Prepared in cooperation with the National Water Census Program

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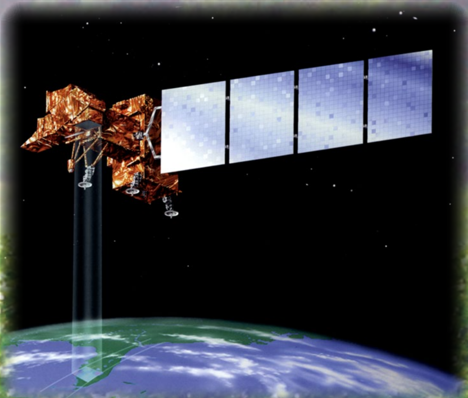

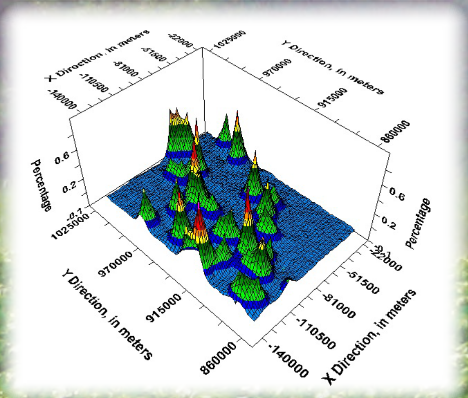

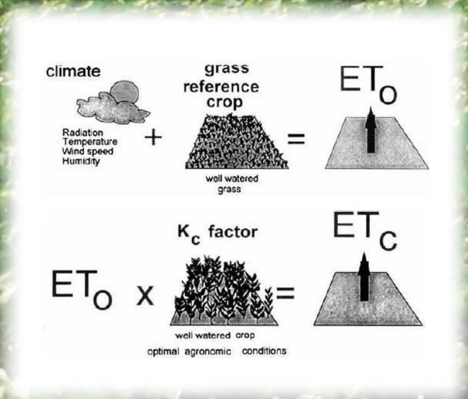

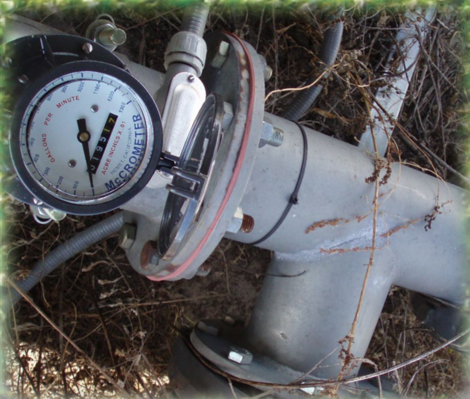

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A	*B*	*C*
D	*E*	*F*

Cover. Data inputs and techniques used in estimating irrigation withdrawal for the Apalachicola-Chattahoochee-Flint River Basin focus area study of the National Water Census: *A*, Landsat 5 satellite; *B*, conditional simulation of irrigation depth; *C*, weather station (photograph from University of Georgia); *D*, evapotranspiration computation (diagram from Allen and others, 1998); *E*, Landsat 5 false-color composite image (from U.S. Geological Survey); and *F*, water meter installed on irrigation system (photograph by Lynn J. Torak, U.S. Geological Survey). Background: Irrigation system in Terrell County, Ga. (photograph by Alan M. Cressler, U.S. Geological Survey).

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

U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2015

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Contents

Figures

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Conversion Factors

[Inch/Pound to International System of Units[

Multiply	By	To obtain
	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)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	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)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons (Bgal)	3,785,000	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

Datum

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).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

ACF-FAS	Apalachicola-Chattahoochee-Flint River Basin Focus Area Study of the National Water Census Program
CDL	Cropland Data Layer
GaDNR	Georgia Department of Natural Resources
GSWCC	Georgia Soil and Water Conservation Commission
NLCD	National Landcover Dataset
USGS	U.S. Geological Survey

