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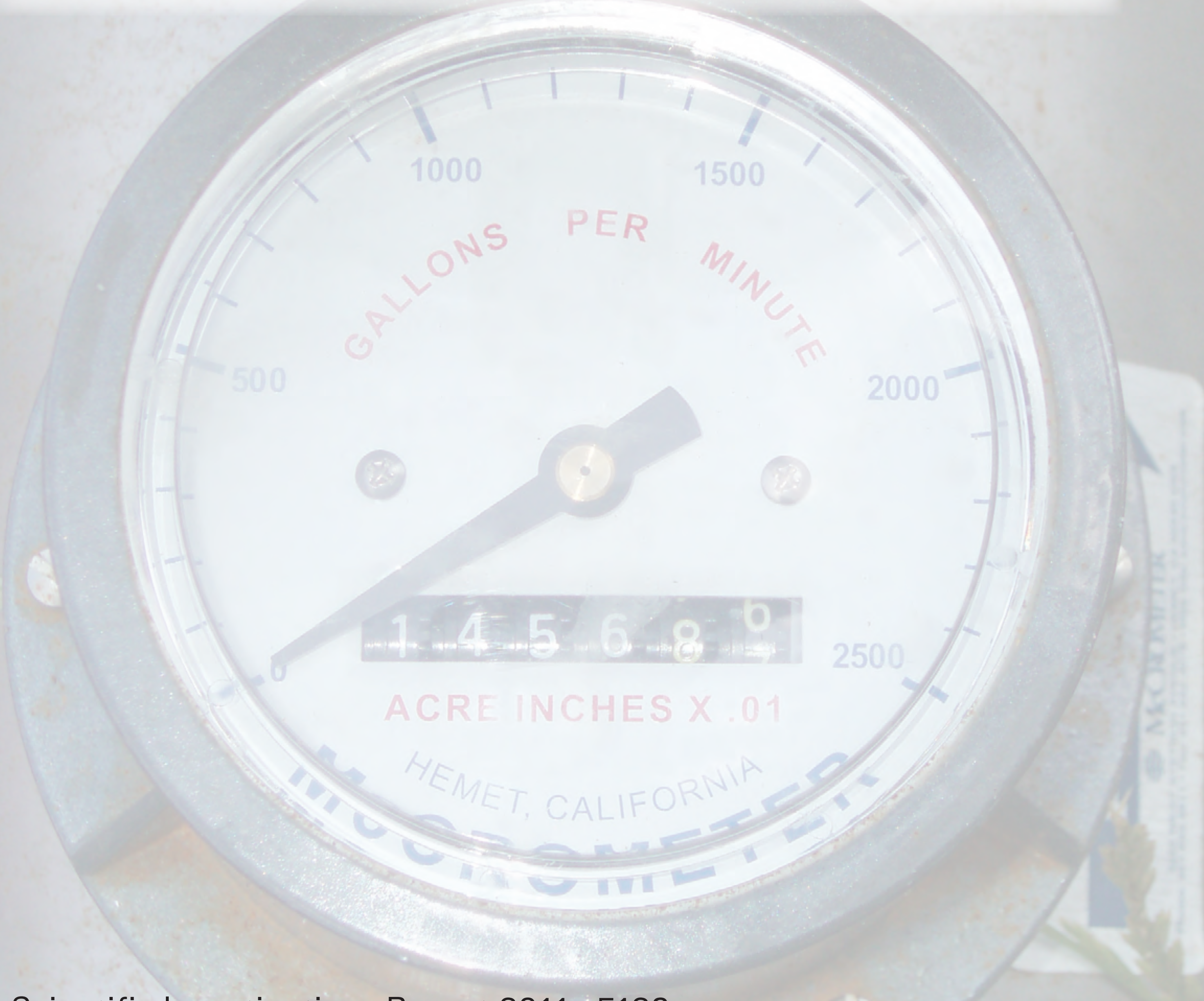
Summary of the Georgia Agricultural Water Conservation and Metering Program and Evaluation of Methods Used to Collect and Analyze Irrigation Data for the Middle and Lower Chattahoochee and Flint River Basins, 2004–2010



Scientific Investigations Report 2011–5126

U.S. Department of the Interior
U.S. Geological Survey

Cover. Water meter installed on irrigation system in southern Georgia (photograph by Lynn J. Torak, USGS).

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Summary of the Georgia Agricultural Water Conservation and Metering Program and Evaluation of Methods Used to Collect and Analyze Irrigation Data for the Middle and Lower Chattahoochee and Flint River Basins, 2004–2010

By Lynn J. Torak and Jaime A. Painter

Abstract

Since receiving jurisdiction from the State Legislature in June 2003 to implement the Georgia Agricultural Water Conservation and Metering Program, the Georgia Soil and Water Conservation Commission (Commission) by year-end 2010 installed more than 10,000 annually read water meters and nearly 200 daily reporting, satellite-transmitted, telemetry sites on irrigation systems located primarily in southern Georgia. More than 3,000 annually reported meters and 50 telemetry sites were installed during 2010 alone. The Commission monitored rates and volumes of agricultural irrigation supplied by groundwater, surface-water, and well-to-pond sources to inform water managers on the patterns and amounts of such water use and to determine effective and efficient resource utilization.

Summary analyses of 4 complete years of irrigation data collected from annually read water meters in the middle and lower Chattahoochee and Flint River basins during 2007–2010 indicated that groundwater-supplied fields received slightly more irrigation depth per acre than surface-water-supplied fields. Year 2007 yielded the largest disparity between irrigation depth supplied by groundwater and surface-water sources as farmers responded to severe-to-exceptional drought conditions with increased irrigation. Groundwater sources (wells and well-to-pond systems) outnumbered surface-water sources by a factor of five; each groundwater source applied a third more irrigation volume than surface water; and, total irrigation volume from groundwater exceeded that of surface water by a factor of 6.7. Metered irrigation volume indicated a pattern of low-to-high water use from northwest to southeast that could point to relations between agricultural water use, water-resource potential and availability, soil type, and crop patterns.

Normalizing metered irrigation-volume data by factoring out irrigated acres allowed irrigation water use to be expressed as an irrigation depth and nearly eliminated the disparity between volumes of applied irrigation derived from groundwater and surface water. Analysis of per-acre irrigation depths provided a commonality for comparing irrigation practices across the entire range of field sizes in southern Georgia and indicated underreporting of irrigated acres for some systems. Well-to-pond systems supplied irrigation at depths similar to groundwater and can be combined with groundwater irrigation data for subsequent analyses. Average irrigation depths during 2010 indicated an increase from average irrigation depths during 2008 and 2009, most likely the result of relatively dry conditions during 2010 compared to conditions in 2008 and 2009.

Geostatistical models facilitated estimation of irrigation water use for unmetered systems and demonstrated usefulness in redesigning the telemetry network. Geospatial analysis evaluated the ability of the telemetry network to represent annually reported water-meter data and presented an objective, unbiased method for revising the network.

Introduction

The Georgia General Assembly enacted House Bill 579 on June 4, 2003, granting jurisdiction to the Georgia Soil and Water Conservation Commission (hereafter referred to as the Commission) to

> "…[implement] a program of measuring farm uses of water in order to obtain clear and accurate information on the patterns and amounts of such use, which information is essential to proper management of water resources by the state and useful to farms for improving the efficiency and effectiveness of their use of water … and [for] improving water conservation" (Georgia General Assembly, 2003).

During late 2003, the Commission began installing water meters for the annually reported and daily telemetry networks to provide estimates of applied irrigation volumes and per-acre irrigation depths derived from groundwater, surface-water, and well-to-pond sources.

Since November 2008, the U.S. Geological Survey (USGS), in cooperation with the Commission, has investigated methods for estimating agricultural water use and growing-season pumping rates through the analysis of water-meter data. Initial investigations assured the quality of irrigation water-meter data collected since the establishment of the metering program in 2003. Geospatial analyses of these data yielded promising results for identifying patterns of seasonal agricultural water use.

Study Objectives

The following objectives describe the USGS investigation of irrigation data collected by the Commission in accordance with and support of the metering program:

- Develop a quality-assurance program to ensure completeness and internal consistency of water-meter data;
- Calculate descriptive statistics of aggregated water-use data;
- Evaluate the potential to relate daily water-use telemetry (telemetered data) to annually reported water-use data through a descriptive statistical model; and
- Identify spatial and temporal distributions of agricultural-irrigation pumpage.

Purpose and Scope

This report summarizes agricultural water-meter irrigation data collected by the Georgia Soil and Water Conservation Commission during 2004–2010 in support of the Georgia Agricultural Water Conservation and Metering Program that has been implemented in Georgia. The report contains maps showing the status of the metering program at years-end 2009 and 2010 for visual comparison of the level of completeness of meter installations at these time horizons.

The report describes an evaluation of methods used to assess the accuracy of the annually reported and telemetry water-meter networks to represent the entire population of irrigation systems in Georgia. Results of this assessment involved irrigation data from the middle and lower Chattahoochee and Flint River basins for the 2007 growing season and are presented as an example.

Described in this report are summary analyses of 4 years of complete irrigation water-meter data collected in the middle and lower Chattahoochee and Flint River basins during the 2007–2010 growing seasons and a detailed geospatial analysis of metered agricultural-irrigation data for the 2007 growing season. The 2007 growing-season data proved to be the most interesting of the 4 years of complete irrigation data, yielding the largest disparity between irrigation supplied by groundwater and surface-water sources as farmers responded to severe-to-exceptional drought conditions with increased irrigation. The geospatial analysis demonstrated the usefulness of this technology for evaluating the ability of the telemetry network to represent annually reported water-meter data and presented an objective, unbiased method for revising the network and estimating irrigation water use at unmetered irrigation sites.

Data and mathematical relations expressed in this report are used solely in a manner consistent with the intent of Georgia General Assembly House Bill 579 (Georgia General Assembly, 2003) and the Privacy Act of 1974 (U.S. Department of Justice, 2010) and the intent of both of these documents to protect the right to privacy of each farmer. Therefore, this report, contains aggregated data and analyses without reference to specific water use by individual farmers.

The cooperative research of agricultural water-use data by USGS and the Commission aligns directly with the USGS mission to provide reliable, impartial, and timely information that is needed to understand the Nation's water resources. The unique water-use dataset generated by the agricultural irrigation water-metering program in Georgia could be integrated with corresponding national water-use and availability datasets under the WaterSMART Availability and Use Assessment Program, which has identified the metered area of the middle and lower Chattahoochee and Flint River basins as part of a focus area study (U.S. Geological Survey, 2010). The analyses of metered irrigation data presented herein demonstrate a possible technique for water-use assessment that could be scaled up to the national level for developing future Water Census products (Eric Evenson, U.S. Geological Survey, Coordinator, WaterSMART Initiative, written commun., May 2011). Researchers for the WaterSMART initiative have expressed interest in comparing these methods of data analysis with that currently used in the national Water Census program (Phillip J. Zarriello, Hydrologist, U.S. Geological Survey, Northborough, Massachusetts; Molly A. Maupin, Hydrologist, U.S. Geological Survey, Boise, Idaho, written commun., June 2011). USGS impartiality in developing results of this cooperative investigation with the Commission enables objective analyses of agricultural water-meter data and provides a scientific foundation for making water-management decisions involving the use of limited groundwater and surface-water resources by agriculture in Georgia.

Summary of the Georgia Agricultural Water Conservation and Metering Program, 2004–2010

Initial meter installations during 2004–2007 coincided geographically with the concentration of agricultural irrigation in south Georgia, focusing mainly in the middle and lower parts of the Chattahoochee and Flint River basins (fig. 1). A few water meters were installed in the southern part of the upper Flint River basin. By year-end 2009, the Commission monitored agricultural withdrawal from a network of 6,985 annually read flow meters and 148 daily reporting, satellite telemetry sites operating at water-withdrawal-permit locations in southern Georgia (table 1).

Installation of water meters continued in other areas of Georgia through 2010, increasing to a total of more than 10,000 annually reported and about 200 telemetry sites (David A. Eigenberg, Georgia Soil and Water Conservation Commission, written commun., May 2011; fig. 2). Compared with the map showing the 2009 status of the metering program (fig. 1*A*), the 2010 map illustrates the effectiveness of the State Agricultural Water Conservation and Metering Program (hereafter referred to as simply the metering program) for installing water meters on nearly every permitted agricultural water-withdrawal system in Georgia.

Installation of annually reported and daily telemetry water-meter networks progressed to completion in the Chattahoochee and Flint River basins in time to monitor water use during the 2007 growing season. Three statistical regions were identified for analysis of agricultural water-meter irrigation data based on completion of water-meter installations by 2007 (fig. 1). Statistical region 1, the middle and lower Chattahoochee and Flint River basins, contained completed networks of annually reported and daily telemetry water-meter data by the beginning of the 2007 growing season. Installation of water-meter networks for statistical region 2, the coastal region, and statistical region 3, central-south Georgia, continued during 2007–2010.

By the end of 2009, in the middle and lower Chattahoochee and Flint River basins, groundwater meters outnumbered surface-water meters by a factor of five (3,609 groundwater meters compared to 748 surface-water meters; fig. 1, table 1). The disparity between these numbers likely is a result of the relative ease of obtaining groundwater from high-yielding wells, installed virtually at the point of irrigation in the field, compared to piping surface water from a limited network of streams, each of which contains limited water availability and the potential to dry up during the height of the growing season.

Table 1. Summary of water-meter installations in southern Georgia, 2009.

