meters per minute) or 14.4 mgd for operation of the Savannah River Plant would not exceed allowable drawdowns in wells being pumped in 1960. Marine and Routt (1975)

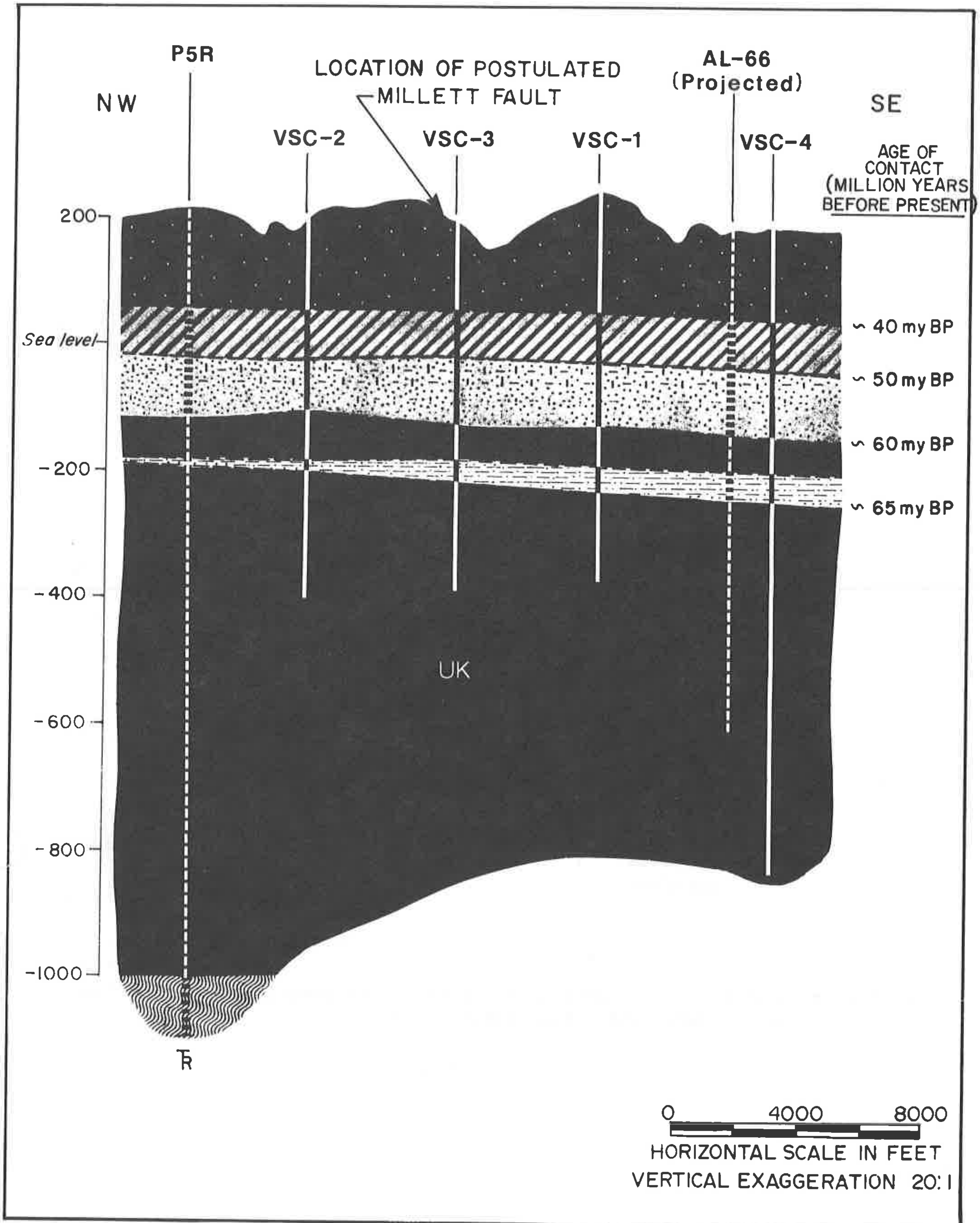

Figure 5. Absence of displacement in postulated Millett fault as determined in line of test wells drilled across the fault (from Bechtel, 1982).

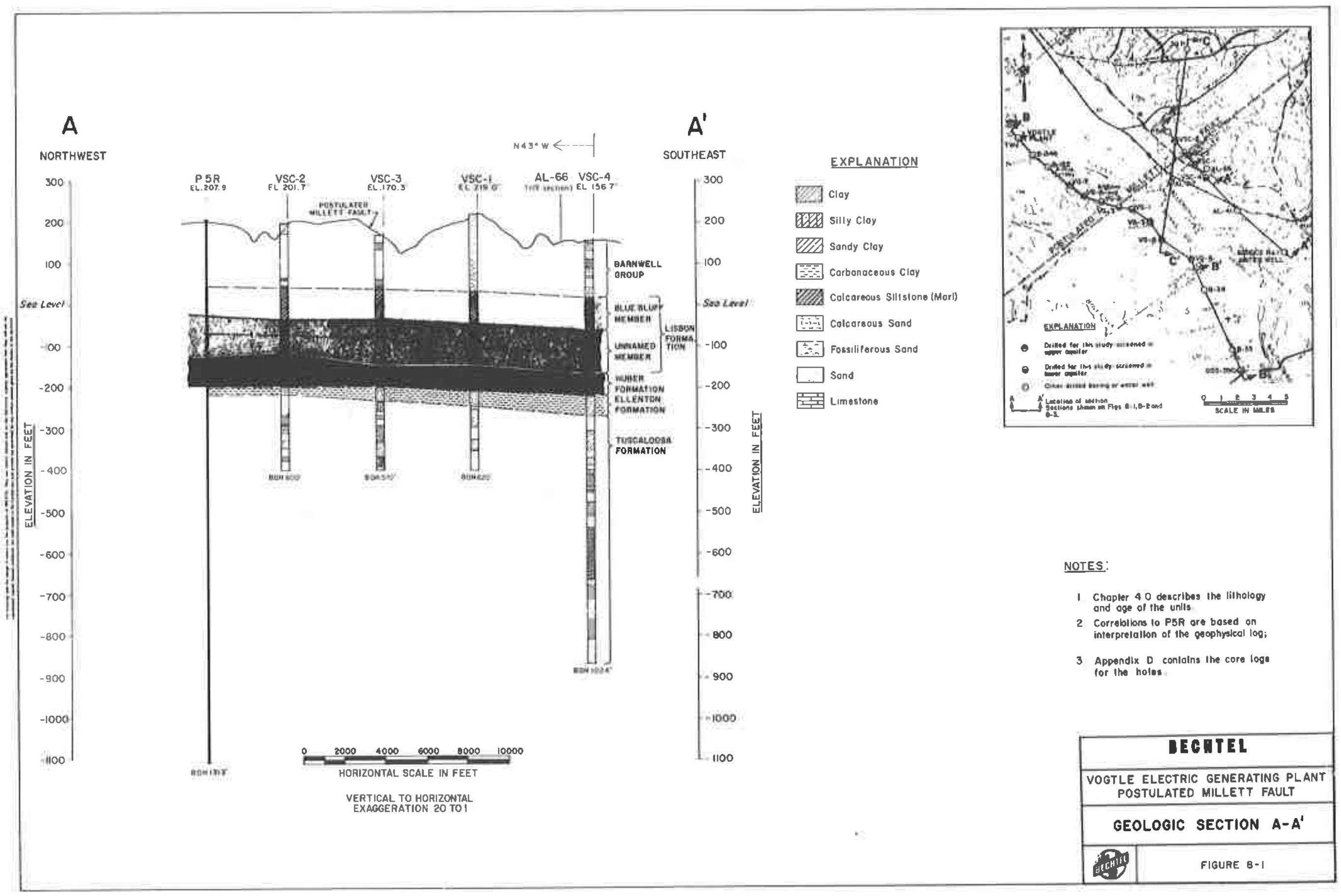

Figure 5A. Geologic cross-section of Figure 5 with location and formational units identified (after Bechtel,1982).

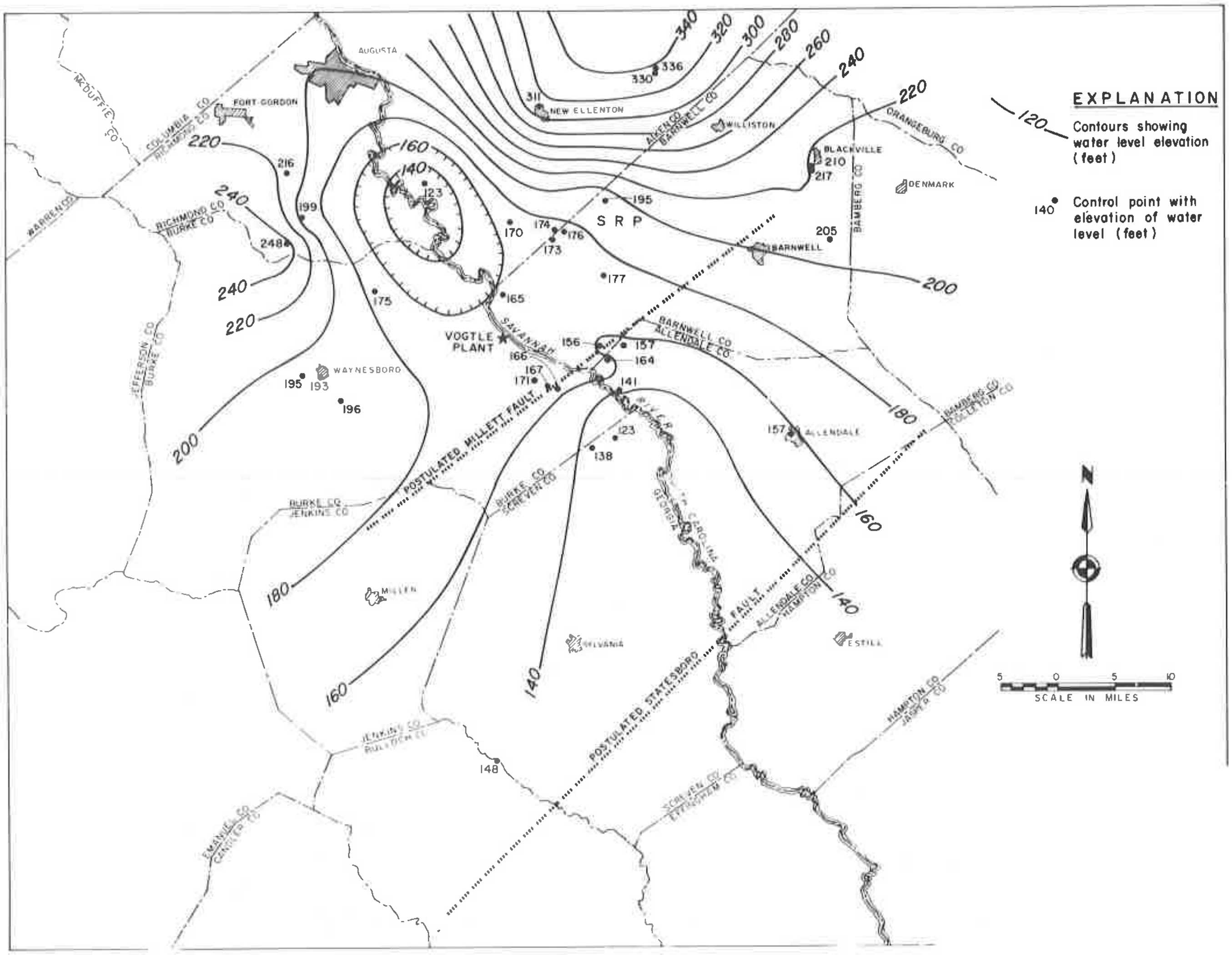

Figure 6. Piezometric surface of Tuscaloosa Formation(from Bechtel,1982).

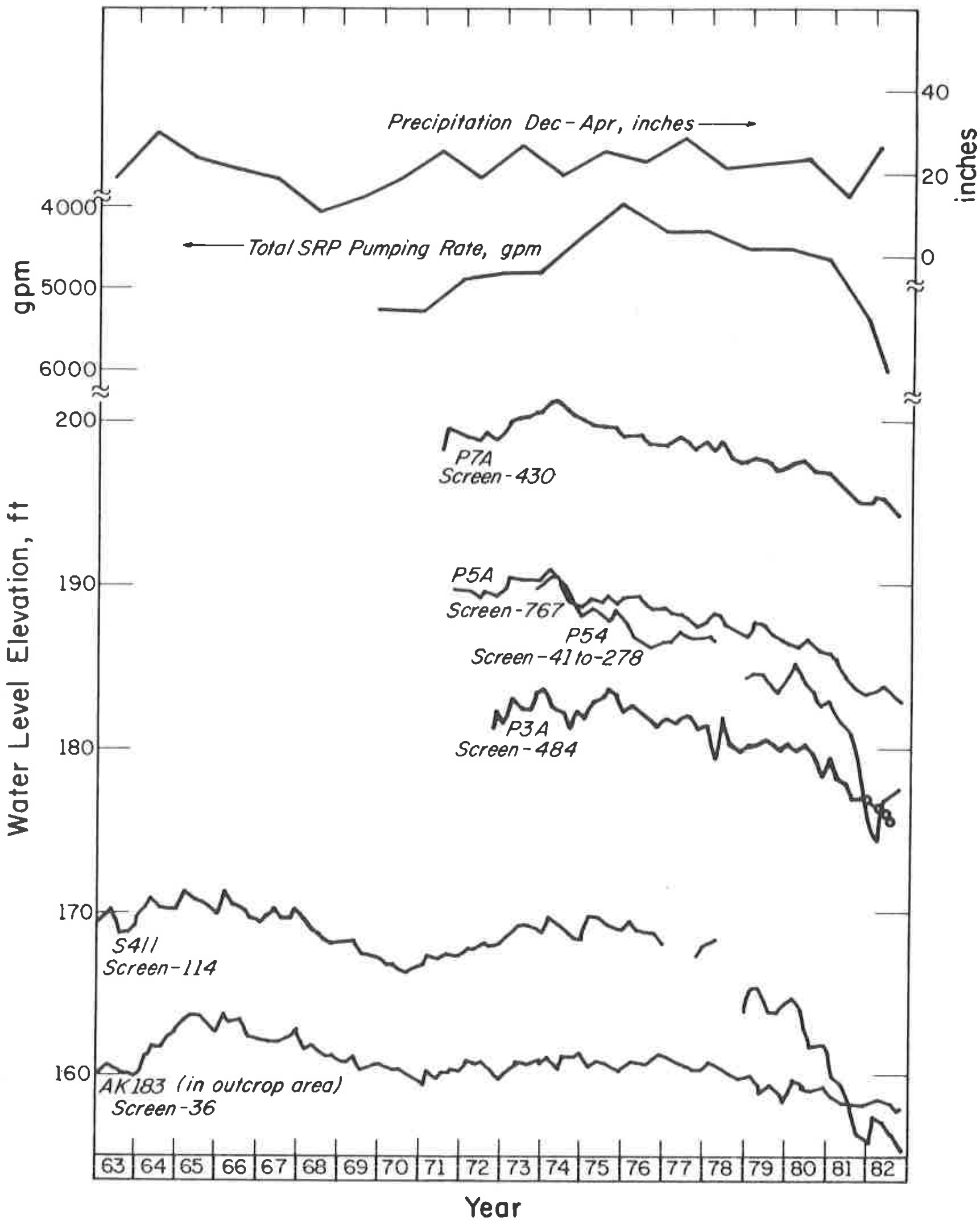

Figure 7. Hydrographs of Tuscaloosa and Ellenton wells (after DuPont,1983).

calculated a flux of 110 m^3/m as representative of conditions in the Tuscaloosa aquifer beneath the Savannah River Plant and vicinity. Thus, the present withdrawal of water from this aquifer, amounting to 26 mgd (68 m3/m), constitutes about 62 percent of the calculated flux. But the pumpage for November, 1983 is calculated to be 31 mgd or about 74 percent of the calculated flux.