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Abstract

Methods to estimate irrigation withdrawal using nationally available datasets and techniques that are transferable to other agricultural regions were evaluated by the U.S. Geological Survey as part of the Apalachicola-Chattahoochee-Flint (ACF) River Basin focus area study of the National Water Census (ACF–FAS). These methods investigated the spatial, temporal, and quantitative distributions of water withdrawal for irrigation in the southwestern Georgia region of the ACF–FAS, filling a vital need to inform science-based decisions regarding resource management and conservation. The crop–demand method assumed that only enough water is pumped onto a crop to satisfy the deficit between evapotranspiration and precipitation. A second method applied a geostatistical regimen of variography and conditional simulation to monthly metered irrigation withdrawal to estimate irrigation withdrawal where data do not exist. A third method analyzed Landsat satellite imagery using an automated approach to generate monthly estimates of irrigated lands. These methods were evaluated independently and compared collectively with measured water withdrawal information available in the Georgia part of the ACF–FAS, principally in the Chattahoochee-Flint River Basin. An assessment of each method's contribution to the National Water Census program was also made to identify transfer value of the methods to the national program and other water census studies. None of the three methods evaluated represent a turnkey process to estimate irrigation withdrawal on any spatial (local or regional) or temporal (monthly or annual) extent. Each method requires additional information on agricultural practices during the growing season to complete the withdrawal estimation process. Spatial and temporal limitations inherent in identifying irrigated acres during the growing season, and in designing spatially and temporally representative monitor (meter) networks, can belie the ability of the methods to produce accurate irrigation-withdrawal estimates that can be used to produce dependable and consistent assessments of water availability and use for the National Water Census. Emerging satellite-data products and techniques for data analysis can generate high spatial-resolution estimates of irrigated-acres distributions with near-term temporal frequencies compatible with the needs of the ACF–FAS and the National Water Census.

Introduction

The U.S. Geological Survey (USGS) established the National Water Census, a "national water availability and use assessment program," authorized by section 9508 of the Secure Water Act of 2009 (42 U.S. C. 10368) to address the following needs:

- "to fund locally cost-shared water management improvements that save significant amounts of water;
- to plan for and reduce the impacts of drought; and,
- to gather and analyze water supply and use information in a consistent manner, which would create a uniform, dependable national assessment of water availability and use" (United States Senate Report of the 113th Congress web site accessed at http://thomas.loc.gov/cgi-bin/cpquery/T?&report=sr230&dbname=113& on February 13, 2015).

Research to develop methodologies that inform water management decisions and address National Water Census needs has been centered on assessing irrigation withdrawal because of its high impact on water resources and susceptibility to climatic extremes. Knowing how much water is withdrawn, consumed, lost, transferred, and disposed of is necessary for effective resource management (Fanning, 2007).

Three methods to estimate when, where, and how much water was applied for irrigation during the 2008–12 growing seasons were developed by the USGS as part of the National Water Census focus area study of the Apalachicola-Chattahoochee-Flint River Basin (ACF–FAS) (fig. 1).The