[See figure 1 for location]

Source	Meter type	
	Annually reported	Telemetry
Middle and lower Chattahoochee and Flint River basins		
Groundwater	3,609	46
Surface water	748	35
Subtotal	4,357	81
Coastal region		
Groundwater	679	20
Surface water	378	16
Subtotal	1,057	36
Central south Georgia		
Groundwater	912	15
Surface water	659	16
Subtotal	1,571	31
Total	6,985	148

A. **Permitted unmetered and metered agricultural water-use sites**

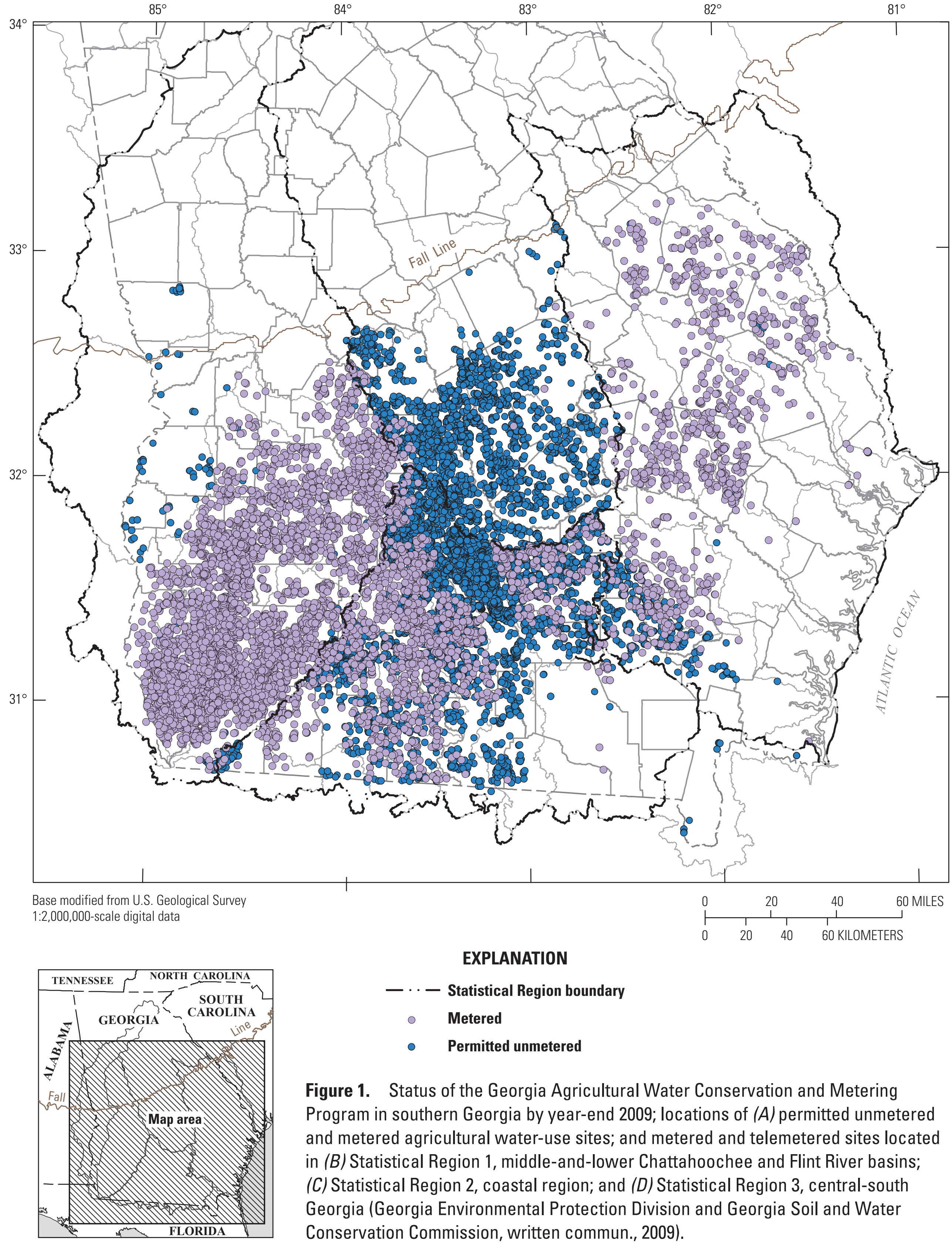
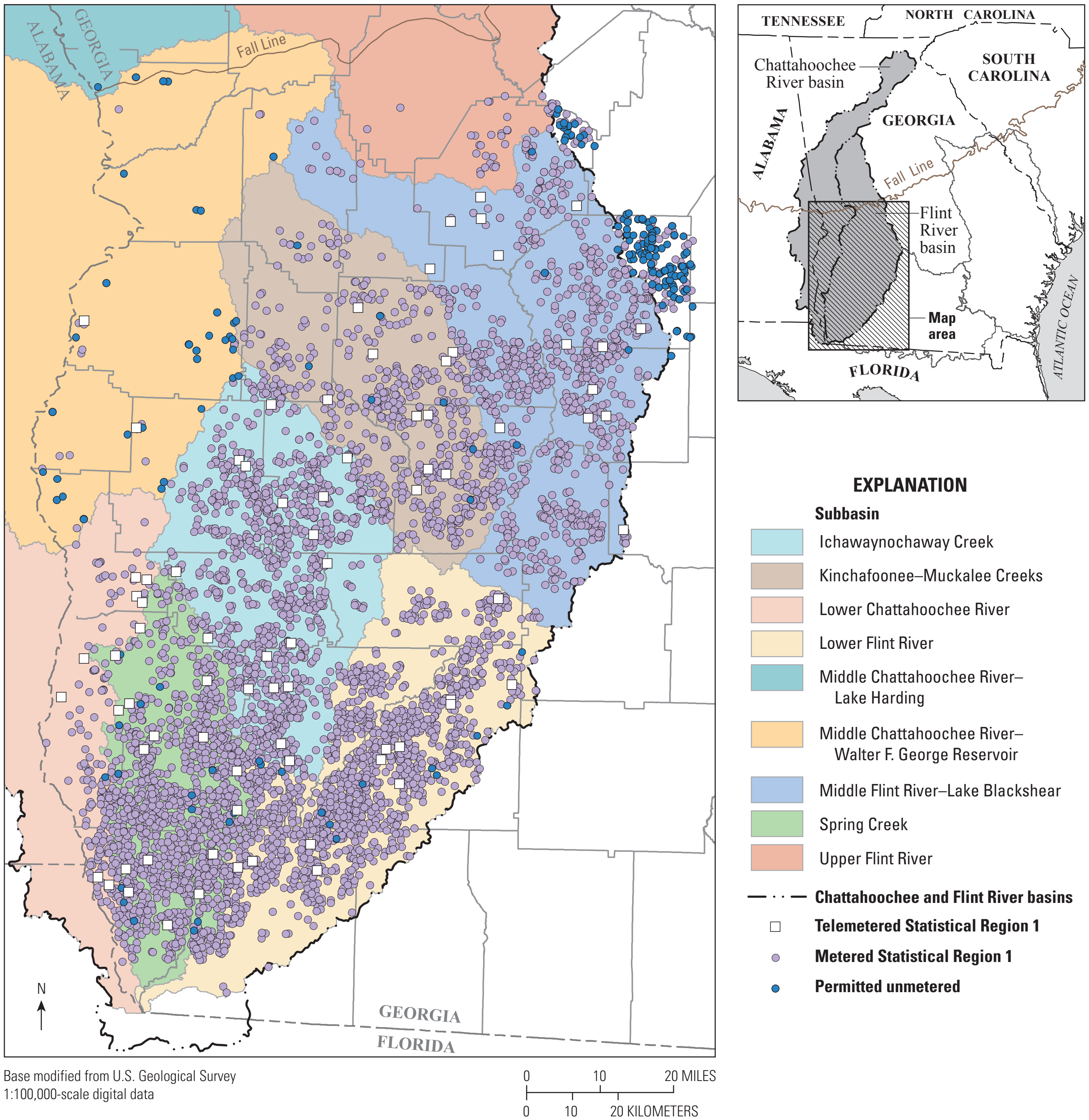


Figure 1. Status of the Georgia Agricultural Water Conservation and Metering Program in southern Georgia by year-end 2009; locations of *(A)* permitted unmetered and metered agricultural water-use sites; and metered and telemetered sites located in *(B)* Statistical Region 1, middle-and-lower Chattahoochee and Flint River basins; *(C)* Statistical Region 2, coastal region; and *(D)* Statistical Region 3, central-south Georgia (Georgia Environmental Protection Division and Georgia Soil and Water Conservation Commission, written commun., 2009).

B. **Statistical Region 1, middle and lower Chattahoochee and Flint River basins**



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***C.* Statistical Region 2, coastal region**

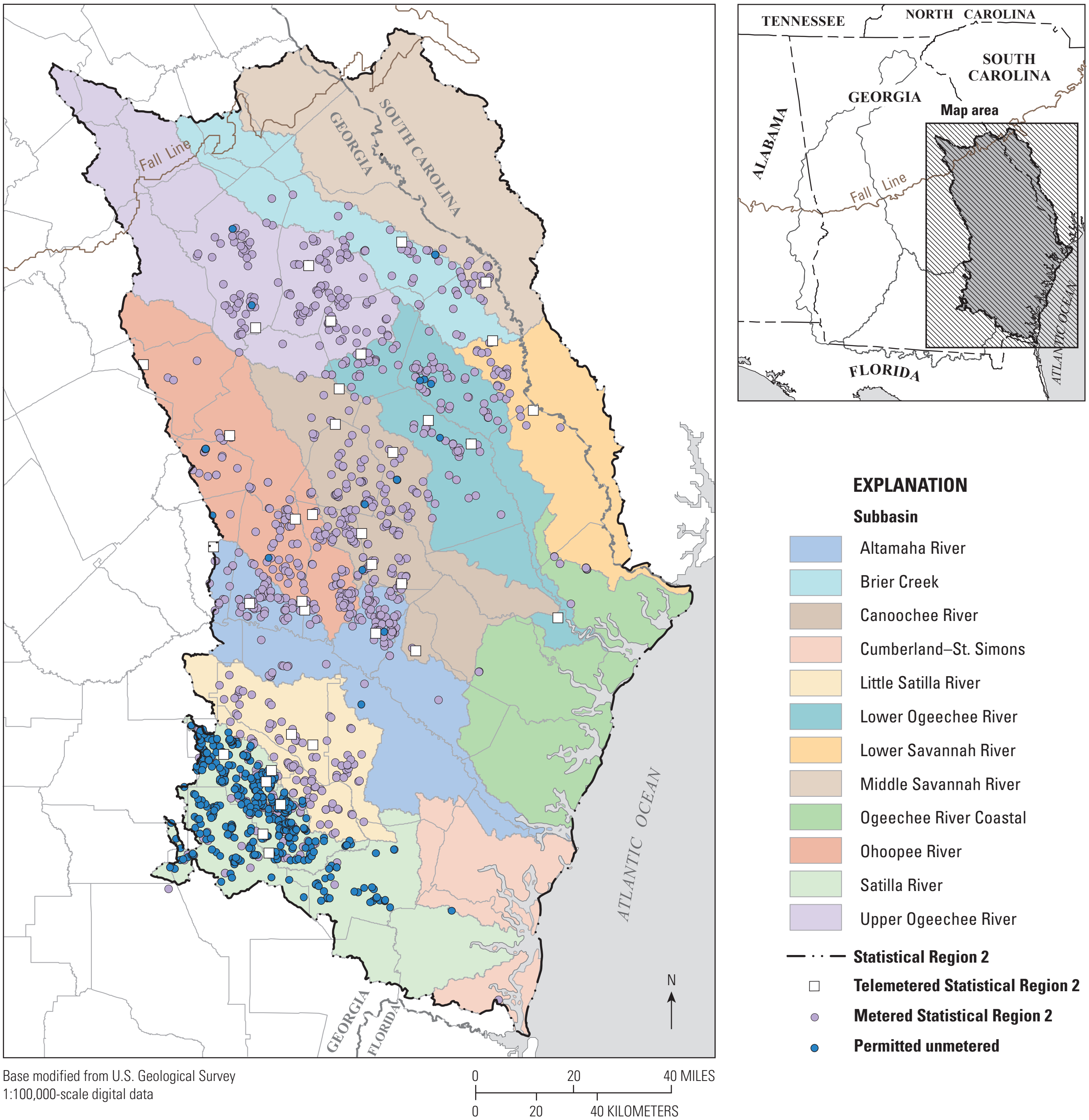


Figure 1. Status of the Georgia Agricultural Water Conservation and Metering Program in southern Georgia by year-end 2009; locations of *(A)* permitted unmetered and metered agricultural water-use sites; and metered and telemetered sites located in *(B)* Statistical Region 1, middle-and-lower Chattahoochee and Flint River basins; *(C)* Statistical Region 2, coastal region; and *(D)* Statistical Region 3, central-south Georgia (Georgia Environmental Protection Division and Georgia Soil and Water Conservation Commission, written commun., 2009).—Continued