SUMMARY

The principal concepts and hydrologeologic model of the SRP and vicinity, determined in the period 1950-65 on the basis of limited data and less than advanced methodology, has apparently remained essentially valid after 25 years of the most rigorous and intensive testing and reevaluation pursued during a number of hydrologeologic investigations. This situation makes it the most unique of any analagous area on this continent. However, time has effected some change.

Even though the potentiometric surface of the principal aquifer remained in a nearly static state from 1954 to 1977, continuous large scale pumping has lowered the overall head by at least 9 feet and hydrographs of wells indicate the lowest stage in their 30 year history. The decrease in head is not yet critical and is still within a safe margin of aquifer utilization, although it may cause problems if proper management and conservation procedures are not initiated and pursued.

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WATER QUALITY OF RELEASES FROM CORPS LAKES IN GEORGIA

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U. S. Army Corps of Engineers

INTRODUCTION

During the 1950's and 60's, a large scale construction program for water resources development was undertaken by the Corps of Engineers in Georgia. Dams were built to provide flood protection, improve navigation, produce electricity, and enhance recreation and fish and wildlife resources. Water supply and water quality benefits also accrued. Buford, Allatoona, Walter F. George, Clarks Hill, and Hartwell dams were constructed and impounded. In the mid-1970's, West Point and Carters Lakes were completed. The basic planning and interagency coordination for these large scale projects had been primarily accomplished in the 1940's, 50's and 60's.

The enactment of the National Environmental Policy Act (NEPA) in 1969, followed by the Federal Water Pollution Control Act (FWPCA) in 1972, resulted in greater consideration being given to water quality aspects in the planning and design of federal water resource projects. While NEPA did not intrinsically restrict the construction of projects with adverse environmental impacts, it did require a full public disclosure of the effects in an environmental impact statement prior to construction. Federal agencies were to consider the environmental concerns of the public and other agencies in the planning and design of projects and minimize the adverse impacts to the extent practicable. The FWPCA placed specific emphasis on water quality considerations and established as an objective "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The promulgation of State water quality standards was mandated but the applicability of the standards to releases from dams was not specially addressed in the FWPCA or in subsequent amendments. The U.S. Environmental Protection Agency (EPA) administratively determined that dams were not point sources of pollution and did not require National Pollutant Discharge Elimination System (NPDES) permits. This EPA determination(1) was challenged in the courts by the National Wildlife Federation and other environmental interests and was sustained. The courts ruled releases from dams were to be controlled similarly to other non-point sources. Thus, federal environmental and water quality laws do not strictly require that releases from dams meet water quality standards but do require the full public disclosure of the expected impacts so that solutions to problems can evolve through a rational process of cost and benefit trade-offs and negotiations. In cases where adverse impacts are subtle, minor, or undefined and the monetary benefits impractical to evaluate, it would be extremely difficult to justify large expenditures for mitigating measures. Furthermore, it should be noted that while progress is being made there is little standard technology readily available for water quality control at dams.

Final planning for the Richard B. Russell Dam(2) on the Savannah River was undertaken in the 1970's, the decade of the environment, and was significantly impacted by the federal environmental legislation. Special attention was given to the water quality of the releases in the planning and final design of the Richard B. Russell project.

PURPOSE

The purpose of this paper is to discuss the Corps' efforts to evaluate the water quality of the releases from existing lakes in Georgia and to describe measures that have been and are being taken to address the situation.

CAUSE OF WATER QUALITY CONCERNS

The primary concern for the quality of the water released from Corps' reservoirs in Georgia has been related to the parameters of dissolved oxygen or conditions resulting from the lack thereof, and temperature. Anoxic conditions in the hypolimnion of the Corps' deep lakes in Georgia combined with low level outlets seasonally produce release water of reduced quality. Normally the water entering these reservoirs has dissolved oxygen levels approaching saturation. The seasonal anoxic condition in the hypolimnion results from the difference in densities between the surface and lower layers which is induced by the temperature variation in the water column. In the summer when the surface waters warm, the difference in densities between the surface and bottom waters restricts vertical circulation of the lake. As a result of this restriction of circulation, the bottom waters of the lake have no potential to renew dissolved oxygen concentrations which are gradually depleted through biological respiration. The warm epilimnetic waters in these lakes commonly approach 30°C and contain adequate nutrients to support abundant levels of algal growth. As these organisms die and gradually drift into the bottom waters where they are decomposed, they place a biological oxygen demand on the bottom waters which seasonally produces an anoxic condition in the stagnant hypolimnion.

The water is released through the low level outlets to insure that water level fluctuations for flood control do not affect power generation. Also, low level outlets generally minimize the energy loss in the penstock and conserve power.

WATER QUALITY EVALUATION OF RELEASES

The South Atlantic Division of the Corps of Engineers has made evaluations of the releases from all of the deep reservoirs within Georgia. Based on results of these evaluations[3], the releases from six Corps of Engineers' reservoirs in Georgia are periodically not in accordance with State water quality standards for dissolved oxygen. These same projects have also generally impacted the natural stream temperature and, in several cases, created beneficial conditions where successful trout stocking has been established, the most popular being the Chattahoochee River below Buford Dam.

Project Characteristics

These six reservoirs are relatively large for the Southeastern United States and range in storage at normal summer pool from about 367,000 acre-ft. to 2,500,000 acre-ft. Maximum depths at normal summer pool vary from 80 feet to 185 feet. Hydropower peaking flows range from 8,000 cfs to 35,000 cfs with a majority of the total volume of water released during a relatively short period of the day. The depth of the centerline of the intakes to the main turbines for all six projects are at least 70 feet below the surface and within the seasonally anoxic hypolimnetic zone. In some cases, the service turbines which provide the minimum flow downstream withdraw from different depths than the main turbines which result in different qualities of the release water. In general, the service units release from higher in the pool and provide higher quality water during low flows. This is the case at Allatoona, Clarks Hill, and West Point. However, Buford Dam has intakes for the main and service units at the same elevation and provides poorer quality water at low flow. Table 1 provides basic characteristics of these six projects. All of these projects release the vast majority of their water through hydropower units and create a total capacity of 894 megawatts. The hydraulic head is used to create electricity and is not readily available for reaeration without accepting an energy loss.

Duration and Intensity

Table 2 shows the average number of days per year the dissolved oxygen concentration of the releases is below prescribed water quality standards and the maximum number of miles required to reaerate to the prescribed water quality standards. In some cases, as noted, these distances are based on theoretical calculated K_2 values. The average number of days in Table 2 represents only two years of data in some cases whereas in other cases it represents seven years of data from continuous electronic water quality monitors. Tables 1 and 2 show that the minimum value of dissolved oxygen in the releases is variable and dependent on a number of factors. Furthermore, the duration of the low dissolved oxygen levels generally occurs for four tc six months per year. Natural downstream reaeration of the releases is generally rapid except in cases where the release enters an impoundment where reaeration characteristics are low.

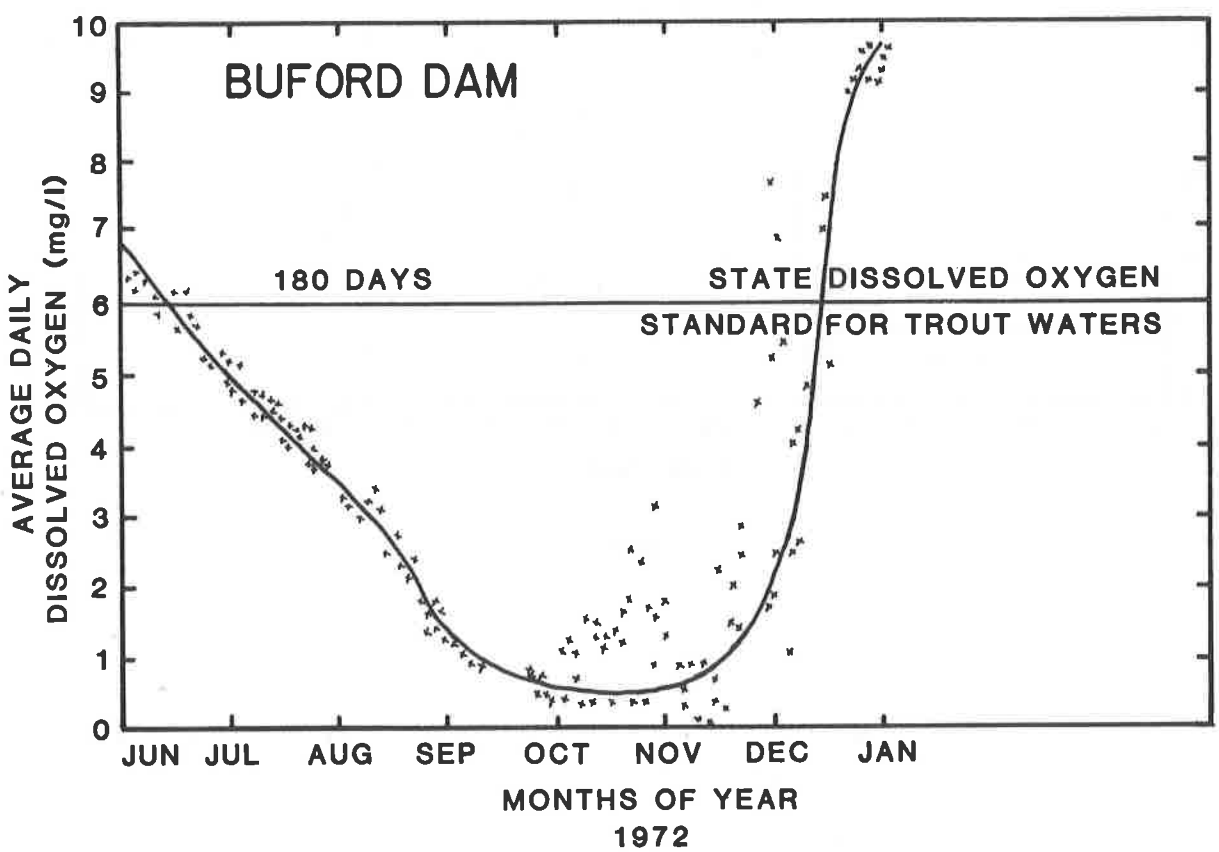

FIGURE 1

Buford Dam and Water Quality

Figure 1 demonstrates the seasonal variation of the average daily dissolved oxygen values of the release waters from Buford Dam in 1972 which would be a typical year. The actual data shows a rather large variation in average daily dissolved oxygen values during the period of minimum values. This is due to the variation in the operational scheme and the significant impact of flows on dissolved oxygen. The lowest average daily dissolved oxygen values are reported on weekends when a continuous minimum flow is maintained. The general shape of this curve is characteristic of the dissolved oxygen in the releases from the other reservoir projects discussed above, however, the rate of seasonal deoxygenation, the minimum values, and the rate of seasonal reoxygenation are variable. The range of the average rate of seasonal deoxygenation is relatively small and between 0.04 and 0.11 mg/l-day. The rates for seasonal reoxygenation are generally higher and fall between 0.06 and 0.25 mg/l-day. The higher value for seasonal reoxygenation of 0.25 mg/l-day is observed at Buford Dam where the intake is the lowest, the lake is relatively deep, the ratio of storage to outflows is higher, and other factors characteristic of strong thermal stratification are present.

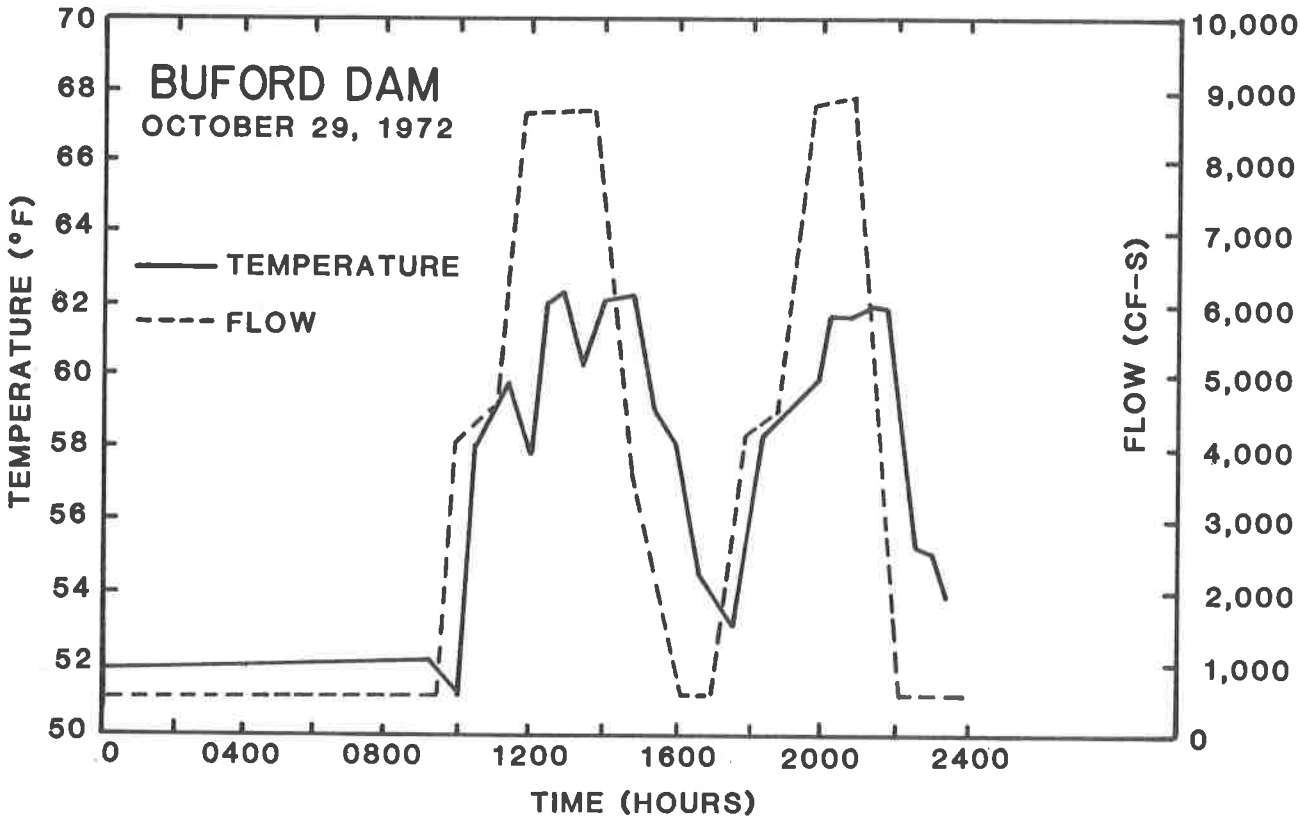

FIGURE 2

TABLE 1
PROJECT CHARACTERISTICS

Project	Normal Summer Reservoir Storage, Acre-Ft.	Max. Normal Depth Ft.	Normal Peaking Power Flows CFS	Min. Flows CFS	No. & Size of Hydro-power Units	Depth of Center-line Intakes, Ft.	Size Penstocks Ft.
Allatoona	367,470	140	8,000	200	2 @36,000 kw 1 @ 2,000 kw	80 Main 55 Service	20 5
Buford	1,917,000	152	8,000	550	2 @40,000 kw 1 @ 6,000 kw	138 Main 138 Service	22 4.5
Clarks Hill	2,510,000	140	27,000	5,800	7 @40,000 KW 2 @ 1,000 KW	76 Main 71 Service	20 4.5
Hartwell	2,549,600	185	25,000	*	4 @66,000 kw	105 Main No Service	24
West Point	604,500	80	18,000	675	2 @35,000 kw 1 @ 3,375 kw	74 Main Service**	None
Walter F. George	934,400	94	27,000	*	4 @32,500 kw	88 Main No Service	None