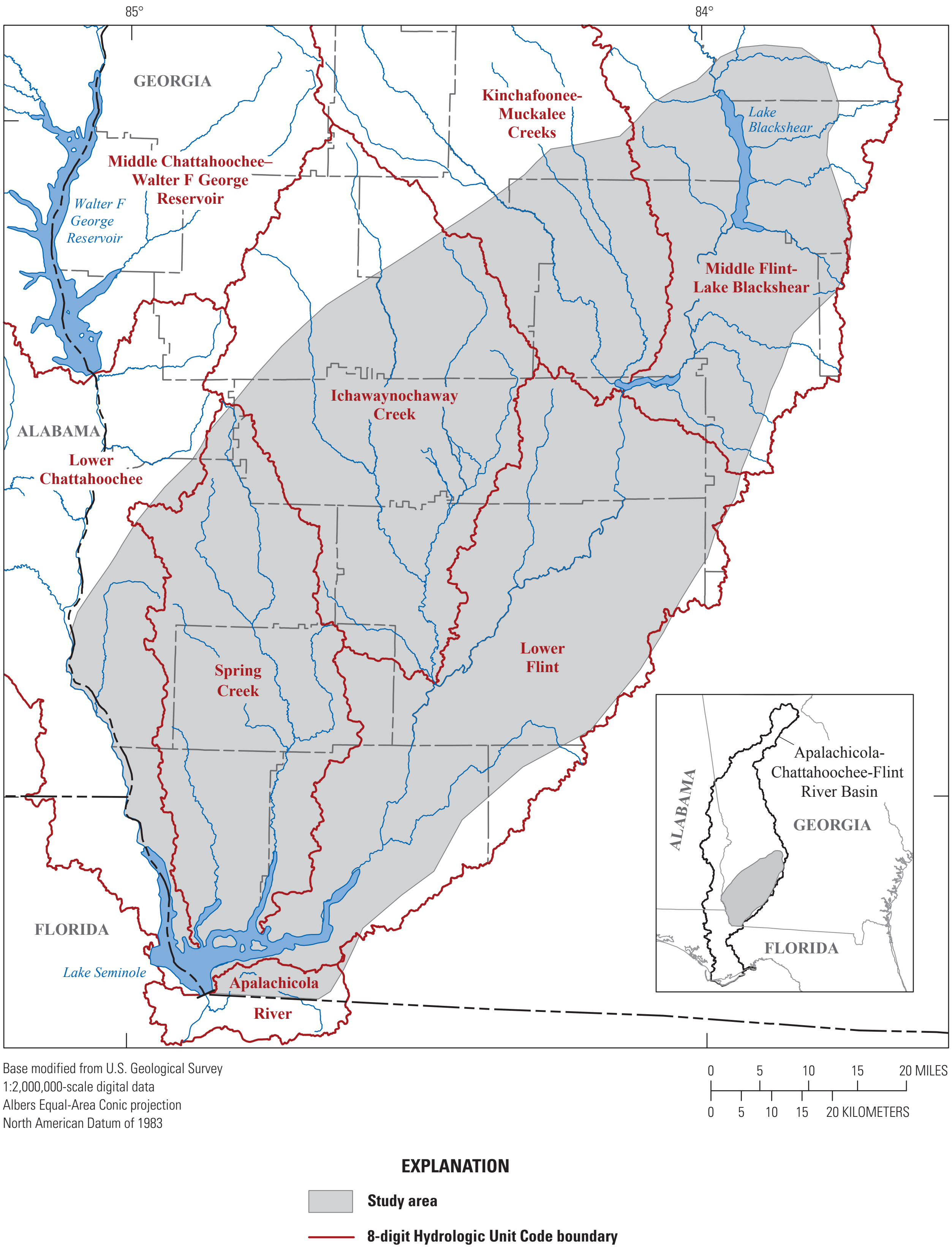

Figure 1. Study area for Apalachicola-Chattahoochee-Flint River Basin.

Apalachicola-Chattahoochee-Flint (ACF) Basin in Alabama, Florida, and Georgia (fig. 1) was selected as one of the initial focus areas for the National Water Census in 2010 because of its extensive development of and competition for water resources by municipal and industrial needs, power generation, and agriculture activities within its boundaries. The temporal extent selected for the irrigation-withdrawal estimates matched the monthly simulation horizons used in groundwater availability modeling activities also developed for the ACF–FAS. One method, termed "gross irrigation" demand, estimated values for the water needed to satisfy crop growth after accounting for evapotranspiration, precipitation, and irrigation inefficiency. A second method applied geostatistical techniques to the region of the ACF–FAS that contained spatially correlated irrigation meter data, and estimated the volume of irrigation water applied per acre, termed "irrigation depth," at metered and nonmetered locations of irrigation withdrawal. A third method analyzed Landsat satellite remote-sensed imagery to generate monthly estimates of irrigated acres.

Apalachicola-Chattahoochee-Flint Focus Area

The ACF River Basin encompasses about 19,256 square miles (mi^2), mostly in western Georgia and partly in southeastern Alabama and northwestern Florida (Jones and Torak, 2006). The principal rivers and tributaries in the lower ACF River Basin in Georgia drain karstic and fluvial plains, which are hydraulically connected to the Upper Floridan aquifer, one of the most productive aquifers in the United States. Irrigation withdrawal is the major use of groundwater in this heavily agricultural region. Nearly 500,000 acres are irrigated with groundwater from the Upper Floridan aquifer (Torak and Painter, 2006). The spatial extent of the ACF–FAS for this discussion consists of the region in southwestern Georgia defined by parts of the lower Chattahoochee and Flint River Basin, approximately 4,080 mi^2 (shaded area in fig. 1), which corresponds to the spatial extent of the groundwater availability modeling activities also used for the ACF–FAS.

Georgia Agricultural Water Conservation and Metering Program

The need to document irrigation withdrawal information prompted the Georgia General Assembly to enact House Bill 579 on June 4, 2003, granting jurisdiction to the Georgia Soil and Water Conservation Commission (GSWCC) 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). This bill created the State Agricultural Water Conservation and Metering Program (hereafter referred to as the metering program) allowing the GSWCC to install more than 11,000 water meters on wells, surface-water intakes, and irrigation systems statewide. Installation of the metering network began in 2004 and was completed in the ACF–FAS in time to monitor irrigation withdrawal during the 2007 growing season.

About 4,400 meters initially were installed in the middle and lower parts of the Chattahoochee and Flint River Basins in southwestern Georgia, which coincides geographically with the concentration of agricultural irrigation. These meters were read annually to measure irrigation withdrawal for the region; a subset of about 60 meters reported daily irrigation withdrawal by satellite (daily telemetry). The telemetry network was replaced for the 2012 growing season with 90–100 manual measurements from a monthly meter network that enhanced spatial representation and measurement of irrigation withdrawal (fig. 2).

Purpose and Scope

This report evaluates three methods used in the ACF–FAS to estimate irrigation withdrawal and describes for each method,

- Limitations that would affect the ability to provide a consistent and dependable estimate of irrigation withdrawal; and
- Advancements or emerging technology or both that became available since the onset of this study that would enhance the accuracy of the irrigation-withdrawal estimates.

Application of methods to estimate irrigation withdrawals are discussed in the context of the amount, type, and availability of data required by each method, and with regard to spatial and temporal limitations that would affect irrigation-withdrawal estimates. These estimates were compared collectively among the methods and with metered irrigation withdrawal to assess the relative accuracy of each method.