D. **Statistical Region 3, central-south Georgia**

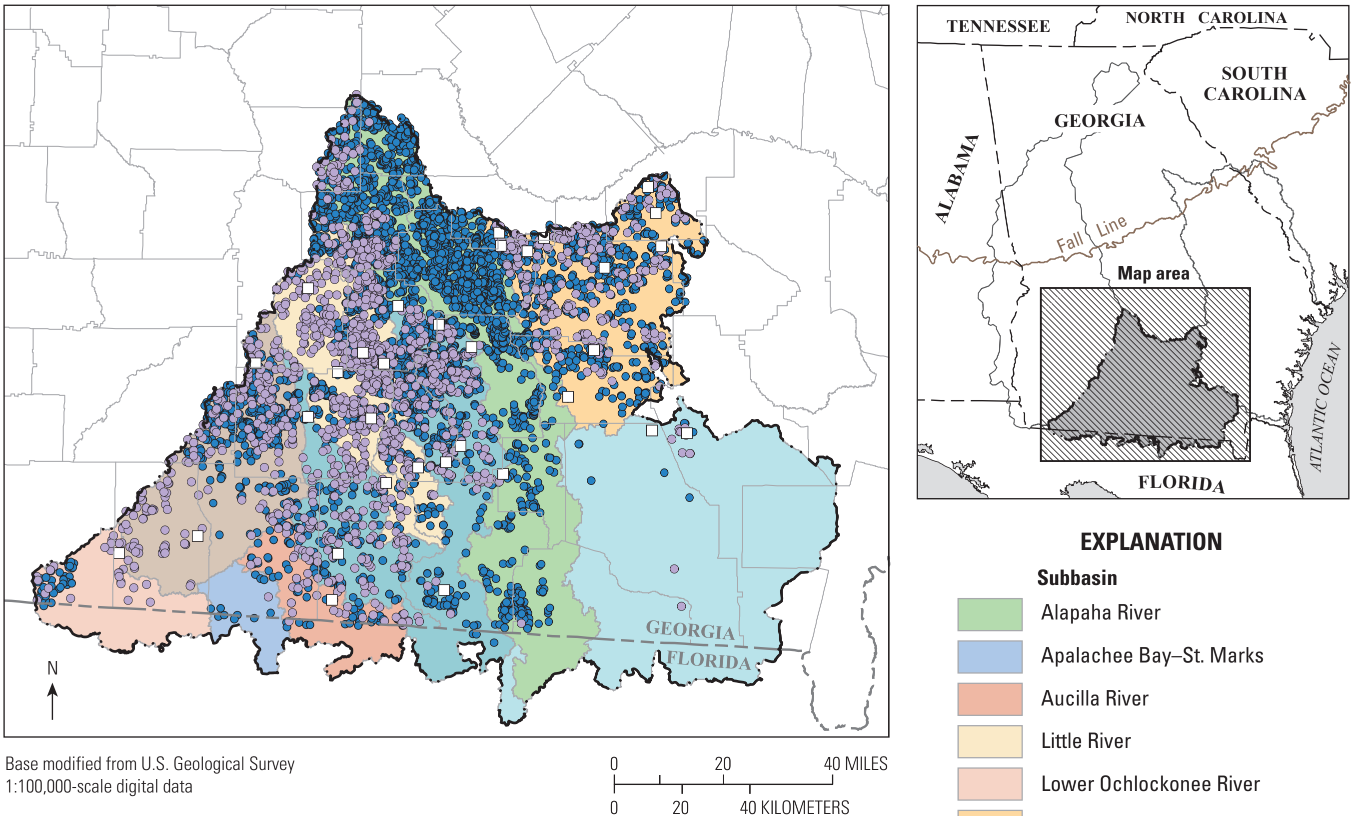


Figure 1. Status of the Georgia Agricultural Water Conservation and Metering Program in southern Georgia by year-end 2009; locations of *(A)* permitted unmetered and metered agricultural water-use sites; and metered and telemetered sites located in *(B)* Statistical Region 1, middle-and-lower Chattahoochee and Flint River basins; *(C)* Statistical Region 2, coastal region; and *(D)* Statistical Region 3, central-south Georgia (Georgia Environmental Protection Division and Georgia Soil and Water Conservation Commission, written commun., 2009).—Continued

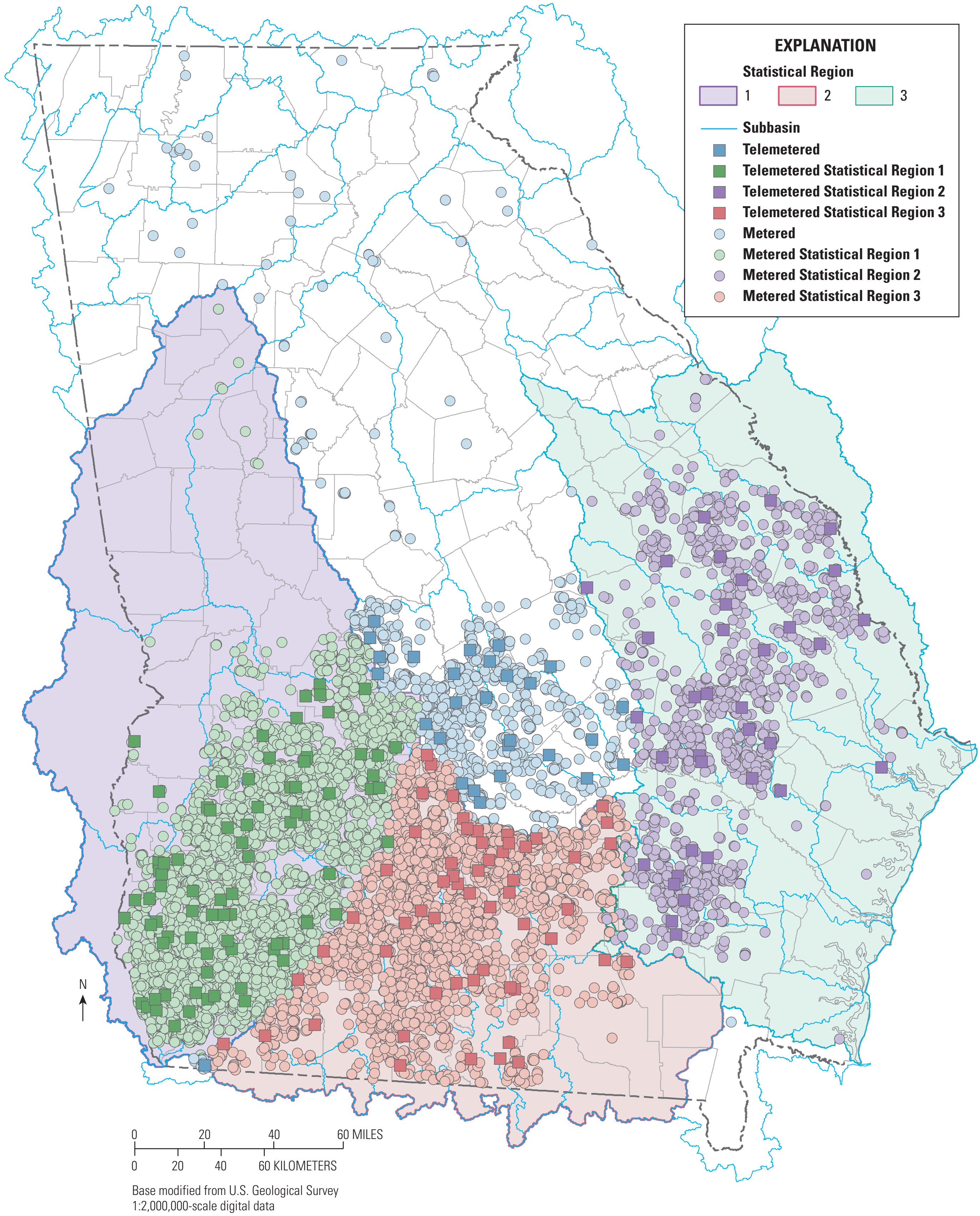


Figure 2. Status of Georgia Agricultural Water and Conservation Metering Program, year-end 2010 (Georgia Soil and Water Conservation Commission, written commun., 2011).

Evaluation of Methods Used to Collect and Analyze Water-Meter Irrigation Data in the Middle and Lower Chattahoochee and Flint River Basins, 2004–2010

Quality assurance, statistical, and geostatistical methods were applied to the annually reported and telemetry water-meter data to verify the accuracy of the metered water-use values and the ability of the meter networks to represent irrigation volumes and depths for the population of irrigation systems located in the middle and lower Chattahoochee and Flint River basins. Quality assurance analyses of water-meter roll back and roll forward (defined in the section "Water Meter Roll Back and Roll Forward") evaluated the integrity of the water meter itself to accurately record irrigation water use. Zero water-use data were analyzed for its effect on annual mean water-use calculations. A two-sample t-test evaluated the ability of the annually reported and telemetry data to represent samples of water use from the total population of irrigation systems including nonmetered systems. Geostatistical methods evaluated spatial trends and characteristics of the metered irrigation water use and the ability of the telemetry network to represent irrigation water use from the annually reported meter network. A telemetry network redesigned on the basis of geostatistical analyses demonstrated the usefulness of these methods for estimating water use from an efficient monitoring network having minimal estimation error.

Quality Assurance of Water-Meter Data

Quality assurance involves the validation of annually reported and telemetered agricultural water-meter data. This validation consisted of identifying water-meter "roll back" or "roll forward," non-water use (meter reading of zero), and zero acreage assigned to a meter. (These validation checks are described in subsequent sections of this report.) Meters were installed either on a distribution line that provided water to one or multiple fields or on a supply line leading from a well, stream, or well-to-pond water source. Most meters registered water-use volume in acre-inches, although some meters reported water use in gallons and others reported in cubic feet.

Water-Meter Roll Back and Roll Forward

Water-meter roll back and roll forward affected some meter readings of annually reported irrigation volumes. Roll back occurs when the impeller of the water meter operates in reverse, causing the meter to operate backwards and the readings to decrease, or roll back. Several conditions in the irrigation system that could cause roll back include the following:

- Suction in the supply pipe that contains the meter, which is caused either by draining or backflow of an irrigation system following pump shutoff. Water flows back to the well causing higher potential head in the distribution pipe than in the well.
- Negative air pressure in a well because of aquifer dewatering, which pulls water from the supply pipe back into the well.

Annually reported meter data compiled for the Chattahoochee–Flint River basin during 2007 indicated a potential for up to 30 acre inches (ac-in) of roll back, eliminating at least 100 water-meter sites from the analyses (table 2). Roll back was assumed to have occurred in water meters that registered close to, or within 30 ac-in of, the maximum meter reading of 9,999.9 ac-in. The bulk of the water meters eliminated because of roll back (99 meters) registered up to 5 ac-in of roll back. The number of water meters registering roll back diminished after about 10 ac-in, and filtering for roll back in excess of 30 ac-in proved non-productive.

Table 2. Mean annual water-use calculations with filtered and non-filtered water-meter data, middle and lower Chattahoochee and Flint River basins, Georgia, 2007.

["Filter" indicates exclusion of specific meter data from analysis: "5, 10, 30" identify acre-inch thresholds for water-use data suspected of containing meter roll back]

Filter, in acre-inches		Mean of metered water use, 2007, in acre-inches (number in parentheses is number of sites)	
		Annually reported	Telemetry
None (non-filtered)		2,323 (4,059)	1,247 (76)
Zero usage		2,429 (3,882)	1,529 (62)
Roll-back analysis			
Filter in acre-inches	**Meter reading greater than, in acre-inches**	**Mean of metered water use, 2007, in acre-inches (number in parentheses is number of sites): Annually reported**	**Telemetry**
5	9,995	1,760 (3,783)	1,529 (62)
10	9,990	1,752 (3,779)	1,529 (62)
30	9,970	1,745 (3,776)	1,529 (62)

Although somewhat easily detected in water meters that did not record water use during a growing season, the potential existed for roll back of up to 5 ac-in in all nonzero, annually reported meter readings. No roll back was detected in the telemetered data. Calculations that included annually reported water-meter data suspected of roll back resulted in a 38-percent overestimation of mean irrigation volume compared with similar calculations that eliminated (filtered out) water-meter readings suspected of roll back (2,429 ac-in compared with 1,760 ac-in; table 2).

Roll forward is the opposite of roll back and results in an erroneous meter reading that indicates a larger irrigation volume than actually was supplied by the metered irrigation system. Positive air pressure in the distribution line, possibly caused by rising groundwater levels after a pump is shut off, or seasonal (or regional) water-level rise could increase water-meter readings from actual water-use values. Clear detection of roll forward occurs when a water meter that has been initialized to zero indicates a small irrigation volume for an irrigation system that has not operated during the growing season. Roll forward of water-meter readings at non-use sites, though possible, did not affect water-use calculations significantly. Roll forward and roll back are difficult, if not impossible, to detect during the growing season at irrigated sites, as meter readings other than zero can be affected unknowingly by these phenomena.

Zero Water Use

Some water meters recorded zero water use (no water use) since the inception of the metering program during 2003. These zero water-use data when combined with non-zero water-use data decreased the value of the mean of metered irrigation volume calculated using annually reported and telemetered data (table 2). Retaining zero-usage values in calculations involving annually reported data resulted in a 4-percent reduction in mean-metered water use, compared with similar calculations with the zero-usage data removed or filtered out (2,429 ac-in compared with 2,323 ac-in). Calculations involving telemetered data that retained the zero-usage values resulted in an 18-percent lower estimate of mean water use, compared with a similar calculation with zero-usage data removed (1,529 ac-in compared with 1,247 ac-in). Sites with zero water use were eliminated from subsequent analyses.

T-Test of Water-Use Mean Values

Two-sample t-tests (Ideal Media, LLC, 2010), or simply t-tests, were performed to determine the effectiveness of the telemetered data, when summed for a growing season, to represent the annually reported data. The t-test addressed the question of whether the means of the telemetry and annually reported meter data represent the same population of water-use data. That is, are the means of the annually reported and telemetry data derived from the same population or different populations of water-meter data, and do the means vary by random chance? The true population mean is unknown, as it would include water use at unmetered sites as well as at metered (and telemetered) sites. The annually reported and telemetry data, therefore, represent two independent samples of water use from the population of metered and unmetered irrigation systems.

The null hypothesis addressed by the t-test states that the means of the annually reported and telemetry data are the same, implying that differences in values of the means occur by random chance, and that the means represent sample means of the entire population of water-use data in the Chattahoochee–Flint River basin. Accepting the null hypothesis implies that the mean of the telemetry network data effectively represents both the mean of the annually reported water-use data and the mean of the entire population of water-use data in the basin. The alternative hypothesis conversely states that the difference between the two means did not occur by random chance; rather, the different values represent sample means derived from two distinct populations. Accepting the alternative hypothesis implies that the mean of the telemetry network data does not effectively represent the mean of the annually reported water-use data, nor does it represent the mean of the entire population of water-use data in the Chattahoochee–Flint River basin.

Other objectives of the t-tests were as follows:

- Determine if the mean water-use volume derived from telemetered data (1,529 ac-in) is statistically different from the mean of the annually reported data (1,745 ac-in);
- Compare mean water-use volumes supplied by groundwater and surface water to determine whether groundwater and surface-water data can be analyzed as if derived from the same population, or whether separate analyses of two distinct populations are required; and,
- Determine if farmers use different application rates for groundwater and surface water—whether groundwater sites denote statistically distinguishable (higher or lower) application rates and volumes from those of surface-water sites.