*No established requirement for minimum flow **Adjustable skimmer weir

TABLE 2
DISSOLVED OXYGEN CONDITIONS

PROJECT	Average Number of Days Per Year Dissolved Oxygen in the Releases is Within Specific Ranges							Miles of River Downstream To Reaerate to Water Quality Standards for Most Severe Case	
	6-5	5-4	4-3	3-2	2-1	1-0	TOTAL	High Flow	Low Flow
Allatoona	--	24	23	70	0	0	117	4.1	2.1
Buford*	27	26	26	26	27	48	180	9.5	5.5
Clarks Hill	--	30	50	28	0	0	108	15	15
Hartwell*	25	20	20	25	20	10	120	5	***
West Point	--	41	52	45	0	0	138	13**	15**
Walter F. George	--	21	23	21	69	0	134	27**	***

*Designated trout stream with a water quality standard of 6.0 mg/1
**Based on theoretical K_2 values. ***No established requirement for minimum flow.

As indicated by Table 2, Buford Dam would be representative of the more severe water quality condition in the releases. The unusual configuration of the Buford penstocks and the morphology in the powerhouse forebay produce a very interesting impact on the water quality of the releases from Buford Dam. Conservation pool elevation is 1,070.0 with the elevation of the invert to the intake structure at 919.0, about the lowest elevation in the lake. The service unit which provides continuous minimum flows utilizes the same 22 foot intake as the main turbines; a 4.4 foot service penstock branches off the main penstocks to feed the service unit. As the powerhouse was located considerably off to the side of the old river channel, but at about the lowest elevation in the lake, it was necessary to excavate a channel from the old river bed to the powerhouse during construction of the project for diversion purposes. This inundated channel which exists today is approximately 80 feet deep and 150 feet wide at the intake structure and appears to cause significant effects on the withdrawal zone as the flows increase from a minimum release of 550 cfs to a peaking flow of about 8,000 cfs. On an average, the peaking hydropower operation occurs about 6 hours per day. A dramatic correlation between increases in dissolved oxygen and flow is observed in Figure 2. The dissolved oxygen increases by as much as 4 mg/l during the peaking power operation. A similar increase in temperature occurs with flow as shown by Figure 3. That is, water temperatures in the releases can increase about 10°F with peaking hydropower operations.

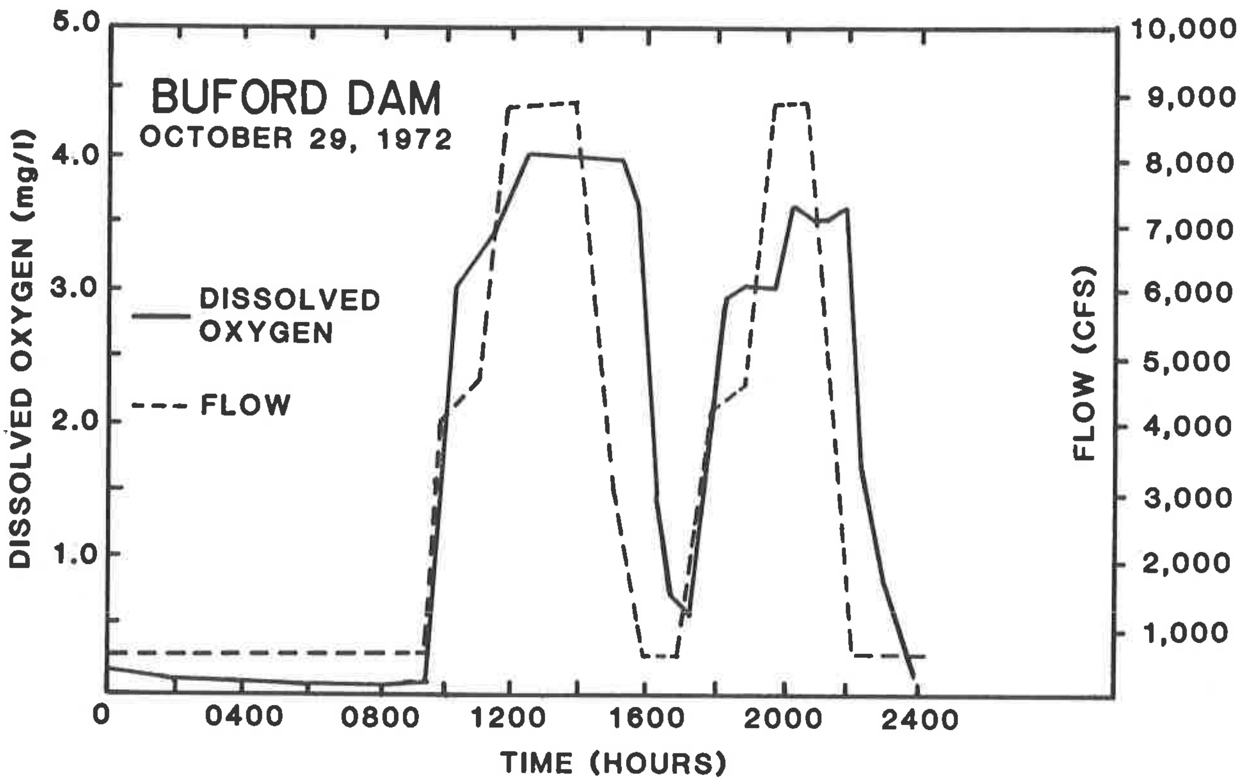

FIGURE 3

Based on the above observation that the dissolved oxygen concentration at high flow is considerably higher than at low flow, it would appear that the number of miles of river to reaerate to water quality standards would be less at high flow. However, as indicated in Table 2, the contrary is true. Even though the initial dissolved oxygen is higher at high flow, the increase in average velocity from about 0.75 miles/hour at low flow to 1.8 miles/hour at high flow, the greater depths, and submergence of shoal areas, approximately 9.5 miles of river is required to reaerate to water quality standards at high flow in contrast to 5.5 miles at low flow during the most severe condition. It would appear that the low dissolved oxygen levels and rapid and dramatic fluctuation in temperature and dissolved oxygen should have resulted in fish kills of trout in the tailwaters of Buford Dam. However, only very small and limited fish kills have been observed in the Chattahoochee River below Buford Dam. Trout were initially stocked in the Buford tailwater area in December 1957 and a progressive stocking program has developed. Low benthic macro-invertebrate populations have been reported in the tailrace area.

Fish kills have been observed at a commercial trout fishing pond which withdraws water from the Chattahoochee River about 2.5 miles below Buford Dam. These fish kills were generally noted in the Fall season during periods of low flow and low dissolved oxygen in the river. This problem was resolved by a simple operational change at the trout fishing ponds which involved withdrawing water from the river only during periods of high flow.

Buford Trout Hatchery Fish Kill

In the Spring of 1976, the State of Georgia Game and Fish Division commenced operation of the Buford Trout Hatchery which withdraws water from the Chattahoochee River about 1.3 miles below Buford Dam. In the Fall of 1976, a massive fish kill occurred in the hatchery. When the Buford State hatchery was designed, aeration equipment was included in anticipation of the low dissolved oxygen levels in the releases. Thus, the low dissolved oxygen levels, per se, was not the cause of the fish kill. Examination of the fish in the hatchery did not reveal any disease, parasites, or other problems associated with hatchery management. The Georgia Environmental Protection Division reported(4) the cause of the fish kill in the hatchery to be a result of the water quality of the releases from Buford Dam. It was hypothesized that reduced toxic constituents produced in the anoxic hypolimnion of Lake Lanier (Buford Dam) remained as residuals after short term reaeration to cause the fish kill in the hatchery. Specific causative agents of the fish kill had not been defined but it was suggested that humic materials were involved. A Joint Technical Task Force was formed between the Georgia Department of Natural Resources, the U.S. Environmental Protection Agency and the Corps of Engineers to address the above condition and develop recommendations. Cooperative studies by this Task Force during the Summer and Fall of 1977 and 1978 included data collection in the hatchery, river and lake. The data collection in the lake was primarily related to water quality characteristics. The study in the river below Buford Dam examined water quality, benthic macro-invertebrates, effects of water quality on fish movements, and collection of trout for pathological analysis.

Several conclusions[5] were derived from the various studies. The increases in mortality rates at the hatchery correlated with increases in total iron and manganese and a decrease in oxidation-reduction potential in the reservoir hypolimnion. This indicated the relationship of fish mortality within the hatchery system to the general water quality conditions during the latter period of summer stagnation. A greater incidence of gill lesions on trout in the tailwater also appeared to be related to increases in iron and manganese levels. The levels of these two elements is indicative of the chemically reduced environment within the hypolimnion.

The fish sampling yielded no evidence that fish movement occurred in the river below the dam during the fall. In addition, there was no significant evidence of river fish mortality caused by the hypolimnetic releases. Lesions were observed on the three species of trout and yellow perch, mainly on the gill. These lesions could be caused by a toxin but also could be due to stress from exposure to low levels of dissolved oxygen. However, these lesions were still found on fish collected from the downstream station, where dissolved oxygen levels are higher. In addition, the results of the histological examinations indicated that rainbow trout were affected the most, followed by brown and then brook trout. This corresponded to the mortality rates in the hatchery: rainbow suffering the heaviest mortality, with brown and brook sustaining lower losses.

It appeared from the data collected during this study that direct effects on the riverine fish population were considerably more subtle than those operating on fish held under culture densities at Buford Trout Hatchery. However, the data did indicate that the riverine fish population was adversely affected physiologically from toxins released from the hypolimnion and/or from low dissolved oxygen concentrations.

The U.S. Environmental Protection Agency conducted several studies on the trout mortality at the Buford Trout Hatchery and suggested[6] that copper or hydrogen sulfide was the toxic constituent.

Buford Dam - Bioassay

As numerous causative agents for the trout mortality were suggested, a bioassay study was conducted under contract by Mobile District during the fall of 1981 in an effort to define through a controlled experiment the toxic constituent responsible for the trout mortality. The experimental design was based on incrementally removing potential toxic constituents by various water treatment schemes. The impact of aeration on the toxic constituent was also investigated. A bioassay experimental testing unit was established on the top of Buford Dam where water could be withdrawn directly from various levels in the lake. Rainbow trout swim-up fry were exposed to water from various depths in the lake. The water from the various depths was extensively analyzed by the Georgia Environmental Protection Division Laboratory. Water withdrawn from the hypolimnion was most toxic and contained the highest levels of manganese (Mn) and iron (Fe). No copper, humics, or hydrogen sulfide were detected. Various water treatment schemes were then applied to the water withdrawn from the hypolimnion prior to exposing the rainbow trout swim-up fry. The following results[7] were obtained:

Treatment	Observation
1. Anion exchange resin to remove organics	No change in toxicity
2. Added Na_2 EDTA	Increased toxicity
3. Added Ca_2 EDTA	Eliminated toxicity
4. Removed Fe and Mn and added hardness back	Eliminated toxicity
5. Increased hardness $\geq$ 25 ppm	Eliminated toxicity
6. Prolonged aeration	Increased toxicity
7. Activated Carbon	Increased toxicity

When Mn^{++} and Fe^{++} were added to non-toxic surface water from Lake Lanier in concentrations observed in the Chattahoochee River and the Buford Hatchery, the water became acutely toxic to trout fry. This study concluded that Fe concentrations of 750 ppb or Mn concentrations of 500 ppb, in the very soft waters of the Chattahoochee River, were the sole causative agents responsible for the trout mortality in the Buford hatchery. The EPA Redbook, Quality Criteria for Water(8), indicated an iron concentration of 1 ppm was adequate for protection of aquatic life whereas no fresh water aquatic protection level was specified for manganese.

The bioassay study also performed in situ studies of fry and yearling trout and blue gill at six stations in the Chattahoochee River below Buford Dam when the lake was still stratified. Heavy mortalities were observed over four days up to 23 Km below the dam for the trout fry with the severity reduced for the yearling. Mortality was not observed in the bluegill which occur naturally in the river.

Clarks Hill Downstream Study

In 1977 and 1978, studies were conducted in the tailwaters at Clarks Hill Reservoir on water chemistry, fishes, and benthos. The study was performed by the University of Georgia under contract with the Savannah District. The results(9) from the year of oxygenation testing in Clarks Hill Lake, which will be discussed later, were compared to a year when oxygenation was not conducted. The results were also compared to normal healthy streams in the vicinity. Five stations spanning a river reach of about ten miles below the dam were utilized in the study. The minimum dissolved oxygen level in the tailwater without oxygenation is about 2.0 mg/l. The conclusions of this study were:

a. Fish population in the tailrace are healthy even without oxygen injections.

b. Growth rate of major species is relatively poor but not significantly different from other streams in the area. Oxygenation did not appear to affect the fishes growth rate.

c. Fishes were more numerous immediately below the dam during the year oxygenation was conducted.

d. Benthic populations in the tailwaters were poor with low diversity. Oligochaets were the dominant benthic species. With the exception of Chironomids, aquatic insects were not numerous. Substrate may be a limiting factor.

e. Snails and clams were more numerous downstream.

WATER QUALITY CONTROL MEASURES

West Point and Carters Lakes

Because of the low dissolved oxygen levels which were observed below the then existing Corps dams in Georgia, concern was expressed by environmental interest in the late 1960's when construction planning for Carters and West Point Dams were being completed. Due to the mixing caused by the pumped storage capability and the turbulence in the reregulation dam spillway at Carters Dam, it was predicted(10) that the releases from the reregulation dam would be well oxygenated and meet water quality standards. This has subsequently been verified. An analysis of West Point Dam and Lake(11) indicated that thermal stratification would occur and that low dissolved oxygen levels would occur in the releases if control measures were not included. An adjustable skimmer weir intake which restricts withdrawals to the surface waters was provided for the service unit which maintains the minimum flows. To address the hydropower peaking discharge, the construction cofferdam in front of the powerhouse was left in place to act as a submerged weir and force withdrawals from the higher levels in the reservoir. Subsequent construction requirements resulted in the cofferdam being breached in one section during the second phase of diversion. While these measures were partially successful, as indicated by Table 2, they did not totally eliminate the low dissolved oxygen condition in the releases.

Allatoona Lake

In 1967, a destratification testing system was installed at Allatoona Lake. Testing of the system occurred in 1968 and 1969. The basic objective of the destratification system was to provide enough energy input and mixing to break up the thermal stratification and promote vertical circulation which would allow the bottom waters to mix with the reaerated surface waters. The releases would then contain water of higher dissolved oxygen levels. The mixing was provided by an air pump through a diffuser system in the bottom of the lake. The system was similar in concept to that used in a household aquarium. The air pump system was powered by five 60 horsepower, electrically powered, rotary type compressors. The minimum capacity of each compressor was 250 cfs air flow at 100 psig. The diffuser system consisted of five individual cross shaped units with 40 air diffusers per unit. The diffuser units were located between 2,500 - 4,000 feet in front of the dam. The diffuser systems were suspended 10 feet above the bottom of the lake with floatations and anchors. Operation of the system could be observed by "boils" at the surface.

Extensive chemical, biological, and bacteriological studies were conducted by the U.S. Environmental Protection Agency and Corps to evaluate the destratification system. A detailed evaluation report[12] of the system was prepared by the Savannah District in 1973.

The dissolved oxygen levels in the lake were influenced for at least four miles upstream of the diffuser system. In early September when the dissolved oxygen approached zero in the hypolimnion on a normal year, the destratification system provided concentrations of 4 to 6 mg/l to depths of about 100 feet in the vicinity of the diffusers. This mixing generally cooled the surface waters and warmed the bottom waters. Reduced concentrations of iron and manganese were also observed.

The biological studies in the lake indicated that the primary productivity increased in the immediate zone of influence of the diffusers but not to nuisance conditions. The bacteriological studies showed no significant influence on either coliform density or vertical distribution.

Downstream of the dam, the dissolved oxygen of the releases during peak flows exceeded 4.0 mg/l when operation of the destratification system commenced in early Spring. For low flows, 4.0 mg/l was exceeded except for one week in August. The water temperature of the releases increased by 2-4°C from June through August. No changes were observed in the downstream flora but subtle changes were noted in the aquatic insect abundance. Common gill-breathing immature insects were more abundant with the destratification system operating. No studies were conducted on the fish.

Overall the Allatoona destratification test system demonstrated the physical feasibility and environmental acceptability of artifically destratifying a large reservoir in the vicinity of the hydropower intakes in order to increase the dissolved oxygen of the releases. The test system has normally remained in operation at Allatoona on a seasonal basis at a somewhat reduced efficiency since completion of the demonstration project.

<u>Clarks Hill Lake - Oxygenation Testing</u>
In 1974, Speece, under contract to the Savannah District, conducted a feasibility study on methods to increase the dissolved oxygen level in the releases from Clarks Hill Dam to 6.0 ppm. The feasibility report[13] recommended that hypolimnion oxygenation be further investigated as the most viable method to improve the dissolved oxygen in the releases to 6 ppm. This system would utilize pure oxygen in lieu of air and not thermally destratify the lake. Field testing of various hypolimnion oxygen schemes was conducted at Clarks Hill Lake between 1975 and 1979. Initially testing was conducted at the face of the dam so that the oxygen transfer efficiency could be rapidly measured. The diffuser scheme consisted of ten 1 square foot diffusers mounted at 10 foot centers on a pipe frame. Three of the frames with diffusers were installed initially ten feet from a turbine intake and the oxygen absorption was unacceptable. When the frames with

diffusers were moved greater than 100 feet from the turbine intake, a marked improvement in oxygen transfer was noted and dissolved oxygen levels of 6-8 ppm were observed in the releases at 85 percent transfer efficiency. Based on these tests, it was concluded(14) that oxygen could be injected in the vicinity of the intakes and meet the 6 ppm requirement if the oxygen injection rate is coordinated with the hydropower release rate. However, it was noted that it would be advantageous and more economical to inject the oxygen over a continuous 24 hour period rather than the shorter period of the day when the peaking hydropower releases were made. Field testing was conducted the next several years in an effort to develop the most cost effective method of injecting the oxygen. Various sizes, configurations, and loading rates of diffusers were evaluated in the laboratory and in the field. Plume deflectors were investigated which would baffle the rising oxygen plume in an attempt to cause the oxygenated water to settle in the withdrawal density layer. Test results indicated that the optimum diffusers had a standard permeability of 0.5 to 2.0 fpm with a loading of 250 to 500 pounds of oxygen per square foot of diffuser per day. The linear placement of diffusers was superior to a four-sided configuration. The plume deflectors had minimal effect on the oxygen placement. Oxygen for the test was obtained from commercial sources in the project area. Large oxygen storage tanks and evaporators were required on site for the test.

Clarks Hill Lake - Turbine Aspiration

In the late 70's, the trout waters classification below Clarks Hill Dam was eliminated reducing the dissolved oxygen State water quality standard from a daily average of 6.0 ppm to 5.0 ppm. This, along with further development of turbine aspiration techniques by Alabama Power Company and the Tennessee Valley Authority resulted in renewed interest in the possible application of turbine aspiration techniques at Clarks Hill Dam.

The turbine aspiration concept depends upon the development of a negative pressure or a vacuum in the draft tube which draws air with the water flow. The air bubbles provide opportunity for oxygen transfer to the water phase increasing the dissolved oxygen in the releases.

At Clarks Hill, the Francis-type turbine produces a negative pressure in the draft tube at low flows and in sudden flow cutoff situations. This negative pressure can be a problem if not controlled and produce cavitation and excessive vibration to the turbine. To control this, the turbine system at Clarks Hill Dam is equipped with a vacuum breaker system which allows air to be drawn into the draft tube at low flows and sudden flow cutoff situations. It was noted that if the vacuum breaker is held open during low flows, large amounts of air are aspirated into the water increasing the dissolved oxygen level in the releases. However, at high flows a negative pressure does not develop and no air is aspirated.

Recent research by Alabama Power Company and the Tennessee Valley Authority indicated that turbine aspiration could be accomplished at high flows if a local negative pressure could be established in the draft tube by installing baffle plates over the existing air vents. In 1981 and 1982, Savannah District added baffle plates to the air vents on the hubs of two turbines and evaluated the system. A detailed evaluation of the hub baffles was conducted and a technical paper[15] prepared. Two different shapes of baffles were examined, one at 45° and another at 60°.

The evaluation examined in detail air flow rates, dissolved oxygen uptake, dissolved nitrogen uptake, power losses, and cost. The results are summarized here. The hub baffles significantly increased the air flow aspirated into the water. Air flows were increased from about 3-6 cfs to about 35-60 cfs depending upon numerous variables. Also, bypassing the vacuum breaker valve increased the air flow. There was not a significant difference in air flows between the 45° and 60° baffle. The dissolved oxygen level of the releases could be increased with the hub baffle by a maximum of 2.0 mg/1 at Clarks Hill Dam from a background dissolved oxygen level of 3.0-3.5 mg/1. Application of the existing hub baffle system to all seven turbines at Clarks Hill would reduce the number of days to about 22 per year when the dissolved oxygen in the release would be below 5.0 ppm. Measurements of dissolved nitrogen indicated levels between 106 to 109 percent saturation which is below the 110 percent established by the U.S. Environmental Protection Agency. Significant power losses could be caused by the hub baffle aspiration system in some cases. The efficiency of the turbines were reduced between slight and 2.6 percent depending upon the flow and shape baffle. The greatest efficiency loss occurred at lower flows. The cost to operate the hub baffle aspiration system per year was estimated to be $102,000 (1982 dollars) for lost energy and capacity, if all seven turbines were equipped.

Richard B. Russell - Oxygenation System

At the Richard B. Russell Project which is currently under construction on the Savannah River, a full scale hypolimnion oxygenation system is being installed. The Russell lake will contain about 1,026,000 acre-feet of storage and cover approximately 26,600 acres at maximum power pool. The maximum depth of the lake will be about 175 feet. Physical and math model studies[16] of the Richard B. Russell and Clarks Hill Lakes were performed in the mid 70's at the Corps Waterways Experiment Station in Vicksburg, Mississippi to predict the expected dissolved oxygen and temperature conditions in the Russell Lake and downstream in Clarks Hill. Results of the model study effort in conjunction with the experience from the oxygenation testing at Clarks Hill indicated that the hypolimnion oxygenation system was the most feasible method to provide 6.0 ppm in the release waters from the Russell dam. Two separate diffuser systems[17] are being installed. A continuous diffuser system located about one mile above the dam will inject oxygen about 24 hours a day. The continuous diffuser system will have the capacity to inject 150 tons per day of oxygen at a loading rate of about 375 pounds per square foot of diffuser per day. About 1,080 diffusers will be mounted on a 1,200 foot length of 8-inch fiberglass pipe. Two of these 1,200 feet lengths of pipe with diffusers will be suspended off the bottom with floatation and anchors. The two lengths will be placed about 100 feet apart and across the old river bed. A pulse diffuser system will be located adjacent to the dam which will have the ability to supplement the oxygen injection capacity of the continuous system on an as-needed basis. The pulse diffuser system will have the capacity to inject 150 tons per day at a loading rate of about 470 pounds per square foot per day. The pulse diffuser system will consist of eight lengths of 240 feet fiberglass pipe with 216 diffusers mounted on about one foot centers. The 240 foot sections will be spaced about 70-80 feet apart and extend out perpendicular from the face of the dam. The diffuser system will be suspended off the bottom with anchors and floatation.

During the initial operational period expected to begin in the summer 1984, oxygen will be purchased[18] from commercial sources and trucked to the project site. Two 20,000-gallon horizontal tanks will store about 190 tons of oxygen. Once the project is fully operational, to include the pumped storage capacity, the feasibility of constructing an on-site cryogenic oxygen production facility will be evaluated.

Currently the Corps Waterway Experiment Station is locating a water quality laboratory at the Richard B. Russell Project site which will be utilized to evaluate the most cost effective operational mode and the environmental effects of the unique oxygenation system. It is envisioned that the evaluation will extend over a number of years.

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IRRIGATION MANAGEMENT IN GEORGIA

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ABSTRACT

The need for irrigation to produce crops in South Georgia has been repeatedly concluded from observations of the normal rainfall patterns and from the low water holding ability of the soils in the region. Year after year most crops produced without irrigation have had low yields, and risks of production were high. As irrigation equipment technology improved from portable pipe systems to dependable, low-labor traveling gun and center pivot system, producers adopted irrigation for their land. The amount of irrigated land in Georgia increased almost tenfold between 1970 and 1982. Corn, soybeans, peanuts and vegetable crops occupied most of the irrigated land. As these crops were irrigated the importance of water application efficiency and of irrigation scheduling became evident. Crop response to water has provided information on the factors affecting water use efficiency and proper scheduling. Several tools are available to aid in irrigation management.

INTRODUCTION

The introduction of irrigation in Georgia in the 1950's and its rapid adoption during the 1970's significantly altered agricultural production techniques in the state. Producers rapidly discovered that recommended rates of seed, fertilizer, etc. for the production of nonirrigated, rainfed crops were not adequate for production of irrigated crops. The application of irrigation management technology developed for irrigated crop production in the arid western United States was found to be inadequate for our humid climate. Irrigation management strategies for the humid Southeast were practically nonexistent. During the 1950's, 1960's and early 1970's the University of Georgia's Coastal Plain Experiment Station responded to this need by initiating irrigation management research, primarily on tobacco and peanuts. In the mid 1970's this program was greatly expanded to include irrigation management of a wide range of horticultural and agronomic crops. As a result of this and other research programs, irrigation technology has been developed which is applicable to crop production in the humid Southeast. This manuscript discusses factors affecting irrigation management and describes appropriate strategies for meeting the needs of irrigated crop production.

STATUS OF IRRIGATION SYSTEMS IN GEORGIA

As indicated in Table 1, irrigated land area in Georgia increased from 58,550 ha. in 1970 to 447,360 ha. in 1982 (Harrison, 1983). This irrigated acreage increased at the rate of approximately 40,480 ha. per year from 1975 through 1981, but leveled off in 1982. We anticipate that the 1983 irrigated land area will reflect only a slight increase. This plateauing of irrigated land could be caused by the current economic crisis in agricultural production or it could indicate that Georgia has essentially reached a point of "saturation" with respect to irrigation need and potential. We believe that this

Table 1. Compilation of Georgia Irrigation Survey
for years: 1970, 1973, 1975, 1977, 1978, 1979, 1980, 1981 and 1982.