T-test results indicated a 24-percent probability (p value equals 0.24, table 3) that the difference between the means of the annually reported data and the telemetry data occurred by random chance. That is, nearly a 1 in 4 chance exists of being wrong by rejecting the null hypothesis, which states that the means of annually reported data and telemetry data are the same, implying means are sample means of the same population. Conversely, there is a 1 in 4 chance that the means are not derived from the same population (accepting the alternative

Table 3. T-test results for mean metered water-use volumes from groundwater and surface-water sources obtained from telemetry and annually reported water meters, middle and lower Chattahoochee and Flint River basins, Georgia, 2007.

Data type	Annually reported mean	Telemetry reported mean	T-test results (probability, p)
	Acre-inches (number in parentheses is number of meters)		
Combined groundwater and surface water	1,745 (3,777)	1,529 (62)	0.24
Groundwater	1,817 (3,172)	1,675 (39)	.59
Surface water	1,365 (605)	1,282 (23)	.71

Data type	Ground-water mean	Surface-water mean	T-test results (probability, p)
	Acre-inches (number in parentheses is number of meters)		
Annually reported	1,817 (3,172)	1,365 (605)	0
Telemetry	1,675 (39)	1,282 (23)	0.24

hypothesis). The 0.24 probability exceeds the acceptable level of risk (5 percent, or p = 0.05) allowed for accepting the alternative hypothesis that the means represent two distinct populations. Therefore, the telemetry network represents a statistically valid and effective sample of the population containing the annually reported meter data, and both samples are derived from the same population of water-use data. No statistical difference exists between the means of the annually reported data and the telemetry data.

T-test results comparing means of metered water use by source indicated a 24-percent probability (p = 0.24) that groundwater and surface-water mean values derived from telemetry data vary by chance and zero probability (p = 0) that similar mean values derived from annually reported water-meter data vary by chance (table 3). That is, annual means of applied groundwater and surface-water irrigation volumes calculated by using annually reported meter data represent sample means from two different populations and require independent analyses. Conversely, annual means of applied groundwater and surface-water irrigation volumes calculated by using telemetry data represent sample means from the same population. For this comparison, well-to-pond irrigation systems were combined with groundwater systems to form one dataset, as the assumption was made that wells supplying ponds were pumped to meet irrigation demand.

On average during 2007, the annual metered irrigation volume supplied by groundwater per irrigation system in the middle and lower Chattahoochee and Flint River basins exceeded that supplied by surface water by about one-third (table 3). As stated previously (table 1), five times more metered groundwater systems (3,609) exist in this basin than surface-water systems (748); therefore, metered water-use data indicate that during 2007, groundwater supplied about 6.7 times the irrigation volume of that supplied by surface water (5 × 1.33).

No statistical difference was noted between the means of water-use calculated using annually read water-meter data and that derived from telemetry for each water source (groundwater and surface water). T-tests yielded high probabilities (59 percent for groundwater and 71 percent for surface water, table 3) that differences in the annual means of water use calculated by the different data networks (annually reported or telemetry) occurred by chance. That is, the telemetry networks for groundwater and surface water effectively represented the same population as corresponding annually reported networks of water meters. Therefore, telemetry and annually reported water-meter data are considered to represent (or sample) the same population of water-use data.

Although t-test results provide statistical validation that the telemetry networks for groundwater and surface water correspond with the same population of water-use data as that sampled from the annually reported water-meter data, mean water use calculated using telemetry-network data consistently underrepresented values calculated using annually reported water-meter data (tables 2, 3). Because the State stipulates that the primary purpose of the metering program is “to obtain clear and accurate information on the patterns and amounts of such [agricultural water] use” (Georgia General Assembly, 2003), geospatial analyses of water-meter data were conducted to identify irrigation patterns and distributions of meters in the annually reported and telemetered networks in an effort to identify the cause(s) for the telemetry network to underrepresent annually reported water use.

Geospatial Analyses of Agricultural Water-Meter Data

Geospatial analyses of telemetered and annually reported water-meter data in the middle and lower Chattahoochee and Flint River basins were performed to evaluate the distribution and randomness of meter locations and their values. The initial telemetry network, although a statistically valid sample of annually reported water-meter data, contained spatial deficiencies (described below) that prohibited the network from representing spatial patterns of agricultural water use as defined by annually reported water-meter data. Hot-spot and cluster and outlier analyses determined the distribution of telemetry sites with regard to annually reported water-meter sites and provided the basis for redesigning the current telemetry network in the middle and lower Chattahoochee and Flint River basins.

Hot-Spot Analysis

The hot-spot analysis, also known as Getis-Ord Gi* analysis (Environmental Systems Research Institute, Inc., 2009b), tested the occurrence of spatial clusters of high and low values of annually reported water use against the random occurrence of such data values. The Getis-Ord Gi* statistic defines a normal z score (or standard score), which is used to assess the distribution of the annually reported water-use values about the mean. Normally distributed z-score values contain a mean of 0 and a standard deviation of 1 (StatTrek.com, 2011). Significant z scores (less than [<] −1.64 or greater than [>] 1.65 standard deviations) of the Getis-Ord Gi* statistic occur in areas containing clusters of either high (positive z scores) or low (negative z scores) irrigation water-use volumes (fig. 3). Separate hot-spot analyses for groundwater and surface water indicated geographic bands of low-to-high agricultural water-use volume that trend northwest to southeast. The location of "hot spots" could relate to water availability in streams, variation in water-producing zones in aquifers, variations in soil type, rainfall variation, or crop distribution.

Cluster and Outlier Analysis

Cluster and outlier analysis, also known as Anselin Local Moran's I (Environmental Systems Research Institute, Inc., 2009a), was used to differentiate groups of annually reported water-use volume containing similar magnitude (clusters) from groups containing dissimilar or heterogeneous values (outliers). Clustering of similar or dissimilar values of annual irrigation volume provides insight into agricultural practices, possibly attributed to water availability from streams or aquifers, numbers of fields or irrigation systems monitored with a single meter, crop types, rainfall distribution, and (or) soil conditions. Clustering or outliers in annual irrigation volume can vary by growing season, and annually reported and telemetered water use can differ in the degree and sign of clustering from year to year.

A normalized z score was used to assess statistical significance of the cluster and outlier statistic, or Local Moran's I, in a similar manner as the z score described previously for the hot-spot analyses. Significant positive z scores (> 1.65 standard deviations) correspond with clusters of similar water use values; significant negative z scores (< −1.65 standard deviations) correspond with areas containing dissimilar values, or outliers (fig. 4). The distribution of significant z-score values derived from annually reported water-use data by source (groundwater and surface water; fig. 4) compared with the distribution of hot spots of annual water-use volume (fig. 3), indicated a concentrated distribution of telemetry sites in areas containing low annual irrigation water use. Although some telemetry sites monitor areas containing clusters of high irrigation water use (positive z scores, fig. 3), the telemetry sites generally underrepresented annually reported water-meter data associated with high water-use volume. This is evident in tables 2 and 3—mean water-use volume calculated with the telemetry network consistently underrepresented mean water-use volume calculated from annually reported water-meter data. Investigation of metered irrigation systems indicated that each telemetry site monitored water use for one irrigation system that served one field, in contrast with annually reported water-meter sites that monitor one or more irrigation systems serving one or more fields. Metered irrigation systems serving more than one field recorded higher water-use volume than telemetered systems, which monitored water use on a single field.

Cluster and outlier analysis in conjunction with hot-spot analysis exposed a shortcoming of the current telemetry network in representing the spatial distribution of the annually reported water-use data. Consistent underrepresentation of mean water-use volume by the current telemetry network indicates a need to better represent the spatial distribution of the annually reported water-use data with a revised telemetry network.

Normalization of Metered Water-Use Data

Normalization of metered water-use data mitigates the effects of design disparities between the annually reported and telemetry networks by factoring out (dividing) acreage from meter readings of water-use volume. Water use, therefore, is expressed as a per-acre irrigation depth (inches) instead of an irrigation volume (ac-in) following normalization. This procedure allowed for evaluation of the patterns and amounts of agricultural irrigation, independent of water source, acres supplied by each system, and volume pumped. Because of differences in the irrigation characteristics at the telemetry and annually reported sites, the groundwater and surface-water means of water-use volume derived from the telemetry network represented samples from a single population, and similar means derived from annually read meters indicated two distinct populations (table 3). Telemetry sites monitored irrigation at one field served by a single, metered water source in contrast to annually reported sites that monitored water use at one or more fields served by one or more metered water sources.

The number of irrigated acres supplied by each metered site affected the mean water-use volume calculated by using telemetered and annually reported water-meter data. Telemetry sites consistently underrepresented mean-irrigation volume (table 2), most likely because each site monitored water use from one irrigation system serving one field. Hot-spot and cluster and outlier analyses indicated a wide range of applied irrigation volume among annually reported metered sites.

The normalized, average irrigation depths for groundwater, surface-water, and well-to-pond metered systems during 2007–2010 indicated that groundwater-supplied fields, which include fields supplied by well-to-pond systems during 2010, received slightly more irrigation per acre than surface-water-supplied fields (table 4). The aggregate value of total metered irrigation volume was divided by total irrigated

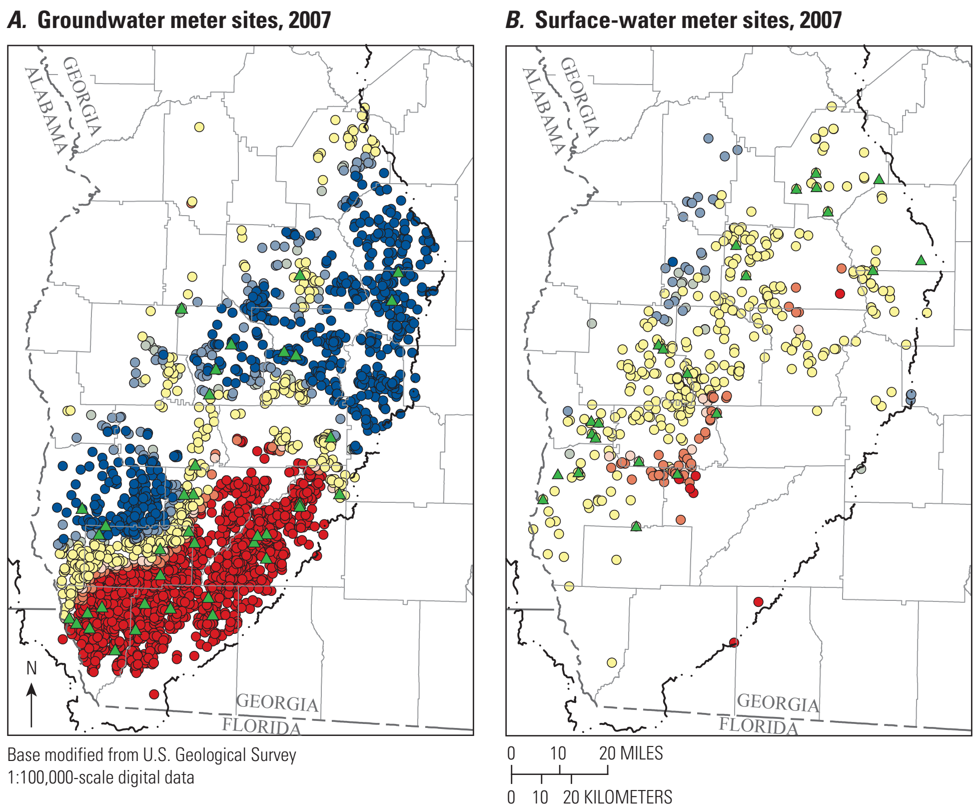


Figure 3. Standard deviation distribution of Getis Ord Gi* statistic resulting from hot-spot analysis of annually reported irrigation water-meter data for *(A)* groundwater and *(B)* surface water, and corresponding telemetry networks for the middle and lower Chattahoochee and Flint River basins, 2007.

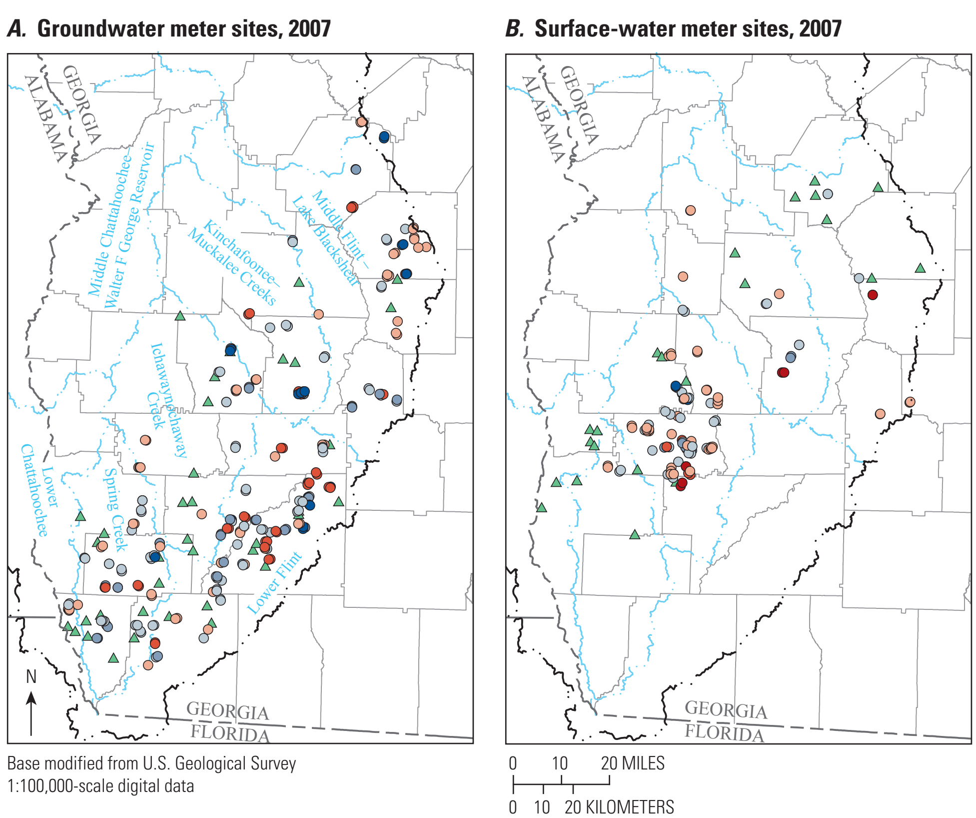


Figure 4. Significant z-score values (standard deviations) from cluster and outlier analysis of annually reported irrigation water-meter data from *(A)* groundwater and *(B)* surface water, and locations of corresponding telemetry sites for the middle and lower Chattahoochee and Flint River basins, 2007.