Years	1970	1973	1975	1977	1978	1979	1980	1981	1982
1. Total acreage under irrigation in Georgia:	144,629	193,857	307,416	592,088	722,075	842,235	988,356	1,094,778	1,104,992
2. Total irrigated acreage by crop:									
Corn	30,418	39,267	76,996	250,227	284,069	330,066	410,241	415,174	319,713
Cotton	2,627	1,440	1,116	779,270	10,630	6,292	17,655	33,933	35,307
Peanuts	38,227	63,982	91,334	190,544	222,059	255,008	271,323	304,077	290,455
Tobacco	42,402	48,304	54,518	46,081	51,234	45,495	46,522	45,212	47,970
Soybeans	795	3,338	4,725	21,728	61,851	113,818	133,695	152,510	219,628
Truck Crops	20,061	28,009	26,223	39,727	49,443	24,689	49,005	65,568	92,832
Pastures	5,440	3,217	4,613	10,668	12,255	8,144	13,991	16,501	22,241
Apples	--	525	152	1,100	1,212	1,353	1,378	1,702	1,243
Peaches	1,542	1,269	721	1,995	4,412	4,524	4,594	5,569	5,730
Pecan	485	1,089	1,356	4,662	8,332	12,507	16,266	28,349	34,353
Nursery	1,453	742	424	602	1,033	1,244	1,115	1,528	2,409
Vineyards	--	70	145	240	379	583	1,581	509	522
Turf Nursery	--	1,650	1,557	1,764	2,127	2,191	2,252	3,073	2,597
All other crops	1,179	955	2,121	7,411	6,132	6,983	7,665	13,505	20,180
*Golf Courses	--	--	--	6,069	6,907	7,278	7,638	8,250	8,655
*Athletic Fields	--	--	--	--	--	423	614	1,112	1,157
3. Total number or irrigation systems in Georgia	6,572	7,718	7,038	8,343	9,145	9,486	10,599	11,559	11,782
4. Total number of irrigation systems by type:									
Portable pipe (hand-move)	6,365	6,440	5,026	4,179	3,613	3,228	2,517	2,125	1,990
Cable-tow	69	694	1,090	2,585	3,157	3,323	3,825	4,077	4,060
Hose Reel (hose pull)	--	--	--	--	--	301	429	723	808
Center Pivot	87	238	478	983	1,636	2,287	2,858	3,434	3,597
Side Roll (side wheel line)	3	8	11	36	39	35	37	36	18
Lateral Move (linear move)	--	--	--	--	--	5	7	11	12
Drip/Trickle	--	--	--	21	60	100	159	341	454
Solid Set Sprinkler	32	46	122	135	201	207	211	292	303
Golf Courses	--	179	291	229	239	248	250	231	229
Athletic Fields	--	113	120	175	200	239	256	289	311
5. Total number of irrigation systems by type of power:									
Gasoline Engine	2,985	2,991	2,009	1,936	1,233	1,033	885	864	835
L.P. Gas Engine	1,116	1,045	1,377	1,033	1,066	1,155	822	787	795
Diesel Engine	2,292	2,629	3,434	4,180	5,802	6,491	6,794	7,386	7,452
Electric Motor	179	327	329	441	592	697	919	1,297	1,472
Undesignated Sources	--	--	--	--	--	--	1,179	1,252	1,228
6. Total number of systems by source of water:									
Wells	582	972	1,118	1,771	2,342	2,939	3,387	4,175	4,357
Ponds	5,542	5,535	5,684	5,388	5,592	5,489	5,202	5,979	5,293
Streams	448	549	574	823	1,022	988	1,176	1,088	1,099
City Water	--	--	--	--	--	--	834	177	192
7. Total number of acres under chemigation:									
Fertilizer	--	--	--	--	--	--	--	120,914	128,927
Herbicide	--	--	--	--	--	--	--	18,358	27,766
Fungicide	--	--	--	--	--	--	--	13,650	14,039
Nematicide	--	--	--	--	--	--	--	140	0
Insecticide	--	--	--	--	--	--	--	8,818	8,308

*These values not included in irrigated acreage by crop.

leveling off merely reflects economic restraints and anticipate that we will see significant increases when the agricultural economy returns to normal. However, we do not expect the rate of increase in the future to equal that during the period of 1975-1981.

Corn, peanuts, soybeans and vegetable crops are the major crops being irrigated at this time. It is important to realize that 98% of the irrigated land in Georgia lies south of the "Fall Line" with approximately 70% of this land being in the southwest area of Georgia. The increased land area under irrigation has been accompanied by a shift in types of irrigation systems used from nonpermanent portable pipe to traveling gun and center pivot systems with some increases in solid set systems. While center pivots comprise only 31% of the total number of irrigation systems, they irrigate 50% of the irrigated acreage in Georgia. Traditionally, the popularity of center pivots evolved from their ease of operation, dependability, uniformity of water application and low labor requirements coupled with the potential for multiple use in applying chemicals as well as water to crops. The traveling gun systems are popular because of their versatility in covering small, irregularly shaped fields and reduced capital investment; however, many producers have found that these systems can require significant labor and are frequently inadequate for irrigating the desired acreage during periods of extended drought. Solid set and drip/trickle systems are primarily used in permanent crops such as orchards and vineyards which can justify the relatively high capital outlay required for installing these systems.

The efficiency of water application for sprinkler systems such as the center pivot is frequently questioned relative to the efficiency of surface irrigation systems used primarily in the arid western U.S. While surface irrigation systems such as furrow irrigation typically have water application efficiencies of only 40-60%, crops grown under our center pivot systems typically receive 75% or more of the water pumped through the system. Drip/trickle irrigation systems are significantly more efficient in water application than our overhead sprinkler systems. However, the capital cost of installing these systems on other than high value, permanent type crops is still prohibitive.

The source of energy used to power Georgia irrigation systems has changed rapidly over the last decade with gasoline and LP gas declining susbstantially while diesel fuel and electricity have rapidly increased as sources of energy. While the use of ground water from wells for irrigation has steadily increased over the last decade, it is significant that 53% of the irrigation systems in Georgia are supplied by surface water from either ponds or streams. Chemigation (application of chemicals through an irrigating system) is a rapidly expanding utilization of irrigation systems with 16% of our irrigated land area being chemigated at least one time in 1982. We anticipate that chemigated land area will continue to increase as more agricultural producers adopt this practice.

An energy survey of Georgia irrigation systems during 1982-83 has shown that our systems are operating at about 82% of standard performance criteria (Butts et al., 1983). Performance ratings for diesel and electric powered systems are 81% and 84%, respectively. Significant energy and savings can be realized by repair or replacement of system components. For example, one system was operating at 69.4% of standard when it was initially tested. After repairs to the pump and pump column, the system was reevaluated and its performance rating was 98.9% of standard.

Coefficients of uniformity have been determined for 32 center pivots. Based on the Christiansen equation, the average coefficient of uniformity is 85%. Based on the Heerman-Hein equation, which weights the sample value as a function of distance from the pivot point, the average coefficient of uniformity was determined to be only 81%. Considerable water use efficiency improvement could be achieved by renozzling sprinklers to bring them back to specifications.

NEED FOR IRRIGATION IN GEORGIA

Most of Georgia's row crop land and nearly all of its irrigated land lies in a region which receives an average of 45-53 inches of rainfall annually. Because less than half of that rainfall would be optimal for any of the crops produced in Georgia, many people question why water should be needed for any irrigation at all. The answer lies in two factors - the low water holding capacity of the soils and the nonideal distribution of rainfall.

The majority of soils throughout South Georgia, particularly those currently being irrigated, are sand or sandy loam soils. They typically hold 1.9 to 3.8 cm of water in the upper 60 cm . That soil water supply will last only 4 to 8 days, on the average, before the crop begins to suffer water stress. Under peak seasonal evaporative demand, the soil water would have to be replenished even more frequently, every 3 to 5 days.

From the rainfall distribution patterns observed in South Georgia, it is clearly evident that rainfall is unlikely to replenish soil water as it is needed (Sheridan, et al., 1979). For example, during average water consumption periods, most crops will transpire 0.5 cm per day or 2.5 cm in 5 days. Long term rainfall records indicate the likelihood for receiving 2.5 cm in 5 days is never better than 33% or one in three years (Figure 1). During maximum consumption periods transpiration may reach 4.4 cm in 5 days. The probability of receiving that much rainfall in any 5 day period is less than 20% at any time during the year.

Another way of viewing the rainfall distribution is the probability of long intervals without rainfall (Figure 2). During any quarter of the year, for one year out of two, 15 or more consecutive days can be expected with less than 6 mm of rainfall on any day. Further, for one year out of ten, 25 or more consecutive days can be expected to be essentially rainless. Van Bavel and Carreker (1957) calculated from these rainfall records that in one of two years, there will be a total of 50 to 70 days from March through October when soil moisture will be insufficient for optimum crop growth.

The expected water deficit was computed for six crops commonly grown in South Georgia using the long term rainfall records and crop water consumption under average conditions (Table 2). These deficits varied from 2.8 cm (1.1 in.) for the short season snapbean crop to 32.5 cm (12.8 in.) for the March 1 planted corn crop. Similar deficits would be obtained for crops planted later in the year.

Rainfall in South Georgia is inadequate for most crops during most years. Yields of nonirrigated crops are far below national averages for these crops and in many cases are below levels of profitability. The principal advantage of irrigation in this sub-humid climate is that, by filling in those rainless periods, optimal yields can be reliably produced.

CROP RESPONSE TO WATER

A need for irrigation in South Georgia has been established. To meet the need through judicious and efficient use of our water resources, it is necessary to understand how plants respond to water.

Typically, crop yield increases in a linear manner with water consumption, that is with the actual amount of water evaporated from plant and soil surfaces during the growing season (Figure 3). This has been documented repeatedly for all of our major row crops, although the response curves vary with type of crop and, to some extent, with climatic and soil conditions of a region (Hammond, et al., 1981, Hillel, 1973, Morey et al., 1980, Musick and Dusek, 1980). Above the threshold evapotranspiration (ET) amount, yield increases with each increment of water made uniformly available during the growing season. The object of

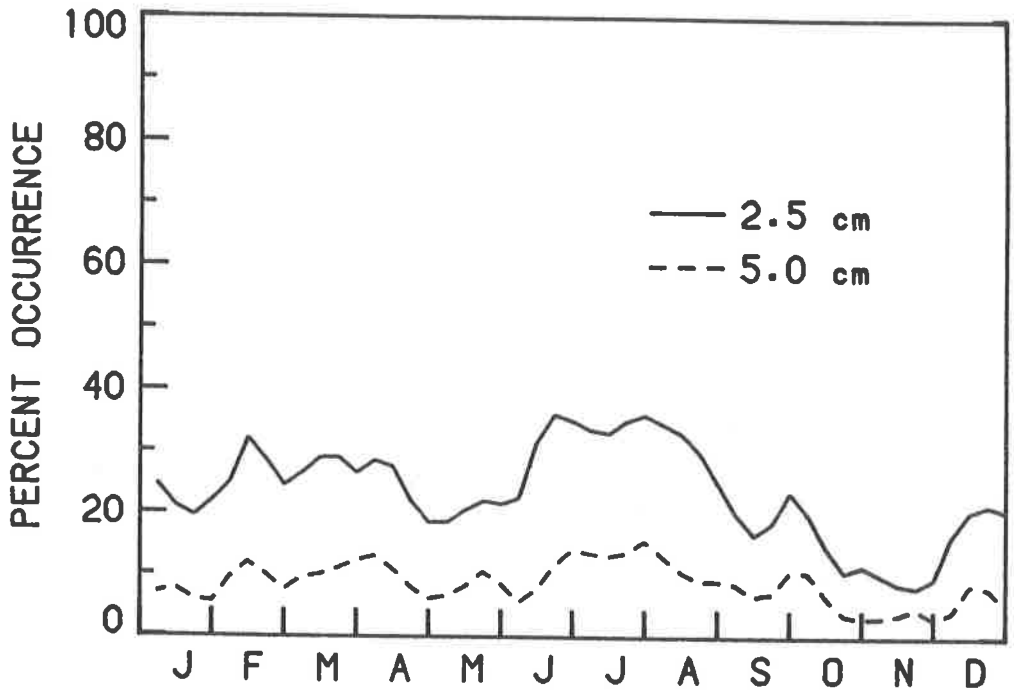

Figure 1. Percent occurrence of selected rainfall amounts by 5-day periods for Tifton, GA. (from Sheridan et al., 1979).

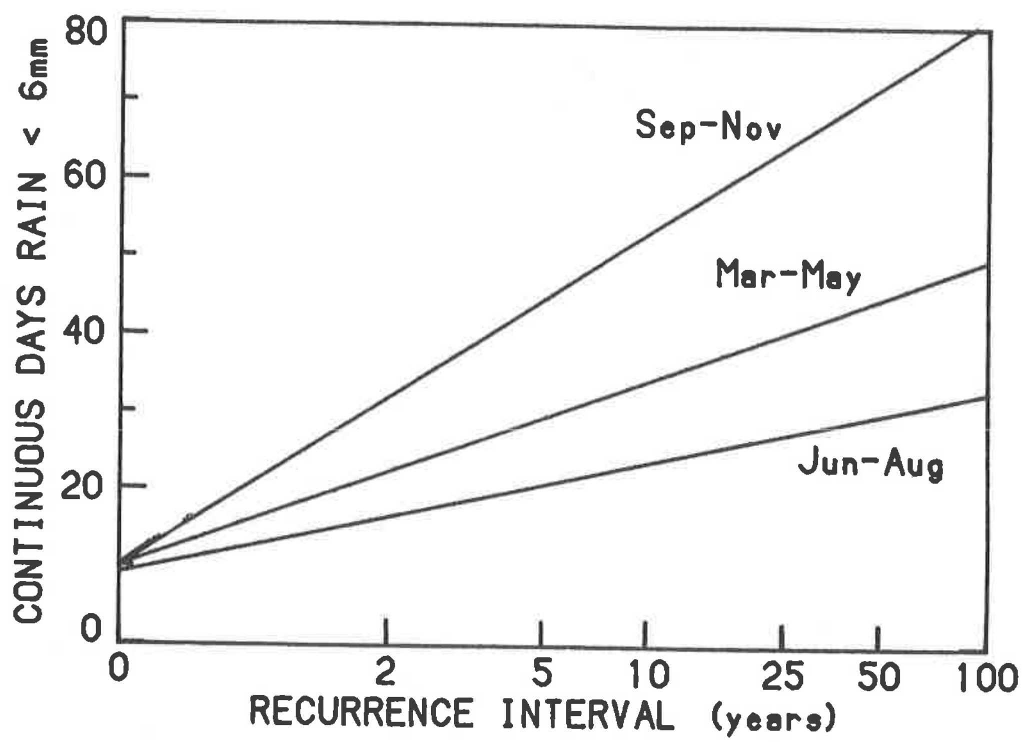

Figure 2. Rainfall-deficient period length vs. recurrence interval for various periods in Tifton, GA. (from Sheridan et al., 1979).

Table 2. Rainfall, Water Use and Water Deficit (in inches) during Growth of Selected Spring Planted Crops Planted on either March 1 or April 1.

Days from planting	Rainfall		Corn (3/1)		Peanut (4/1)		Soybean (4/1)		Tobacco (4/1)		Sweet corn (3/1)		Snap bean (3/1)	
	(3/1)*	(4/1)	use	deficit	use	deficit	use	deficit	use	deficit	use	deficit	use	deficit
20	3.0	2.6	1.0	0.0	1.0	0.0	1.0	0.0	1.4	0.0	1.0	0.0	1.0	0.0
40	2.9	2.5	3.0	0.1	1.6	0.0	1.6	0.0	2.4	0.0	1.0	0.1	3.0	0.1
60	2.8	2.4	4.4	1.6	2.6	0.2	2.6	0.2	4.4	2.0	4.4	1.6	3.8	1.0
80	2.4	3.2	6.2	3.8	5.6	2.4	5.6	2.4	3.0	0.0	3.1	1.9		
100	2.7	3.5	7.0	4.3	6.4	2.9	6.4	2.9						
120	3.0	3.7	6.0	3.0	5.8	2.1	5.8	2.1						
140		3.4			3.0	0.0	3.0	0.0						
Total	water use		27.6		26.0		26.0		11.2		11.5		7.8	
Total	rainfall		16.8		21.3		21.3		10.7		9.8		8.7	
Total	deficit		12.8		7.6		7.6		2.0		3.6		1.1	

* Planting Date

efficient irrigation is to supply that increment uniformly so that each increment of water added will produce that same increment in yield.

The threshold ET, as shown here for corn, is about 25 cm. That much water must be available before any yield can be produced. For soils which hold only 4 to 10 cm of water in the root zone, it is evident that rainfall or irrigation is needed to make any yield at all.

At the maximum yield, approximately 50 cm of water will be consumed. This amount differs little among crop species for growing seasons of 100 to 110 days. When water is freely available in the root zone and when vegetative cover is complete, water consumption is primarily a function of meteorological conditions. While some view farming as a practice of replacing native vegetation with water wasting crops, the native tree or other canopies consume as much water as crops as long as it is available. Differences in consumptive use among plant species occurs primarily when water becomes limited. For most species, growth slows and yield declines as water becomes unavailable to meet evaporative demand.

Adding water to allow consumption to proceed at full rate increases yields. By allowing plants to function optimally, irrigation increases the water use efficiency (WUE = yield per amount consumed) in most years (Figure 4). While specific responses of WUE varies from season to season, the first increments of irrigation water typically result in sharp increases in efficiency. Successive applications continue the increase until the full consumption is met. Further additions may actually be detrimental to growth so that WUE can decline with excess water.

Adding water increases the efficiency of use of other crop inputs in a similar manner. For example, when water is not limited, 12.5 T/ha corn yields can be produced with nitrogen additions of 250 kg/ha - for a N use efficiency of 50kg grain/kg N. If ET were limited to 0.8 of the full rate, yield would drop to 7.5 T/ha and N use efficiency would decline to 30 kg grain/kg N. Similar relationships exist for other crop inputs.

The purpose of irrigation scheduling is to apply water to meet consumptive use throughout the season without causing periods of water stress in the crop. The sensitivity of yield to the number of days of water stress has been documented in several ways. For corn grown in North Carolina even one or two days of stress had a significant effect on yield (Sopher et al., 1973). That effect was more severe during the late vegetative and the early reproductive stages than at other times. For example during the early reproductive stage each day of severe stress caused a yield reduction of 1.4 T/ha. Similar effects of days of stress during various growth stages have been observed for soybeans and peanuts as well. Sensitivity of yield to irrigation delay in Georgia showed the importance of correct timing of irrigation on yield (Figure 5). Delays of two days at each irrigation significantly lowered yields. Corn was also found to be sensitive to days when specific zones of the soil were dry. Yields were lowered an average of 0.2 T/ha for each day the deep subsoil was dry prior to tasselling and 0.1 T/ha for each day the second foot of soil was dry after tasselling. The sensitivity of crops to timing and placement of water makes it clear that efficient water use will only accompany carefully timed and managed irrigation.

While a plant cannot be forced to consume water wastefully, irrigation water can be applied in a wasteful manner. For a hypothetical case (Figure 6), if we assume all water is supplied by irrigation, the line to the left indicates the maximum efficiency (yield per water consumed). The dashed line would indicate water pumped versus yield assuming that no water was lost to leaching and that all water was supplied at optimum times - the best practical irrigation system. The difference between the lines is due to the normal inefficiency of the irrigation operation. Typically, 10 to 25% of the pumped water is lost to direct evaporation or wind drift. Yield per pumped water is less than yield per

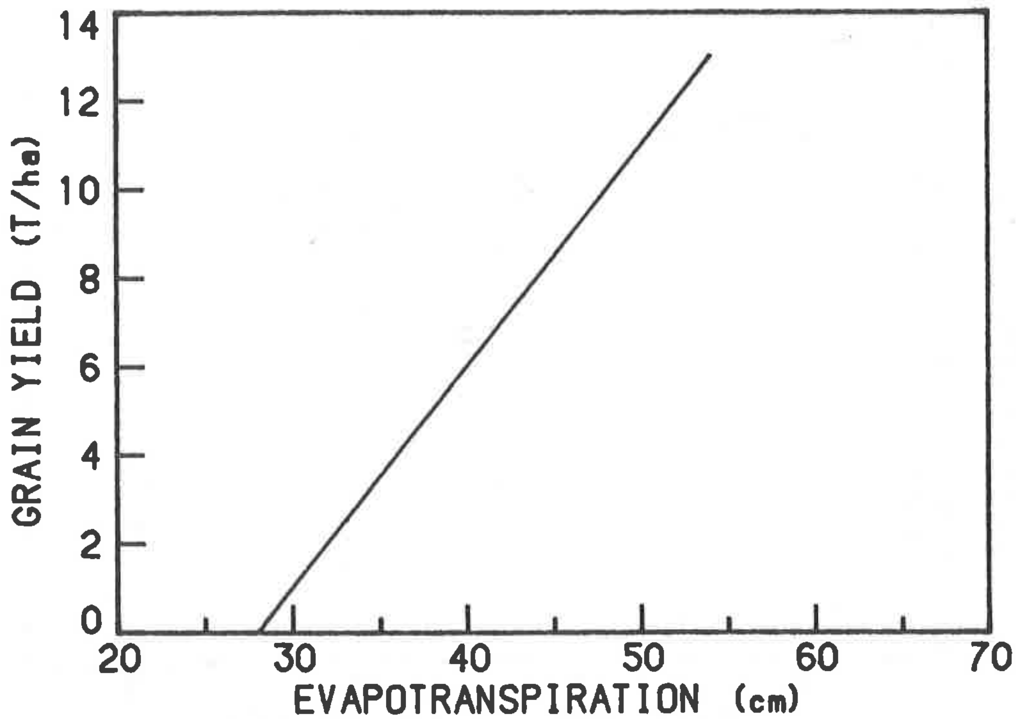

Figure 3. The relationship of cumulative evapotranspiration vs yield for a corn crop in Florida (from Hammond et al., 1981).

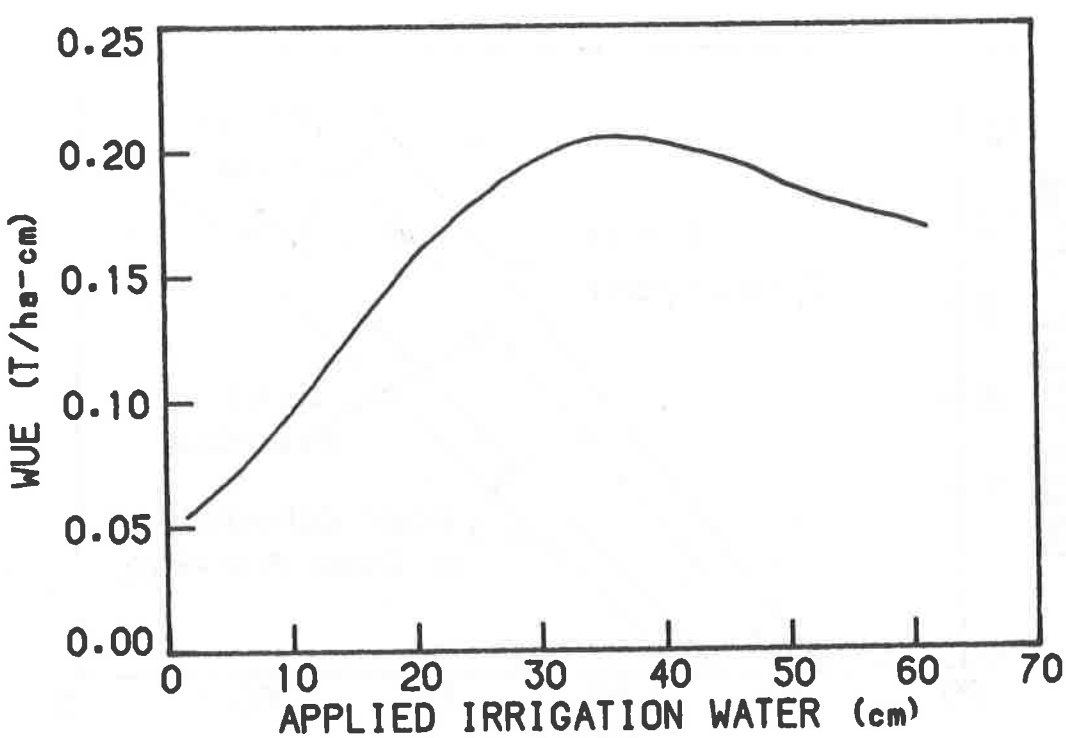

Figure 4. Typical water use efficiency (WUE) based on total water consumption as affected by applied water.

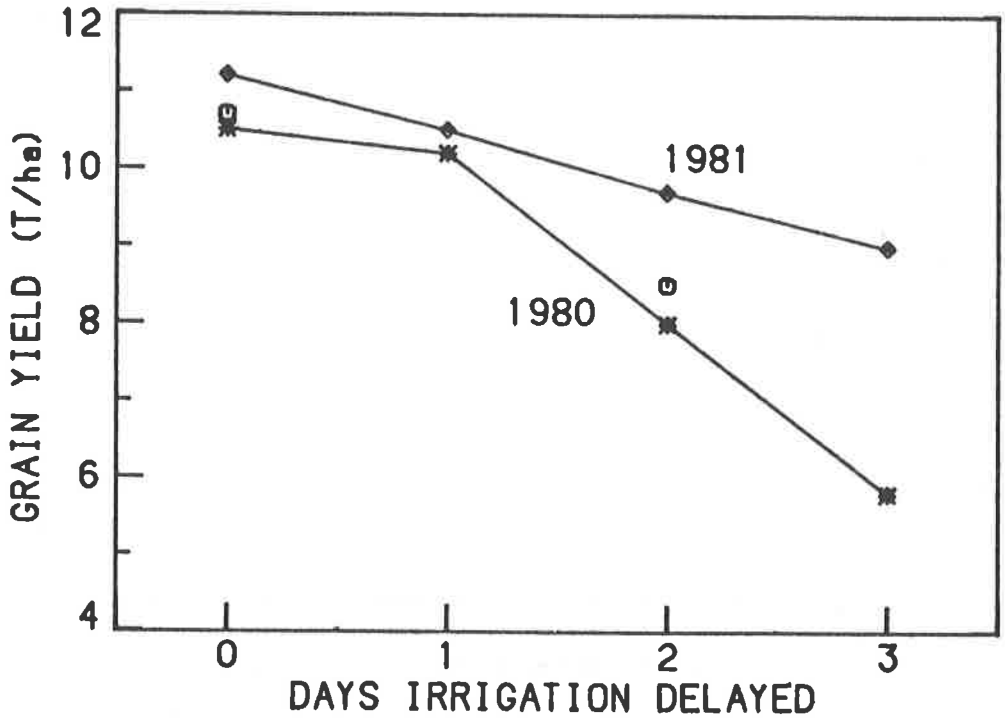

Figure 5. Response of corn yield to systematic delays of irrigation after tensiometers indicated a need for water (Hook, Unpub. Data).

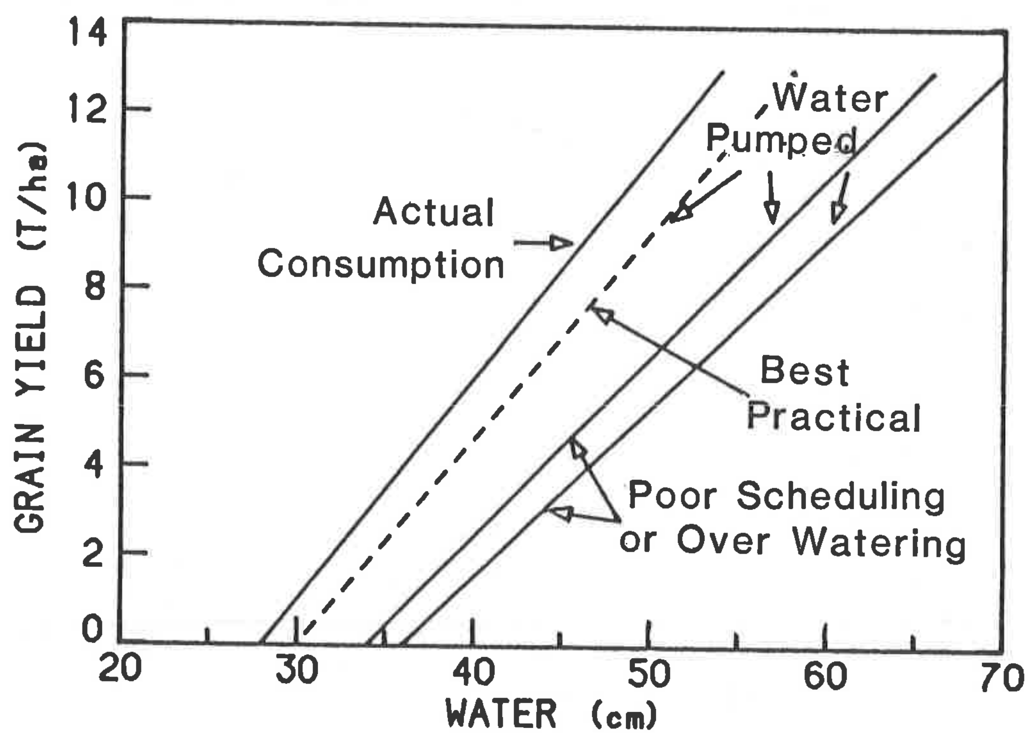

Figure 6. Hypothetical yield response to water consumed by the plant compared with amounts pumped with various causes of inefficiency.

consumed water. The other lines are possible response curves when less efficient management occurs. For example, when irrigation amounts exceed soil water holding capacity leaching occurs. Also, when timing of application allows some days of crop stress, even though the total amount of water applied is high enough for maximum ET, the water use efficiency is lowered.

DETERMINING WHEN TO IRRIGATE

Our knowledge of crop response to water suggests several ways we can determine when to irrigate. First response of crops to soil moisture conditions allows us to use soil water monitoring devices to determine water needs. Tensiometers, gypsum blocks and neutron probes are currently available for practical detection of soil water condition (Bruce et al., 1980). Incipient water stress conditions in plants provide direct information about crop water needs. Infra-red thermometers detecting leaf temperature and several devices measuring leaf water pressure or stomatal opening are capable of such measurements. However, none are in practical use in the typically cloudy and humid conditions of the Southeast. Evapotranspiration estimates, determined either from pan evaporation or from temperature, sunlight and wind observations, are becoming increasingly accurate. Several crop models using these estimates are practical tools for scheduling irrigation (Jensen, 1981).

SUMMARY

Irrigation is required in South Georgia for row crop production. Irrigation removes the risk of crop failure, improves the use efficiency of land and water resources, and improves the use efficiency of crop inputs. The tools for efficient timing and the irrigation equipment for efficient application are available. With proper timing and efficient application, water consumed by crops is effectively used for the production of food.