Table 4. Average irrigation depth at annually reported water-meter sites in the middle and lower Chattahoochee–Flint River basins in Georgia for the 2007–2010 growing seasons.

[N/A, not available]

Source type	Average irrigation depth, in inches, by growing season (number in parentheses is number of meters)			
	2007	2008	2009	2010
Groundwater	14.4 (2,299)	11.0 (2,134)	8.9 (2,069)	11.8 (2,687)[a]
Surface water	11.4 (651)	9.7 (534)	7.9 (510)	11.6 (474)
Well-to-pond	N/A	10.9 (579)	8.9 (580)	[a]

[a] Well-to-pond water-use data combined with groundwater data for average irrigation depth computation.

acres, respectively, for each year 2007–2010, to normalize the metered water-use data and obtain values of irrigation depth listed in table 4. Normalizing meter data by factoring out irrigated acres from the metered water-use volumes nearly eliminated the disparity between volumes of applied irrigation derived from groundwater and surface water (table 3). The normalized water-use data also confirmed the previous assumption that well-to-pond systems supply irrigation at rates similar to groundwater and, therefore, that the well-to-pond irrigation data can be combined with groundwater irrigation data for subsequent analyses. Surface-water availability, governed by the proximity of fields to streams and the amount of streamflow, could explain the remaining differences between irrigation depths supplied by groundwater and the depths supplied by surface water. Average irrigation depths during 2010 indicated an increase from the average irrigation depths during 2008 and 2009, most likely the result of relatively dry conditions during 2010 compared to conditions in 2008 and 2009. Groundwater and surface-water metered irrigation data were combined for further statistical and geospatial analyses.

Telemetry Network Redesign

Computations of mean-metered irrigation volume (table 3) indicated underrepresentation of irrigation volume with the current telemetry network, which has been in operation since 2007, thus demonstrating a need to redesign the telemetry network. Current telemetry network sites each monitored one irrigation system serving one field in contrast to most annually reported water-meter sites that monitored more than one irrigation system or served multiple fields. Normalization of metered water-use data eliminated spatial trends that were indicated with hot-spot and cluster and outlier analyses (figs. 3, 4). Geostatistical methods that evaluated the spatial-correlation structure of normalized, annually reported water-meter data (per-acre irrigation depths) were used to redesign the telemetry network as described in subsequent sections of this report. This revised telemetry network and additional geostatistical methods provided a basis for estimating irrigation water use for unmetered agricultural-irrigation systems.

Geostatistical Analysis of Metered Water-Use Data

Geostatistics (Matheron, 1971; Journel and Huijbregts, 1989) represent a “collection of techniques for the solution of estimation problems involving spatial variables” and employ a “systematic approach to making inferences about quantities that vary in space” (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a, b). Such quantities vary as a function of spatial coordinates. Water-use estimates in southern Georgia rely heavily on metered and telemetered data consisting of applied irrigation volume; however, as demonstrated previously, spatial variability of water-use data precludes error-free estimation of water use everywhere, not only in areas containing unmetered agricultural systems. Geostatistics provides the tools to (1) calculate the most accurate water-use estimates based on well-defined criteria, measurements, and other relevant information; (2) quantify the accuracy of these estimates; and (3) select the parameters to be measured and determine where and when to measure them, given the opportunity to collect more data (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a, b).

Geostatistical techniques—autocorrelation or variogram analysis, interpolation (kriging), and cross validation—were applied to the normalized, metered water-use data for the middle and lower Chattahoochee and Flint River basins during the 2007 growing season to

- Evaluate the spatial-correlation structure and regional distribution of annually reported water-meter data, yet preserve local variations of per-acre irrigation depth;
- Revise the 2007 telemetry network using the spatial-correlation model of water use developed from the normalized annually reported meter data, expressed in inches; and
- Quantify and reduce estimation error associated with representing annually reported water-meter sites with a telemetry network, thereby increasing the effectiveness of the telemetry network.

Semivariance: Overview

Water-use data (Z) are spatially correlated based on the separation distance (h) between pairs of data (z_i and z_{i+h}, which are elements of Z) and their difference ($z_i - z_{i+h}$), where "i" indexes each meter. Semivariance, $\gamma(h)$, accounts for the difference in meter values between data pairs ($z_i - z_{i+h}$) located within a distance-class interval h for all $N(h)$ data pairs in the distance class as

$$\gamma(h) = \frac{\sum_{i=1}^{N}(z_i - z_{i+h})^2}{2N(h)}$$

(American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a).

Each distance class h contains semivariance data for all data pairs in the class. A plot of data pairs and corresponding variance values for a specific distance class constitutes a variance cloud and indicates the dispersion of the differences in annual water-use values and corresponding separation distance among data pairs in the distance class. For example, the variance cloud for normalized annually reported water-meter data having a distance class of 450 meters (m; fig. 5) indicates a closely grouped distribution of $\gamma(h)$ values less than about 1.7. Outliers plot away from the clustered $\gamma(h)$ values in the variance cloud and can negatively affect the correlation structure of water-use data by skewing the average $\gamma(h)$ value corresponding with the distance class. The plot of average semivariance by average separation distance for each distance class constitutes the experimental semivariogram, which gives a measure of the spatial correlation structure of the water-use data, as discussed in the following section.

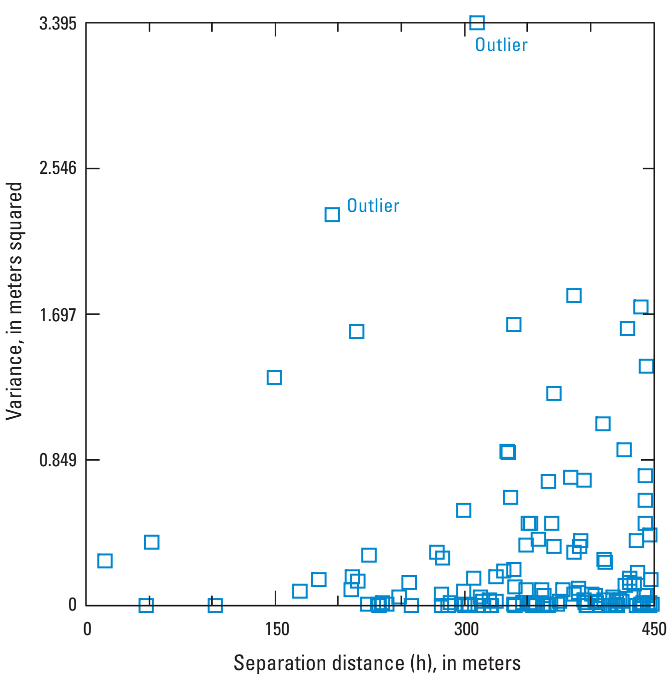


Figure 5. Variance cloud within separation distance of 450 meters derived from normalized annually reported water-meter data in the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

Semivariogram Development and Geostatistical Estimation: Structural Analysis

A prerequisite to geostatistical estimation of normalized annually reported water-meter data involves assessment of the statistical structure (structural analysis) of the data. The first two statistical moments of the data, namely the mean and covariance (or the semivariogram), constitute the statistics of interest during structural analysis (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a). The semivariogram consists of a plot of the average semivariance for each distance class (derived from variance clouds, fig. 5) by average separation distance in the class. The resulting plot (symbols, fig. 6) represents the spatial-correlation structure of annually reported water-use data, termed the *experimental semivariogram* or *variogram*. Judicious selection of distance classes yielded a strong correlation structure of water-meter data with distance. A commonly used graphical method for structural analysis consists of fitting a function to the experimental semivariogram to produce a variogram model. An exponential function (exponential variogram model) fits the experimental semivariogram derived from the normalized, annually reported water-use data (fig. 6; American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a).

The exponential variogram model indicates strong spatial correlation among water-meter data where the model is curved; that is, for water-meter sites separated by less than about 2,000 m, or about 1.3 miles (mi; fig. 6). Conversely, no spatial correlation exists between water-meter data separated by more than 2,000 m, which is where the model becomes nearly horizontal. This distance (2,000 m) defines the *range* of correlation for the model. Correlation structure cannot be resolved in water-use data separated by more than about 2,000 m. Consequently, semivariance and the experimental semivariogram is nearly constant beyond this distance. The variogram model could be used in an interpolation process to estimate annual water use at unmetered sites located within about 2,000 m, or about 1.3 mi, of annually reported water meters.

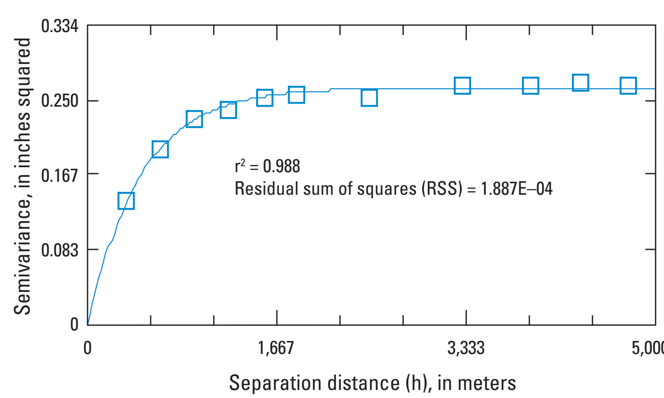
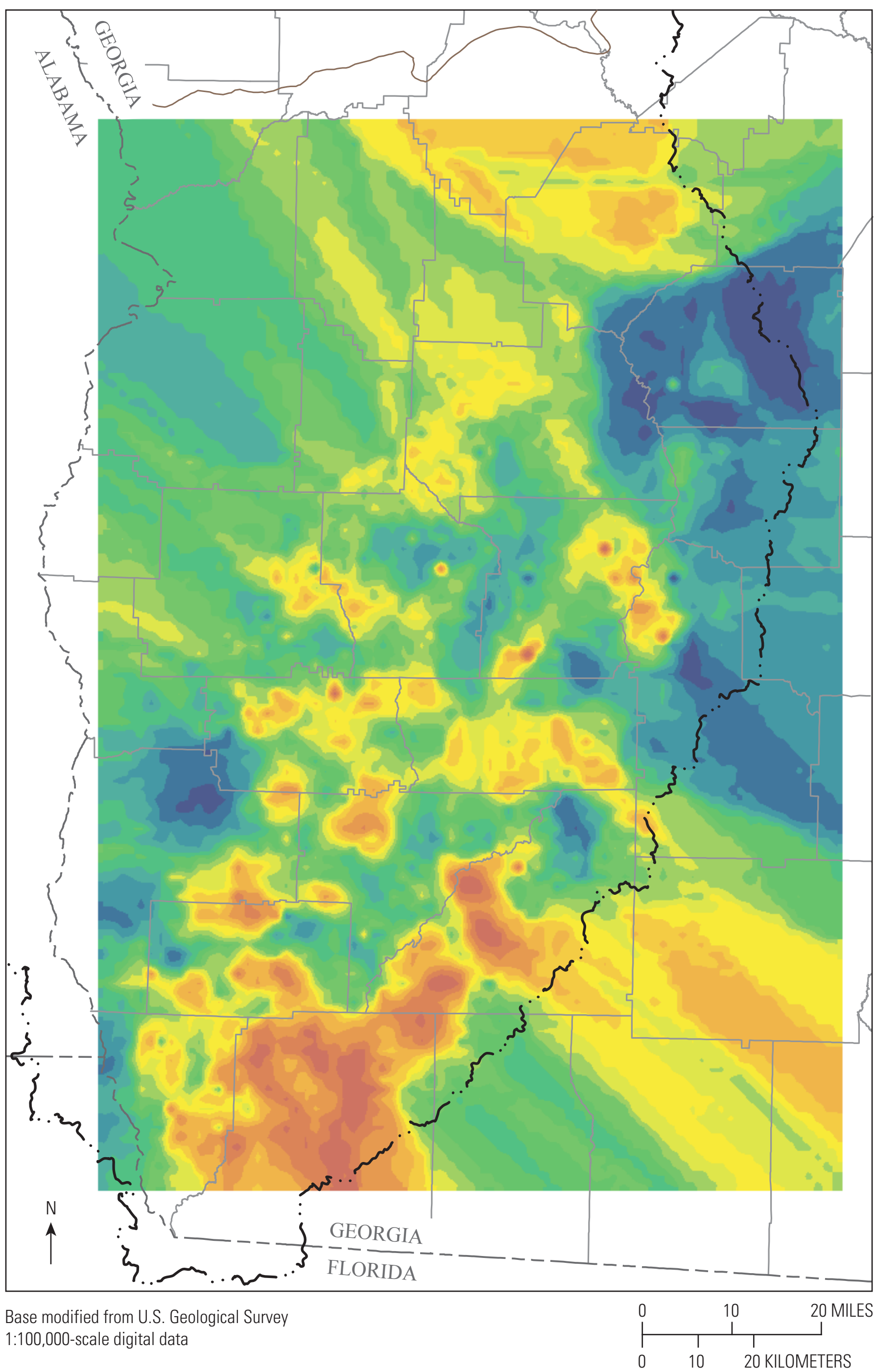


Figure 6. Variogram model derived from normalized, annually reported water-meter data in the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

Linear Interpolation of Water-Use Data: Kriging

Linear interpolation uses the underlying spatial-correlation structure of the data (variogram model, fig. 6) to estimate expected values of a spatial variable (such as the normalized annual water-meter data) as a weighted sum of the measured data in areas where no measurements have been made. Kriging provides unbiased estimates for the expected values of the spatial variable as a weighted sum of the measured data having minimum estimation variance (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a).