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PRECIPITATION RESULTS OF CLOUD SEEDING RESEARCH IN FLORIDA

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INTRODUCTION

The Florida Area Cumulus Experiment (FACE), which began in 1970 and ended in 1980, was a randomized experiment to determine whether seeding cumuli for dynamic effects (dynamic seeding) can be used to augment convective precipitation over a substantial target area (Fig. 1). Dynamic seeding is based on the theory that massive artificial ice nucleation in updraft regions (100 or more nuclei per liter for the Florida clouds) increases buoyancy through release of the heats of fusion, deposition and condensation, thereby producing taller, wider and longer lasting clouds (Simpson et al., 1965). Joint modeling and randomized single-cloud experimentation in the Caribbean suggested an effect on cloud heights and lifetimes (Malkus and Simpson, 1964: Simpson et al., 1967). Since larger and longer-lasting clouds process more water, it was then postulated that seeded clouds would produce more rain than their unseeded counterparts. A series of randomized single-cloud experiments in south Florida indicated that the seeded clouds produced an average rain volume 2-3 times that of the controls, primarily as a result of their larger size (average 20% increase in cloud height) and duration (Woodley, 1970; Simpson and Woodley, 1971). Based on these results, the decision was made to test dynamic seeding concepts for rain enhancement in a multiple cloud seeding experiment over a fixed target area in south Florida. This effort came to be known as FACE.

The FACE dynamic seeding conceptual model evolved during the years of the experiment. The conceptual model in force through most of the experimentation is presented by Woodley et al (1982).

FACE was conducted in two phases. The first or exploratory phase (FACE-1, 1970-1976) produced strong indications of increased rainfall upon examining the basic data and upon employing predictive relationships, derived using linear analyses of covariance (Woodley et al, 1982). The second or confirmatory phase (FACE-2, 1978-1980) did not confirm the results of FACE-1 in the manner specified by Woodley et al, (1978) beforehand nor were the indications of enhanced, seeding-induced rainfall as strong as in FACE-1 (Woodley et al, 1983).

This paper presents the rainfall results for the overall FACE program, encompassing 64 seed days and 62 no seed (control days). Analyses with and without predictors are presented and the possibility that seeding may have affected the rainfall outside of the intended target is addressed. The implications of the results to the water resources of Georgia are discussed.

DESIGN

FACE employed a single-area, randomized design. On days meeting objective suitability criteria up to three seeding aircraft flew the target area seeding vigorous, supercooled (i.e. tops of the clouds cooled below 0°C) clouds. Silver iodide flares (5 to 10 per pass) were introduced on seed days and either no flares or placebo flares on control days. Rainfall throughout FACE was estimated using S-band radar observations after adjustment by rain gages. In FACE-2, however, independent measures of target rainfall were provided by a large array of rain

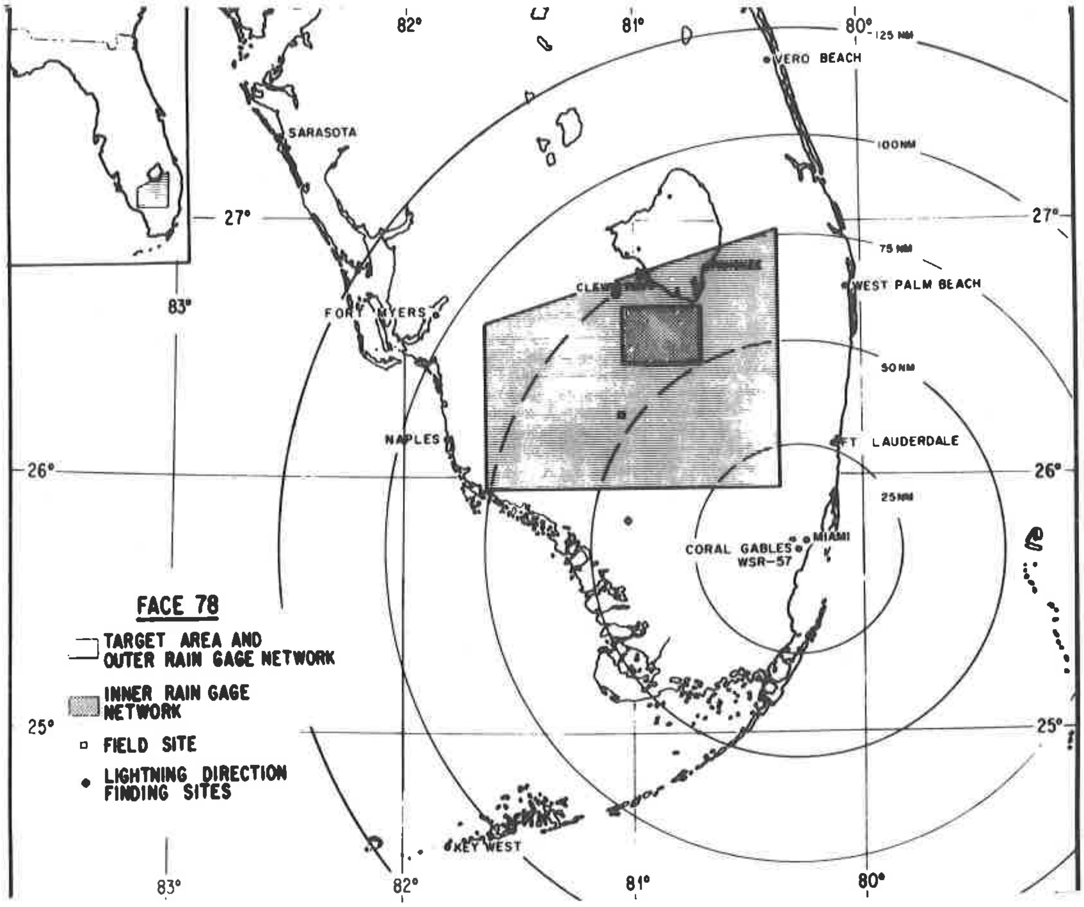


Figure 1. Map of the FACE target area (irregular quadrilateral) and the surrounding waters.

gages to serve as a check on the radar measurements.

The two primary response variables in FACE are rain volumes in the total target (TT) and in the floating target (FT), the most intensely treated portion of the target. The experimental unit is the day and the main observational period is the 6 hours after initiation of treatment. During all but the first two, limited years of the programs (a total of 12 days of experimentation), the treatment decisions were kept secret until all of the rainfall analyses had been completed. Details on the design and execution of the FACE program are provided by Woodley et al (1982) and by Barnston, et al (1983).

FLOATING AND TOTAL TARGET RAINFALL RESULTS

Initial evidence for the presence of a treatment effect in FACE is displayed in Fig. 2 in the form of a back-to-back "stem-and-leaf" plot (eg. Tukey 1977) and the accompanying "six-number summary" of the seed (S) and no-seed (NS) floating target (Fig. 2a) and total target (Fig. 2b), radar-estimated gage-adjusted, daily rainfall for all days of FACE (in the 6h period after initial treatment) in which 60 or more flares were fired (B days). A stem-and-leaf plot provides an ordered display of the data such that each individual value is shown. The stem contains the integer part of the values and the leaf contains the fractional part. For example, day 7/29/78 produced an estimated TT rainfall value of 25.81 mm (the largest value in the experiment) of which the integer part (25) is presented by the stem and the decimal part (0.81) by the two-digit leaf.

A

No.	No Seed Days		Seed Days	No.
(19)	95,95,94*,91*,85*,76,75,74*,62,40*,38,36*,36*,33*,33,28*,26*,25*,10*	0.00	09,15*,15*,20*,22*,24,25*,45,47*,60,69*,83,90*,92	(14)
(13)	82*,81*,74,64*,58*,53,50*,45,22*,13,06*,04,00	1.00	02*,05*,24,33*,38,49*,58*,81,82*,89,91,96	(12)
(11)	93*,91*,84,82*,76*,41,33,32*,21,18*,10	2.00	09*,12*,13*,22*,36,50*,59,63,65*,95*	(10)
(7)	97*,86*,80,71*,27,22*,20*	3.00	02*,30*,35,57,58*	(5)
(7)	96*,86,78*,63,53,35*,06*	4.00	26,32*,42*,69*,77*,95*	(6)
(0)		5.00	16*,24*,33*,62,81*,88*	(6)
(2)	82,19	6.00	20,37,65*,84	(4)
(1)	08	7.00		(0)
(0)		8.00	23*,39,52*	(3)
(1)	22*	9.00	15	(1)
(0)		10.00	43*,45*	(2)
(0)		11.00	50	(1)
(0)		12.00		(0)
(0)		13.00		(0)
(0)		14.00		(0)
(0)		15.00		(0)
(0)		16.00		(0)
(0)		17.00		(0)
(0)		18.00		(0)
(0)		19.00		(0)
(0)		20.00		(0)
(0)		21.00		(0)
(1)	22	22.00		(0)
(0)		23.00		(0)
(0)		24.00		(0)
(0)		25.00		(0)
62				64

N=62

M	1.82	
$Q_{1,3}$	0.91	3.71
$Q_{0,4}$	0.10	22.22

N=64

M	2.55	
$Q_{1,3}$	1.15	5.20
$Q_{0,4}$	0.09	11.50

B

No.	No Seed Days		Seed Days	No.
(7)	94,89*,77,68,53*,45*,33*	0.00	24*,60*,66,67,72*	(5)
(6)	78*,64,56,55,49*,18	1.00	02*,13,15,21*,31,41*,80*,84*,87	(9)
(11)	81*,79,73,65*,65*,45*,32,28*,28*,22,16*	2.00	03*,05,05,32*,37*,40,67,83*,91*,95	(10)
(11)	92*,84*,64*,61,52,49,45*,37*,36*,27,11	3.00	05*,12*,22,38*,47,78*,84,86,94	(9)
(11)	95*,78*,76*,70*,66,46*,43,38,19*,09*,04	4.00	05*,18*,21*,42*,64*,93	(6)
(1)	83*	5.00	83*,87*	(2)
(5)	72,58*,58*,21*,06*	6.00	25,48*,52*,66*,74*	(5)
(4)	98*,26,13*,12*	7.00	18*,18*,60*,67,79*,97*	(6)
(2)	85,36	8.00	12,14*	(2)
(2)	47,18*	9.00	13*,13,24,95,98*	(5)
(0)		10.00		(0)
(1)	14*	11.00	13*	(1)
(0)		12.00	16	(1)
(0)		13.00	31*	(1)
(0)		14.00		(0)
(0)		15.00	03,92*	(2)
(0)		16.00		(0)
(0)		17.00		(0)
(0)		18.00		(0)
(0)		19.00		(0)
(0)		20.00		(0)
(0)		21.00		(0)
(0)		22.00		(0)
(0)		23.00		(0)
(0)		24.00		(0)
(1)	81	25.00		(0)
62				64

N=62

M	3.57	
$Q_{1,3}$	2.28	5.83
$Q_{0,4}$	0.33	25.81

N=64

M	3.90	
$Q_{1,3}$	2.05	7.39
$Q_{0,4}$	0.24	15.92

Figure 2. Visual displays of the FACE rainfall data (mm per 6h) a) for the floating target; and b) for the total target. All rain values are gage-adjusted, radar estimated rainfalls for B type (>60 flares) days of experimentation. The asterisk indicates a rainfall value from FACE-1 (1970-1976). The top of each figure is a stem-and-leaf plot; the bottom is the corresponding six numbers summary.

In comparing the patterns of the S with the NS days for the floating target (FT) and total target (TT) variables (tops of Figs. 2a and 2b), two results are noteworthy: 1) there is a tendency for some of the S days to be shifted to slightly higher values and 2) there is a single NS value (7/29/78) which is separated substantially from the other NS values. It is a "far-out" (i.e. $\geq$ median plus three times the inter-quartile range) value when applying the Tukey (1977) criterion, and hence merits special attention. There are no such "far-out" values in the S sample.

The accompanying six-number summaries of the FT and TT stem-and-leaf plot (bottoms of Figs. 2a and 2b) suggest a slight positive seeding effect in that the second quartile or median (M), and the third quartile (Q_3) values are somewhat larger in the S days. Furthermore, the interquartile range (IR, which is Q_3-Q_1) is larger for the S days. Note, however, that the fourth quartile or maximum value is substantially greater for the NS distribution due to the "far-out" value.

Additional comparative results for the FT and TT in the 6h period beginning with initial treatment are presented in Table 1. Because of the presence of the single "far-out" NS value, the results will be presented both with and without it. Ratios (R) of S to NS days are tabulated for the mean ($\bar{X}$), median (Mdn) and standard deviation (SD). P-values from significance tests also are presented, and all reported P-values are one-tailed.

The results for the FT indicate that the S days have more rainfall in the mean (ratio of means give 1.28), more in terms of the median (1.40), but about the same variability as measured by the standard deviation (0.91). The P-value support for the mean and median differences is fairly strong. When the single far-out rain day (7/29/78), having a FT rainfall value over seven times greater than the NS FT mean, is deleted, the results are strongly suggestive of an effect of seeding. As examples, the ratios of means, medians and standard deviation are 1.46, 1.41 and 1.48, respectively, and the corresponding P-values are 0.01, 0.03 and 0.00

Table 1. Basic FACE and One-Tailed Signficance Tests for the FT and TT.

Floating Target

	TRMT	N	$\bar{X}$	R$\bar{X}$	P value[1]	Mdn	RMdn	P value[2]	SD	RSD	P value[3]
All	S	64	3.42	1.28	0.08	2.55	1.40	0.05	2.88	0.91	0.22
Days	NS	62	2.67			1.82			3.18		
Without "far-out"	S	64	3.42	1.46	0.01	2.55	1.41	0.03	2.88	1.48	0.002
Day	NS	61	2.35			1.81			1.95		

Total Target

	TRMT	N	$\bar{X}$	R$\bar{X}$	P value[1]	Mdn	RMdn	P value[2]	SD	RSD	P value[3]
All	S	64	4.99	1.15	0.17	3.90	1.09	0.19	3.69	0.99	0.47
Days	NS	62	4.35			3.57			3.72		
Without "far-out"	S	64	4.99	1.25	0.04	3.90	1.11	0.14	3.69	1.47	0.002
Day	NS	61	3.99			3.52			2.51		

1 one-tailed t-test

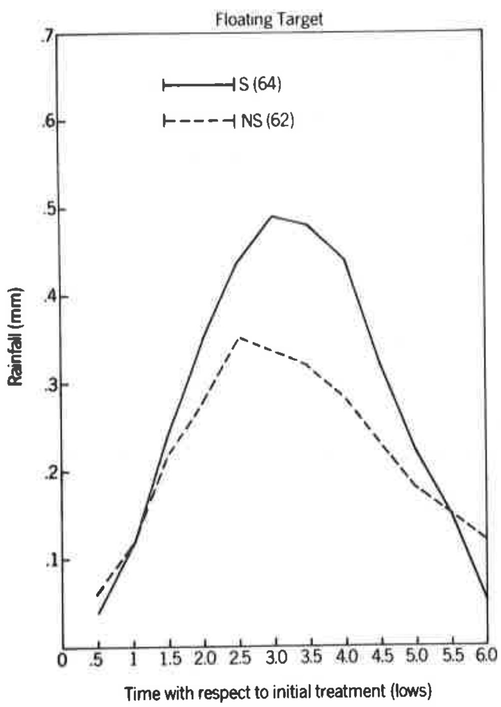
2 one-tailed Wilcoxon-Mann-Whitney test

3 one-tailed F-test

The TT results are similar to these for the FT except the indicated effects are smaller and the associated P-values are weaker. Once again, deletion of the single far-out rain day, having a rain value nearly six times the NS TT mean, strengthens the results.