Kriged estimates of normalized annual irrigation water-meter data indicate a diverse distribution of per-acre water-application rates (or irrigation depth, in inches) in the middle and lower Chattahoochee and Flint River basins (fig. 7). Kriged estimates of per-acre irrigation rates were computed at intersections of a regular grid of 77 rows by 111 columns, or at 8,547 locations in the basin. Each grid block represents a 1,740-m square.



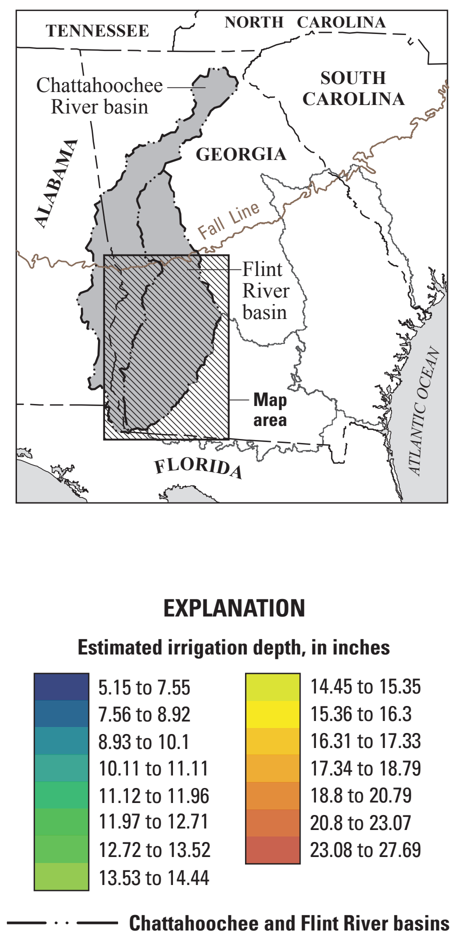


Figure 7. Kriged estimates of normalized annually reported water-meter data in the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

Evaluating Effectiveness of Variogram Model and Kriging: Cross Validation and Estimation Variance

Cross validation provides a means to evaluate the semivariogram model and parameter selection used in kriging. Cross validation consists of systematically (independently) estimating water use at each annually reported meter location using kriging. This is accomplished by removing measurements associated with annually reported water meters one at a time and estimating the corresponding values with successive applications of the semivariogram model through the kriging process. A plot containing the most accurate (best) 200 estimates of annually reported water use and corresponding meter data for the middle and lower Chattahoochee and Flint River basins demonstrates the effectiveness of the variogram model and kriging to represent the actual data (fig. 8). Water-meter locations associated with these estimates provide the basis for redesigning the telemetry network, discussed in a subsequent section of this report.

The "regression coefficient" identified at the bottom of the graph (fig. 8) represents a measure of the goodness of fit for the least-squares model describing the linear regression equation. A perfect 1:1 fit (without error) would have a regression coefficient (slope) of 1.00, and the best-fit line (solid line) would coincide with the dotted 45-degree line on the graph.

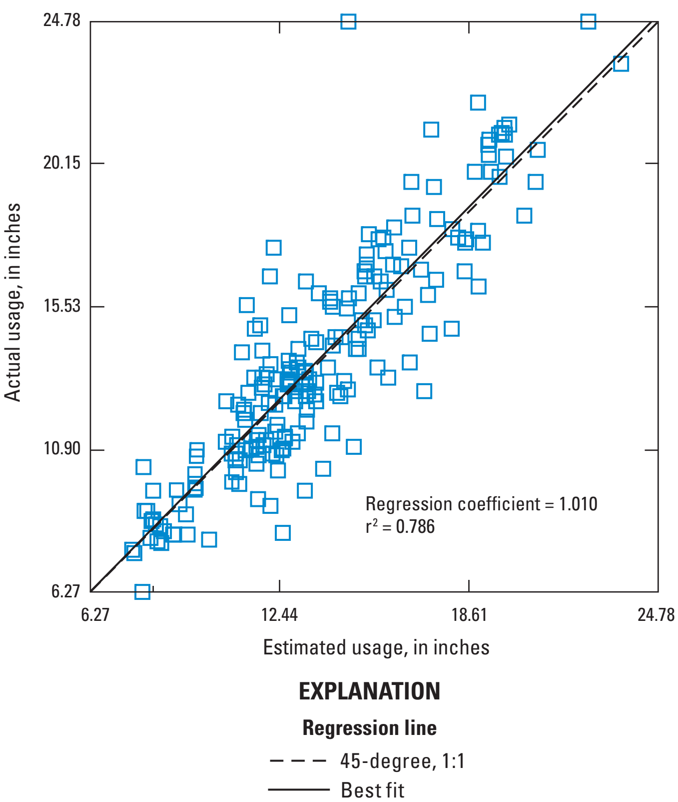


Figure 8. Cross validation of kriged estimates of normalized annual water-meter data in the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

The standard error (SE = 0.037) refers to the standard error of the regression coefficient (Robertson, 2008) and gives a measure of the amount of sampling error in the regression coefficient; that is, the standard deviation of the regression coefficient (McGraw-Hill, 2003; Siegel and Shim, 2005).

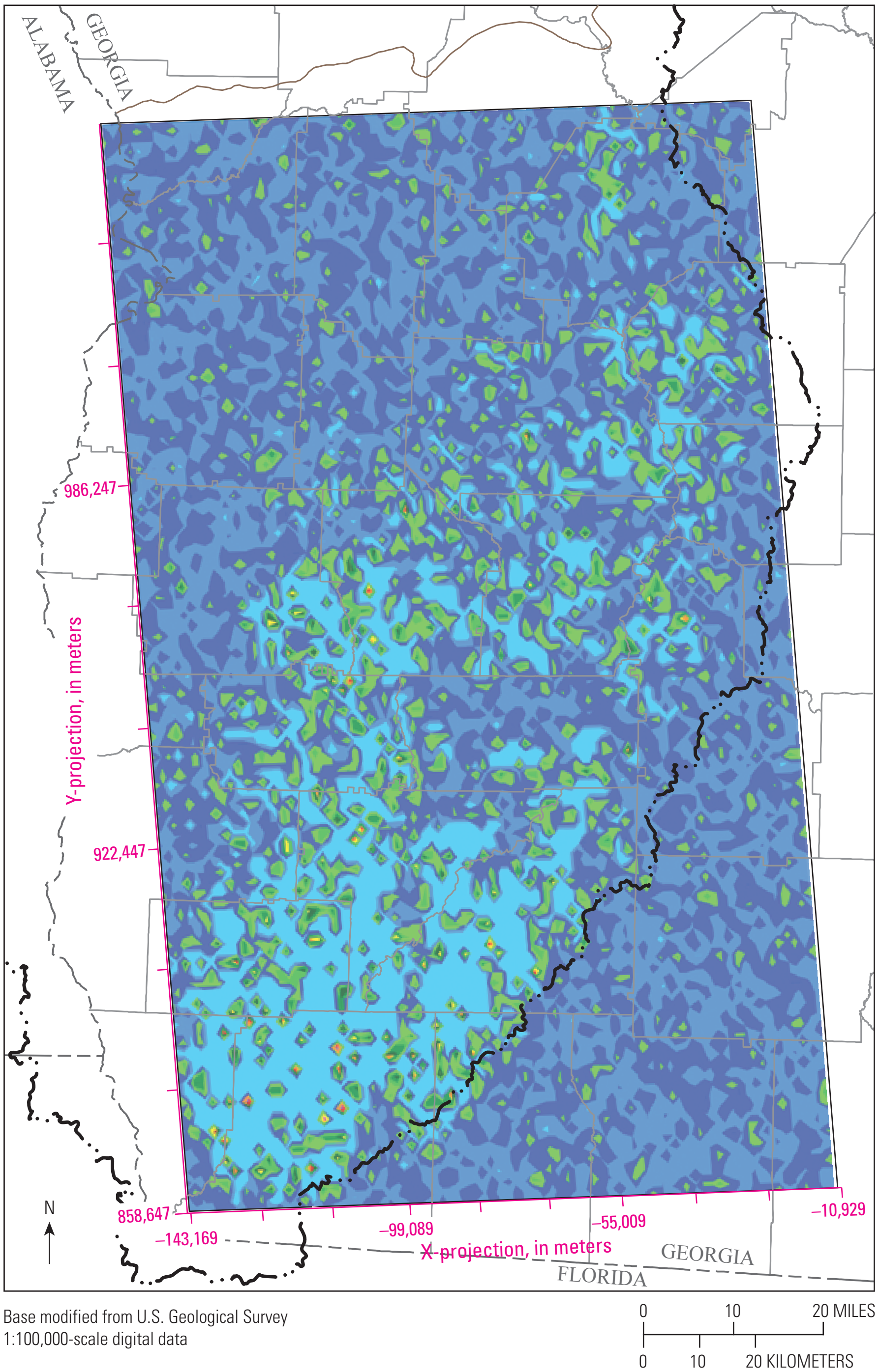
The r^2 value (0.786, fig. 8) gives the proportion of the total variation in normalized annual irrigation water-meter data explained by the regression. It is the square of the sample correlation coefficient, or the coefficient of determination, commonly expressed as R^2. The coefficient of determination indicates a strong correlation (0.887) between the estimates and actual measurements of irrigation water use. The coefficient of determination gives the proportion of variability around the mean, as explained by the regression (in this case 78.6 percent; Montgomery and others, 2006). The y-intercept of the best-fit line also is provided. The SE prediction term is defined as standard deviation (SD) × $(1 - R^2)^{0.5}$, where the SD corresponds to the actual data (graphed on the y-axis; Robertson, 2008).

A variance map (fig. 9) illustrates the spatial distribution of estimation error inherent to the kriged values of annual water use calculated at locations on the estimation grid of 8,547 points. These variances give a measure of the accuracy of the kriged estimates, which have been shown to be more accurate than estimates associated with the arithmetic mean. The kriged estimates differ substantially from the arithmetic mean, however, and are more consistent with the observed spatial variability than the variability of estimates derived from using arithmetic means (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990a).

Developing a Revised Telemetery Network: Two Approaches using Kriging

The plot of estimated and measured annually reported water-meter data derived from cross validation (fig. 8) provides a means of selecting sites for revising the telemetry network. Plotted values close to the regression line represent the most accurate estimates of normalized annually reported water use; the distribution of the plotted values in the basin can serve as potential sites for a revised telemetry network. The range of spatial correlation associated with the variogram model (fig. 6) that yielded these estimates, however, extended about 2,000 m (about 1.3 mi).

A second approach to revising the telemetry network involves semivariogram analysis using the 200 most accurate water-use estimates derived from cross validation (fig. 8). The resulting variogram model (fig. 10) indicated a spatial correlation distance (or range) of about 59,000 m (about 37 mi), or about 30 times the range associated with the variogram model originally developed using the entire dataset of annually reported water-meter data (fig. 6). Values of the regression parameter ($R^2 = 0.997$) and residual sum of squares (RSS = 1.248E−05) indicate an excellent fit of the variogram model to the annually reported water-meter data.



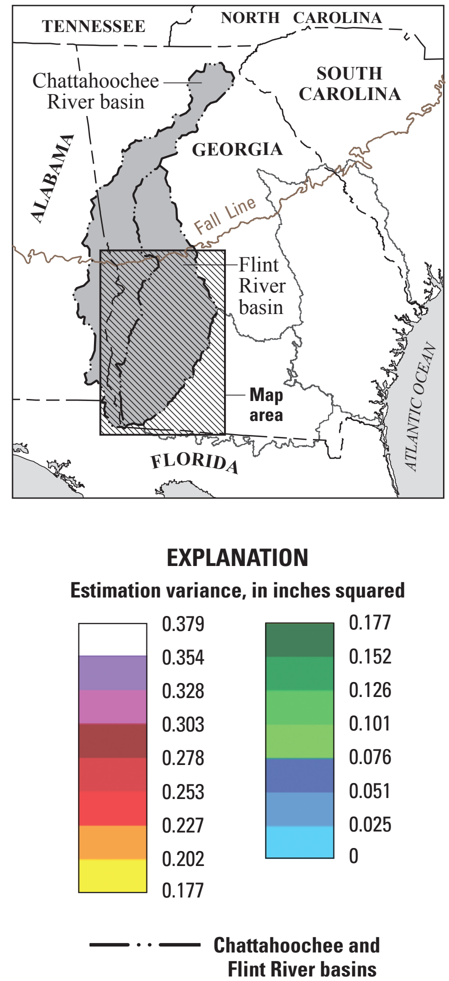


Figure 9. Variance map of estimation error for annually reported water use in the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

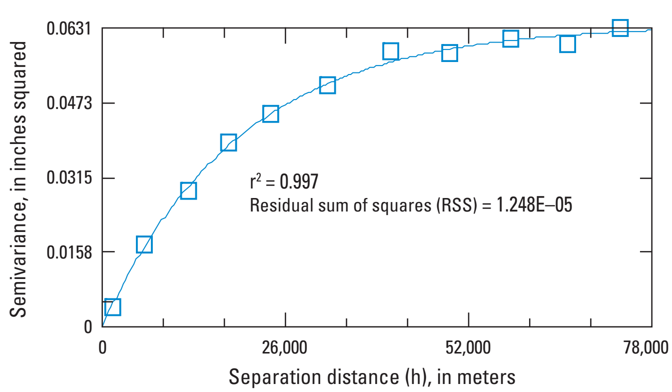


Figure 10. Variogram model resulting from cross validation of annually reported water-meter data from the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

Estimation-Variance Reduction and the Revised Telemetry Network

The process that repeated the semivariogram development, kriging, and cross validation of normalized annually reported water-meter data using the "best" 200 values from cross validation, as described in the previous section, extended the range of correlation of estimated water-use values to about 37 mi, compared with the 1.3-mi range derived from application of these geostatistical methods to the entire set of annual water-meter data. Using the extended-range semivariogram model as a starting point to the development of the new telemetry network, a second semivariogram model was developed based on the best 100 estimates of annual water use.

Estimation-variance maps derived from semivariogram models using the best 200 values from cross-validation results—that is, the values plotting closest to the regression line in figure 8—and from a second step of semivariogram development, kriging, and cross validation using the best 100 values provided graphical evidence of the reduction in estimation variance attained by the respective semivariogram models (fig. 11). Dark-red to dark-orange colors indicate relatively low estimation variance compared to medium-orange to yellow colors, which indicate relatively high estimation variance. Coalescence of the dark-red to dark-orange colors on the variance map for the best 100 points (fig. 11*B*) compared with the variance map for the best 200 points (fig. 11*A*) indicates a reduction of estimation variance within the distances separating estimation points. These plots demonstrate the utility of geostatistical methods in providing accurate, spatially correlated estimates of water-use in unmetered areas and in developing a telemetry network from the annually reported water-meter network that contains the spatial correlation structure of the annually reported water-meter data.

The revised telemetry network for the middle and lower Chattahoochee and Flint River basins contains a subset of 60 sites from the best 100 points model (fig. 12). Design criteria considered during selection of the 60 sites included (1) number of sites requested by the Commission (60) for the revised network; (2) spatial distribution that avoids clustering and underrepresentation in the basin; and (3) spatial correlation structure of the telemetry network derived from the structure of the annually reported water-meter network.

Comparison of the current and revised telemetry networks in the middle and lower Chattahoochee and Flint River basins (figs. 12, 13) indicates a complete redesign of the current network, which has been operating since 2007; no current telemetry network sites were retained in the revised telemetry network. Sites in the revised telemetry network are dispersed as uniformly throughout the basin as the annually reported water-meter network would allow. The revised telemetry network sites do not exhibit clustering, as occurred in the current telemetry network distribution. Design of the current telemetry network followed an algorithm developed by Fanning and others (2001) for estimating irrigation water use in southern Georgia and used a stratified random sampling of permitted irrigation sites, termed *Benchmark Farms Study sites*.

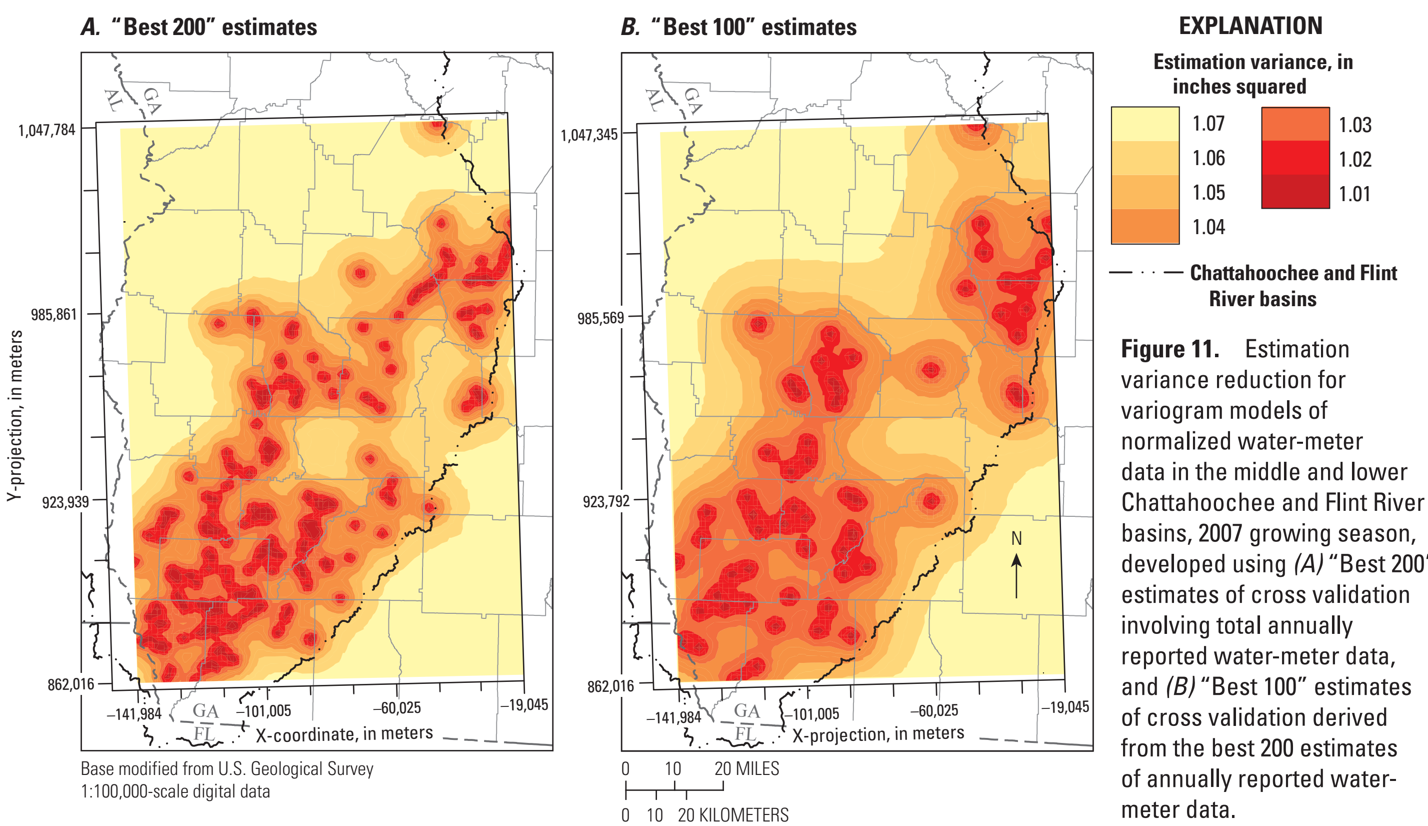


Figure 11. Estimation variance reduction for variogram models of normalized water-meter data in the middle and lower Chattahoochee and Flint River basins, 2007 growing season, developed using *(A)* "Best 200" estimates of cross validation involving total annually reported water-meter data, and *(B)* "Best 100" estimates of cross validation derived from the best 200 estimates of annually reported water-meter data.

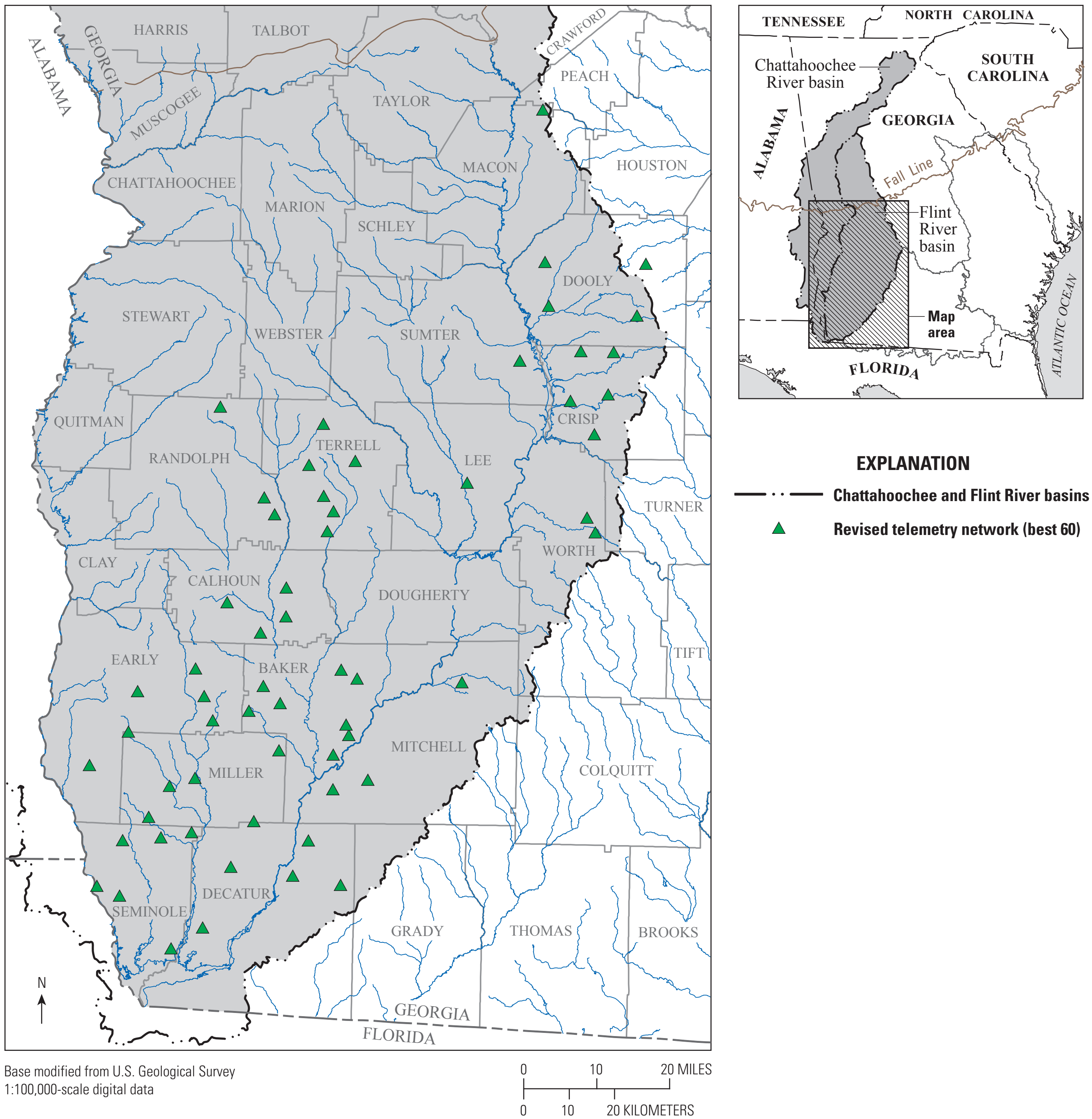


Figure 12. Revised telemetry network for daily water-use data collection and satellite transmission in the middle and lower Chattahoochee and Flint River basins.