This initial look at the results for FACE definitely suggests that the rainfall may have been enhanced by seeding by perhaps 25 to 50% in the FT and 15 to 25% in the TT.

Plots of the FT and TT rain volumes relative to the time of initial treatment are provided in Fig. 3. Both plots show small S-NS differences early in the treatment period; S rainfall exceeding NS rainfall (especially in the FT) in the period 2 to 4h after initial treatment and small differences once again.



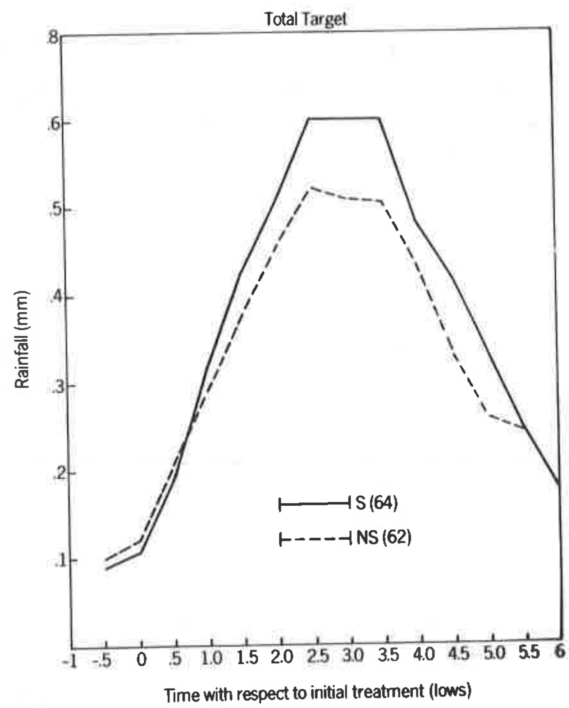


Figure 3. Plots of area-mean rainfall (mm) with respect to the time of initial treatment. Floating target on left and total target on right.

ASSESSMENT OF TREATMENT EFFECT USING LINEAR MODELS

Natural rainfall variability is the major obstacle to assessment of cloud seeding experiments for rain enhancement. In an experiment with a limited sample, how can one detect the signal (the seeding effect) in the noise (natural rainfall variability)? One means of accounting for the natural variability in the assessment of the treatment effect is to devise a linear model which incorporates prognostic or covariate variables. Our approach has been to employ separate linear models for the FT and TT response variables which incorporate prognostic variables and an index variable for treatment effect (i.e. an analysis of covariance). We have also employed a modified approach to the analysis of covariance by fitting only the covariates and then analyzing the residuals for evidence of treatment effect (i.e. a "sweepout" method). The results of these various analyses can be found in Woodley et al 1982; 1983 and in Flueck et al (1983). A brief summary is presented in Table 2.

All of the models addressed in Table 2 incorporate the following prognostic variables: 1) the rate of change of precipitation within the target before treatment (preslope), 2) the time of initial treatment on each day, 3) the amount of rainfall predicted by a one-dimensional cloud model, and 4) the wind speed normal to the Florida peninsula. All of these variables are correlated with target rainfall (the first three positively and the last negatively correlated). The only difference between the "meteorologically meaningful" and "all possible subsets" regression models was the logarithmic transformation of the model-predicted rainfall which was used in the all subsets regression model.

The r^2 entry in the table provides an estimate of the amount of rainfall variability explained by the equation. Note that, in the case of the FT, r^2 ranges between 14 and 16% and, in the case of the TT, between 28 and 31%. Thus, the predictor equations account for a rather small portion of the overall rainfall variability, especially for the FT.

The estimates of treatment effect and their (one-tailed) P-value support (i.e. significance level) suggest that seeding increased the rainfall in both the FT and TT. The apparent effect in the FT ranges between 25 and 40% with all P-values less than 0.05, and in the TT the range of effect is 19 to 25% with P-values between .05 and .11.

Table 2. Assessment of Treatment Effects(%) in FACE Using Linear Models.

		Analysis of Covariance		Sweepout	
		F T	T T	F T	T T
Model 1*	r^2	0.18	0.30	0.16	0.28
	T	35%	20%	34%	19%
	P	0.05	0.09	0.04	0.11
Model 2**	r^2	0.31	0.31	0.14	0.29
	T	25%	25%	40%	24%
	P	0.05	0.05	0.02	0.07

Model 1 is the "meteorologically meaningful" model

Model 2 is the "all subsets" regression model

r^2 = amount of variance explained by the correlation coefficient (i.e. square of the correlation coefficient)

T = inferred treatment effect in %

P = P-value or significance level of the inferred treatment effect

ADDITIONAL EVIDENCE FOR SEEDING EFFECTS ON THE CELL SCALE

As a further test of the effect of dynamic seeding on rainfall, convective cells were examined before and after treatment with either silver iodide or sand during FACE-2 (1978-1980). Convective cells are identified by radar as regions of maximum reflectivity or rainfall intensity within an overall radar echo. Radar echoes can have from one to five or more cells embedded within them. Convective cells as seen on a radar scope are analogous to height maxima as seen on a topographic map of a mountainous region. With convective cells the contours are reflectivity or rain intensity and with mountains the contours are height above sea level.

In the FACE-2 study, radar in conjunction with sophisticated computer software was used to track the cells and measure their properties (eg. area, height, rainfall intensity, rain volume, etc.). It was possible to infer the effect of seeding on cells within 100km of the radar by examining their properties as a function of time and as a function of treatment (either silver iodide or sand). Not only was it possible to form the ratio of seed to no seed cell properties (i.e. T_{AgI}/T_{sand}) as an estimator of seeding effect, but it was also possible to account for potential biases in this treatment ratio by using untreated cells near the treated cells as controls. Thus, the treatment ratio T_{AgI}/T_{sand} for a particular property (eg. height) for all cells in the sample was divided by the ratio C_{AgI}/C_{sand} for the control cells in the sample to provide an estimate of seeding that accounts for natural biases.

This study was spearheaded by Dr. Abe Gagin of Hebrew University in Jerusalem, Israel, and Dr. Raul Lopez of the Environmental Research Laboratories in Boulder, Colorado and the results have not yet been published in the formal literature. A portion of their results are summarized here.

The most noteworthy initial finding of the research was the substantial ($\sim$0.80) positive correlation between maximum cell height and cell area, rain rate, rain volume and duration. The finding supports the dynamic seeding concept in that increased rainfall is a reasonable expectation if one can induce increased cloud growth through seeding.

The second finding worthy of note upon examining 140 treated cells (80S and 60NS) and 2695 control cells (1479S and 1216NS) is that seeding with silver iodide altered cell properties relative to the properties of the sand-treated cells and that the size of the apparent effect is proportional to the amount of nucleant used. The results are presented in Table 3 as a function of the number (N) of flares (70gm each) expended.

Examination of Table 3 reveals virtually no effect for $N \leq 4$. The single ratio (S.R.) of T_{AgI} to T_{sand} is close to 1.00 and the significance levels (SL). obtained using rerandomization procedures are rather large. The results after forming the double ratio (D.R.) $T_{AgI}/T_{sand} \div C_{AgI}/C_{sand}$ are little different in that no effect of treatment is evident. As one moves to higher flare expenditures, however, the picture changes and an effect of seeding is indicated, particularly for the highest flare expenditure category. Here there are indications of an effect on all cell properties and the significance is nearly 5% or less in most cases. As an example, there is nearly a factor of 2 or 100% increase in rain volume. In addition, in almost every instance, the effect increases after accounting for natural biases. These results strongly support the Florida studies cited earlier in the text (i.e. Woodley, 1970; Simpson and Woodley, 1971) which indicated that dynamic seeding increases cloud growth and rainfall.

POSSIBILITY OF EXTENDED-AREA EFFECTS OF SEEDING

A major concern in every weather modification experiment is whether seeding affects the precipitation outside of the intended target. An exploratory analysis was conducted in FACE-2 to investigate this possibility (Meitin et al, 1983). Rainfall was estimated over a $3.5 \times 10^5 km^2$ area centered on the target using geosynchronous, infrared satellite imaging and the Griffith/Woodley rain estima-

Table 3. Seeding Effect as a Function of Flare Expenditure.

FACE-2

(1 flare produces 70 gm AgI)

	Parameter	T sand	T_{AgI}	S.R.	S.L.	D.R.	S.L.
$N \leq 4$	RVOL ($m^3 \times 10^3$)	129.0	139.9	1.09	45.4	1.25	37.6
	ZMAX (dbz)	43.9	43.9	1.00	38.2	1.04	17.8
	HMAX (km)	9.3	9.2	0.99	49.0	0.99	49.5
	AMAX (km^2)	86.1	73.7	0.86	77.5	0.82	79.5
	Duration (min)	26.1	28.6	1.096	26.0	1.10	22.6
	N	17	25				
$5 \leq N \leq 8$	RVOL ($m^3 \times 10^3$)	190.3	223.5	1.17	30.4	1.35	13.8
	ZMAX (dbz)	45.5	45.1	0.99	50.8	1.03	1.7
	HMAX (km)	8.3	9.2	1.11	14.9	1.11	4.6
	AMAX (km^2)	84.3	88.4	1.05	25.7	0.995	46.6
	Duration (min)	24.2	26.2	1.08	20.6	1.09	19.6
	N	18	28				
$9 \leq N$	RVOL ($m^3 \times 10^3$)	142.7	262.0	1.84	4.7	2.13	1.9
	ZMAX (dbz)	43.9	46.8	1.066	1.5	1.10	0.3
	HMAX (km)	8.2	9.7	1.178	5.2	1.18	2.7
	AMAX (km^2)	79.4	99.3	1.25	5.3	1.18	8.6
	Duration (min)	24.2	30.5	1.26	5.8	1.27	3.5
	N	25	27				

tion technique (Griffith et al, 1978; Woodley et al, 1980). The satellite rain estimates for the extended area were adjusted based on comparisons of rain gage and satellite rainfall estimates for the entire FACE target ($1.3 \times 10^4 km^2$). All daily rainfall estimates were composited in two ways: 1) in the original coordinate system, and 2) in a relative coordinate system that rotates the research area as a function of wind direction. After compositing, seeding effects were sought as a function of space and time.

The results show more rainfall (in the mean) on seed than no seed days both in and downwind of the target but lesser rainfall upwind. All differences are confined in space to within 200 km of the center of the FACE target and in time to the 8 h period after initial treatment. In addition the positive correlation between untreated upwind rainfall and target rainfall is degraded on seed days, suggesting possible intermittent negative effects of seeding upwind. Although the development of these differences in space and time suggests that seeding may have been partially responsible for their generation, the results do not have strong inferential (P-value) support.

An example from Meiten et al (1983) showing a potential extended-area effect of seeding in FACE-2 is provided in Figure 4. The plotted S-NS rain differences (top) and percentage rain differences (bottom), cumulative in both space and time, have been put into a rotational framework relative to the center of the target (i.e. upwind, downwind and both upwind and downwind). The evening mean winds between 1.5 and 6.0 km were used to determine the upwind and downwind directions. The vertical arrow marks the average boundary of the target.

Note the clear dichotomy in rain differences, averaging about 20% downwind and -10% upwind. If these differences represent real effects of seeding, the explanation would be that seeding increases the cloud growth and rainfall within the target and these clouds then move downwind while at the same time producing some rainfall decreases (due to compensating subsidence) upwind.

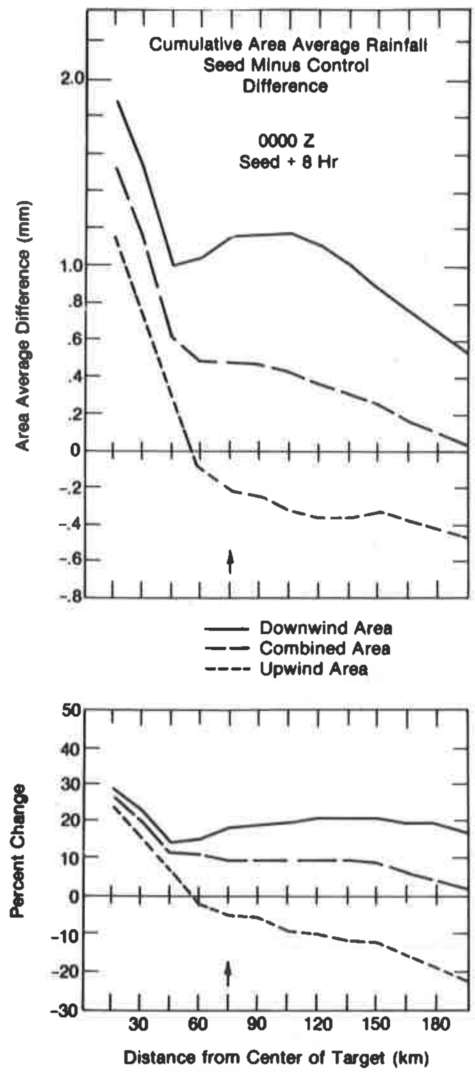


Figure 4. Plots of mean rain differences (top) and mean percentage differences (bottom)which are cumulative in space and in time (out to 8h) for the 0000GMT sounding.

CONCLUSIONS

The results of the FACE studies suggest, but do not prove, that it may be possible to increase rainfall by cloud seeding. The results for individual clouds are strong (P-values < 0.05) and fairly persuasive, indicating as much as a 100% increase in rainfall due to the increased size and duration of the seeded clouds. The results for groups of convective clouds (the floating target) suggest rainfall increases between 25% and 40% with rather strong P-value (statistical significance) support between .05 and .10. For the entire FACE target the apparent effect of treatment ranges between 15% and 25% with weaker (.05 to .17) P-value support. Studies of the extended-area effects of seeding in FACE indicate the possibility that seeding increased the rainfall downwind of the target with compensating decreases of a lesser magnitude upwind. All apparent extended-area effects are confined to within 200km of the center of the FACE target and within the 8 hour period after initial treatment.

Because of the similarity of cloud and weather conditions in Florida and Georgia, the FACE results suggest that there may be rain enhancement potential in

Georgia. Caution is advised, however, in any attempt to modify the weather to make certain that the effect of treatment is not different from what was intended. There are no shortcuts to well-planned, well-executed weather modification research. If done properly, Georgia and its water resources may well benefit ultimately from such a program.

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