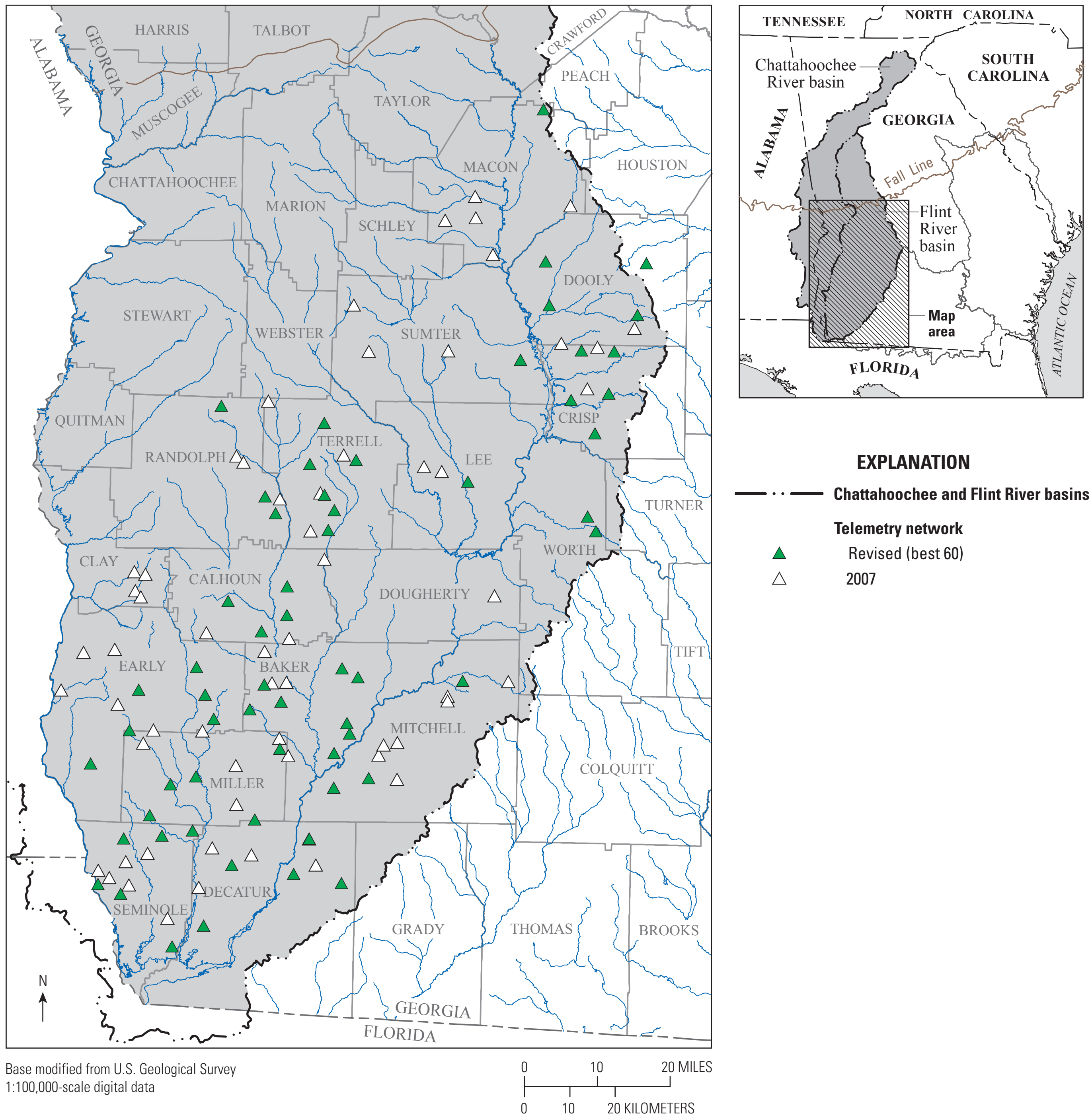
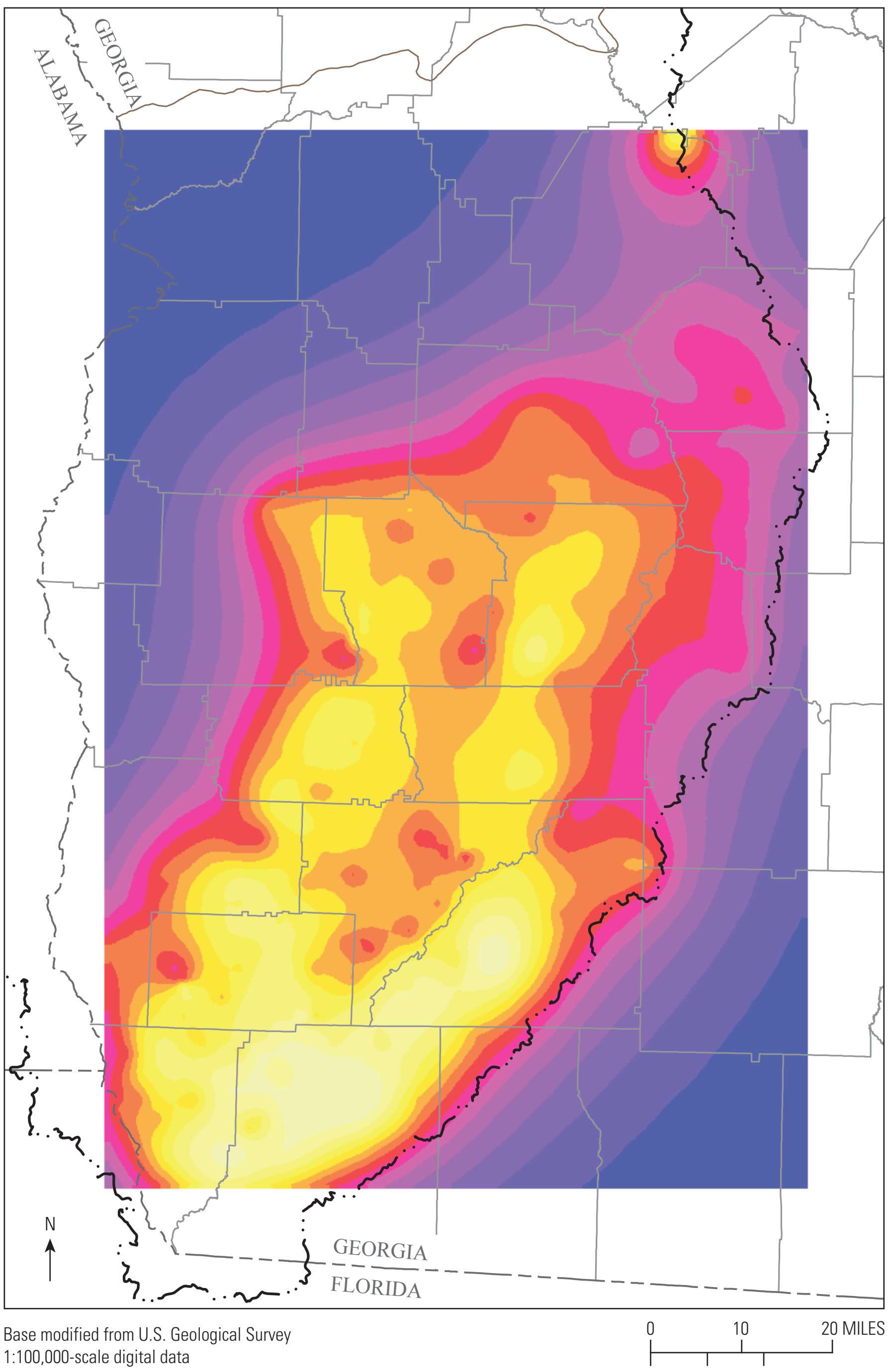


Figure 13. Revised and 2007 telemetry networks for daily water-use data collection and satellite transmission in the middle and lower Chattahoochee and Flint River basins.

Interpolation of Unmetered Water Use by Conditional Simulation

Despite the State's legislative mandate in HB571, which required metering of all irrigation systems, many unmetered systems still exist for which water-use estimates are needed. Conditional simulation involving the variogram model provided estimates of water use for these unmetered irrigation systems. Conditional simulation honors the values of the annually reported water-meter data at each site and uses the spatial correlation structure expressed in the variogram model to estimate values of water use in unmetered areas. Unlike kriging, which smooths out local variations in water use, conditional simulation preserves the spatial complexity and heterogeneity of the water-use data within short distances (fig. 14).

A method to obtain estimates of irrigation depth per acre for unmetered irrigated acres would involve associating the map showing estimates of normalized annually reported water-meter data (irrigation depth in inches, fig. 14) with maps showing unmetered irrigated acres. Knowing the acreage and estimated per-acre irrigation depth of each unmetered irrigated field provides a means of calculating annual irrigated water-use volume.



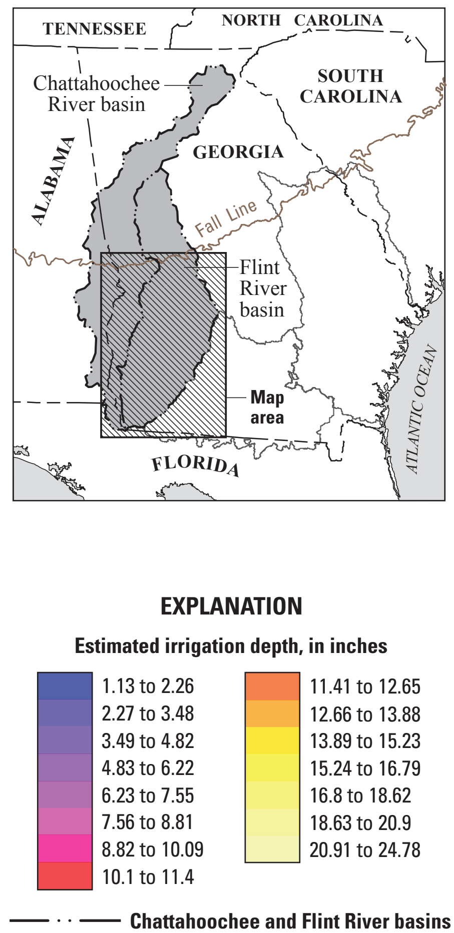


Figure 14. Conditional simulation of normalized annually reported water-meter data in the middle and lower Chattahoochee and Flint River basins for the 2007 growing season.

Importance of Geospatial and Geostatistical Analysis to Agricultural and Water Management in Georgia and the Nation

Geospatial and geostatistical analysis provides an enhanced understanding of the spatial relations among water-meter locations and estimated water use. A revised telemetry network enables more accurate determinations of annual and seasonal water withdrawals than are available with the current telemetry network. The following attributes and applications of the revised telemetry network demonstrate its value for agricultural and water management in Georgia:

- Provides the Commission and agricultural community with data on growing season irrigation rates in near real time. Such information can be used for agricultural management of water resources and for implementing alternative water-management strategies in near real time in the basin.

- Provides a water-use stress component to aid resource managers with decisions to implement the Flint River Drought Protection Act (FRDPA; Georgia General Assembly, 2000). Provisions of the FRDPA state that the director of the Georgia “Environmental Protection Division of the Department of Natural Resources shall each year predict whether drought conditions are likely in the Flint River basin; to provide for an irrigation reduction auction; to provide that certain persons holding water withdrawal permits may offer to cease irrigating a number of acres in exchange for a certain sum of money; to provide for the acceptance of bids; to provide for an order requiring certain permit holders to cease or reduce irrigation….” In support of provisions to the FRDPA, the revised telemetry network could assist in identifying streamflow sensitivity to agricultural pumping. Maps showing such sensitivity could provide an objective, hydrologic basis for accepting auction bids that minimize acreage removed and groundwater-level decline (drawdown) while maximizing streamflow and cost savings in auction awards.

- Uses correlation structure of the telemetry network to estimate growing season pumping rates at annually reported water-meter sites from which the revised telemetry network was derived. These calculations could validate irrigation projections for future years *during the growing seasons that the irrigation data are collected*.

- Assists soil and crop scientists with defining water-use patterns related to soil type, moisture retention, and cropping.

- Provides an unprecedented collection of real-time, spatially correlated water-use data that can be leveraged for future research endeavors related to climate change and developing causal relations between irrigation, climate, soil type, water availability, and soil moisture.

- Provides a tool for assessing agricultural and resource potential for various crop choices that enhance agricultural production and improve the State’s energy, water, and financial resources.

The Federal interest in evaluating the Nation’s water resources and the potential for water-resources development by agriculture and other entities could be served at local and regional scales nationwide through cooperative programs of comprehensive water-use monitoring and geospatial analysis such as described herein. The near-total coverage of irrigation systems monitored with water meters in southern Georgia and the methods and analyses presented herein have nationwide application to agricultural communities in need of assessing water use and identifying cause-and-effect relations between agricultural water-use stress and hydrologic-system response. Although possible to apply the methods described to other agricultural settings across the Nation, the success of such application would be limited only by the ability of those agricultural settings to provide a representative water-use monitoring network as provided by the Commission through the Georgia Agricultural Water Conservation and Metering Program. A lack of comprehensive water-use-data collection and managing infrastructure limits the usefulness and benefits of geospatial analysis in areas where agricultural water-use data are relatively sparse.

Ongoing and Planned Data Analysis

Ongoing and planned analysis of metered and telemetered agricultural-irrigation data include application of geostatistical techniques to relate water use to crop patterns, groundwater and surface-water availability, soil moisture, and rainfall variation in the middle and lower Chattahoochee and Flint River basins. Other applications of geostatistical techniques could enable estimation of growing season pumping rates at the annually reported water-meter sites.

An interactive, on-line accessible map of the middle and lower Chattahoochee and Flint River basins is planned to show a compilation of water-meter data by counties and sub-basins and to provide estimates of growing season pumping rates at unmetered and metered agricultural locations derived from geostatistical modeling. This map is intended to provide scientifically based information on agricultural water use that can be used as a tool for assessing how climate, crop patterns, and soil moisture affect growing season pumping rates; such a tool is essential for informing farmers and water managers about water use, crop selection, and the effects of climate and pumpage change on groundwater and surface-water resources.

The effectiveness of telemetry networks in the coastal region and central-south Georgia (figs. 1*C* and 1*D*, respectively) could be evaluated by applying a regimen of geospatial analysis to annually reported and telemetered water-use data in a manner similar to that applied to water-use data in the middle and lower Chattahoochee and Flint River basins. Conditional simulation using a geostatistical process similar to that described herein could identify gaps and redundancies in the telemetry network that could be rectified through elimination of some sites and deployment of others elsewhere in the basins to reduce estimation variance and improve estimates of growing season pumping rates.

Summary and Conclusions

The following conclusions address previously stated objectives of the U.S. Geological Survey investigation of irrigation data collected by the Georgia Soil and Water Conservation Commission in accordance with and support of the Agricultural Water Conservation and Metering Program. Study objectives are listed below in italics and precede each corresponding conclusion.

Develop a quality-assurance program to ensure completeness and internal consistency of water-meter data. A quality-assurance program consisting of geospatial and non-geospatial statistical methods proved invaluable in verifying the accuracy of metered water-use values and the integrity of the water meter itself to accurately record irrigation water use. Without these statistical evaluations, inconsistencies in reporting irrigation water use would have gone unnoticed and (or) confounded summary statistics of metered water use. Roll back detected at zero-irrigation water-use sites demonstrated the potential to cause up to a 40-percent overestimation of metered, annually reported, irrigation water use. Zero-value meter readings (without roll back) affected annual water-use calculations by only a few percent, and roll forward had a negligible effect on water-use calculations. Cluster and outlier analyses, and hotspot analysis, enabled identification of sites containing potential metering error and of locations where the telemetry network misrepresented the annually reported meter data.

Calculate descriptive statistics of aggregated water-use data. Calculation of mean water-use volumes for the annually reported and telemetry meter networks indicated consistent underrepresentation of the mean by the telemetry network data, despite t-tests that indicated the annually reported and telemetry network data represent valid samples from the same population of irrigation systems in the study area. Normalization of metered water-use data effectively removed the telemetry network bias that resulted in the telemetry data reporting less irrigation water use than reported with the annually reported meter data. Factoring out irrigated acres from the metered-volume data allowed water use to be expressed as an irrigation depth and allowed combining meter data from both networks (annually reported and telemetry) and water sources (groundwater and surface water) for analysis.

Evaluate the potential to relate daily water-use telemetry (telemetered data) to annually reported water-use data through a descriptive statistical model. Descriptive statistics of metered water use indicate a high potential to relate annually reported water-use data to telemetered data, which had been summed to represent annual irrigation volumes. T-tests validated each metering network as representative samples of the entire population of irrigation systems. Geostatistical analyses strengthened the relation between annually reported and telemetered irrigation water-use data by yielding a spatially correlated model of annually reported metering data from which a revised telemetry network was derived. The revised telemetry network, in turn, could be used to define growing season irrigation depths at locations of annually reported water meters.

Identify spatial and temporal distributions of agricultural-irrigation pumpage. Geospatial methods of cluster and outlier analysis, and hot-spot analysis, identified a northwest-to-southeast trend of low-to-high metered irrigation volumes that could signify relations of irrigation volume to water availability, climatic variability, soil-type variation, and cropping patterns. Geostatistical analyses identified a strong spatial-correlation structure within the annually reported water-meter data that could be used to estimate irrigation water use at unmetered agricultural sites. Cross validation and conditional simulation with the geostatistical model demonstrated the robustness of the method to estimate annual irrigation water use with minimal estimation error. A revised telemetry network based on the geostatistical model of the annually reported water-meter data provided the basis for estimating irrigation depths during the growing season at metered and unmetered irrigation sites.

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