Study Objectives and Tasks

A primary research objective for the ACF–FAS was to develop new tools that would support water management decisions and "create a uniform, dependable national assessment of water availability and use" (United States Senate Report of the 113th Congress Web site accessed at http://thomas.loc.gov/cgi-bin/cpquery/T?&report=sr230&dbname=113& on February 13, 2015). These tools were evaluated herein according to the spatial, temporal, and quantitative accuracy of irrigation-withdrawal estimates as they were applied during the growing seasons (March–October) of the years 2008–12. Irrigation-meter data were used to ground-truth, compare, and assess the accuracy and consistency of computed irrigation-withdrawal estimates derived from these new tools.

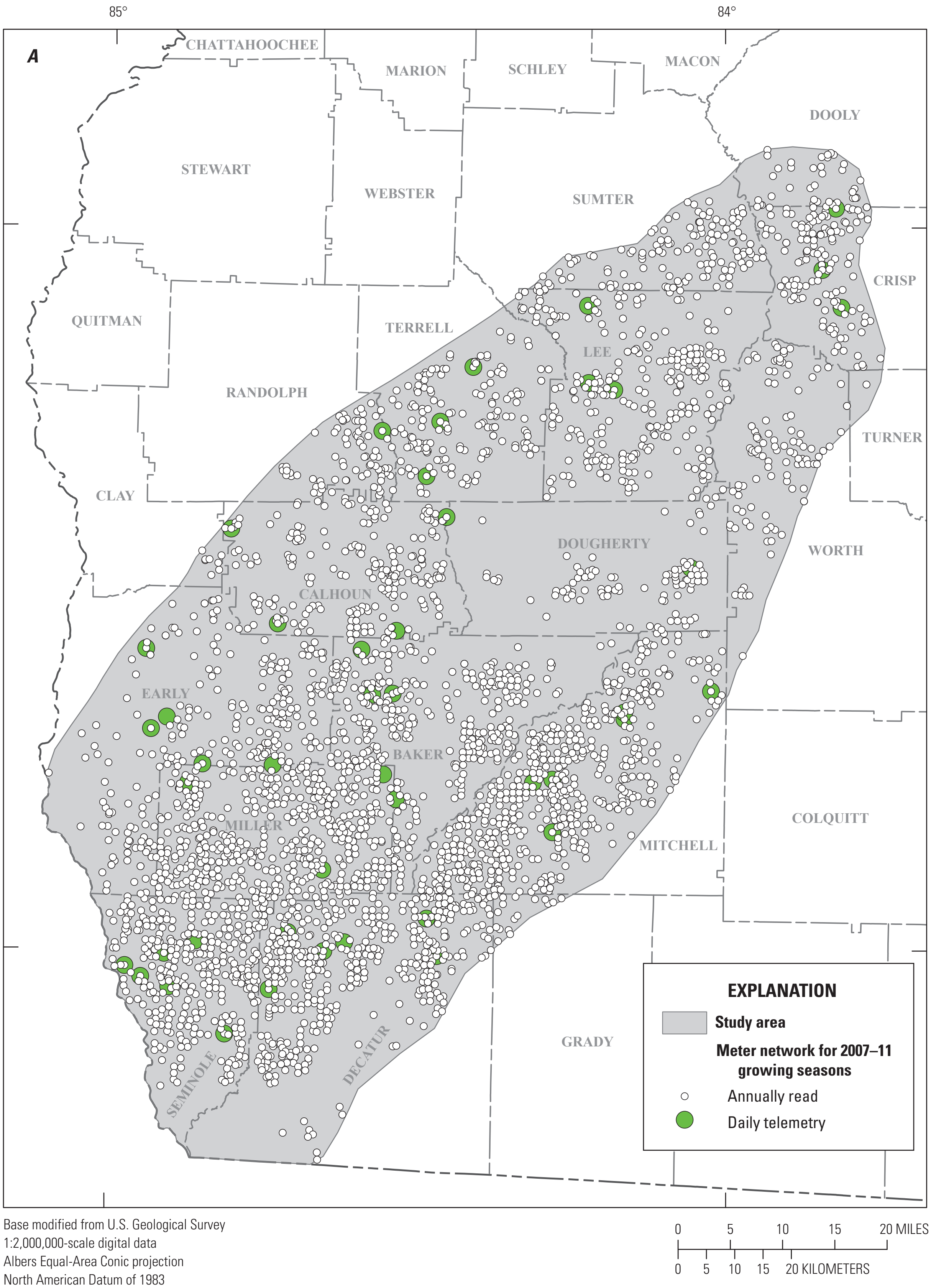

Figure 2. The metering program in the Chattahoochee-Flint River Basins of Georgia, *A*, annually read and daily telemetry network, 2007–11 growing seasons; *B*, annually read and monthly meter network, 2012 growing season.

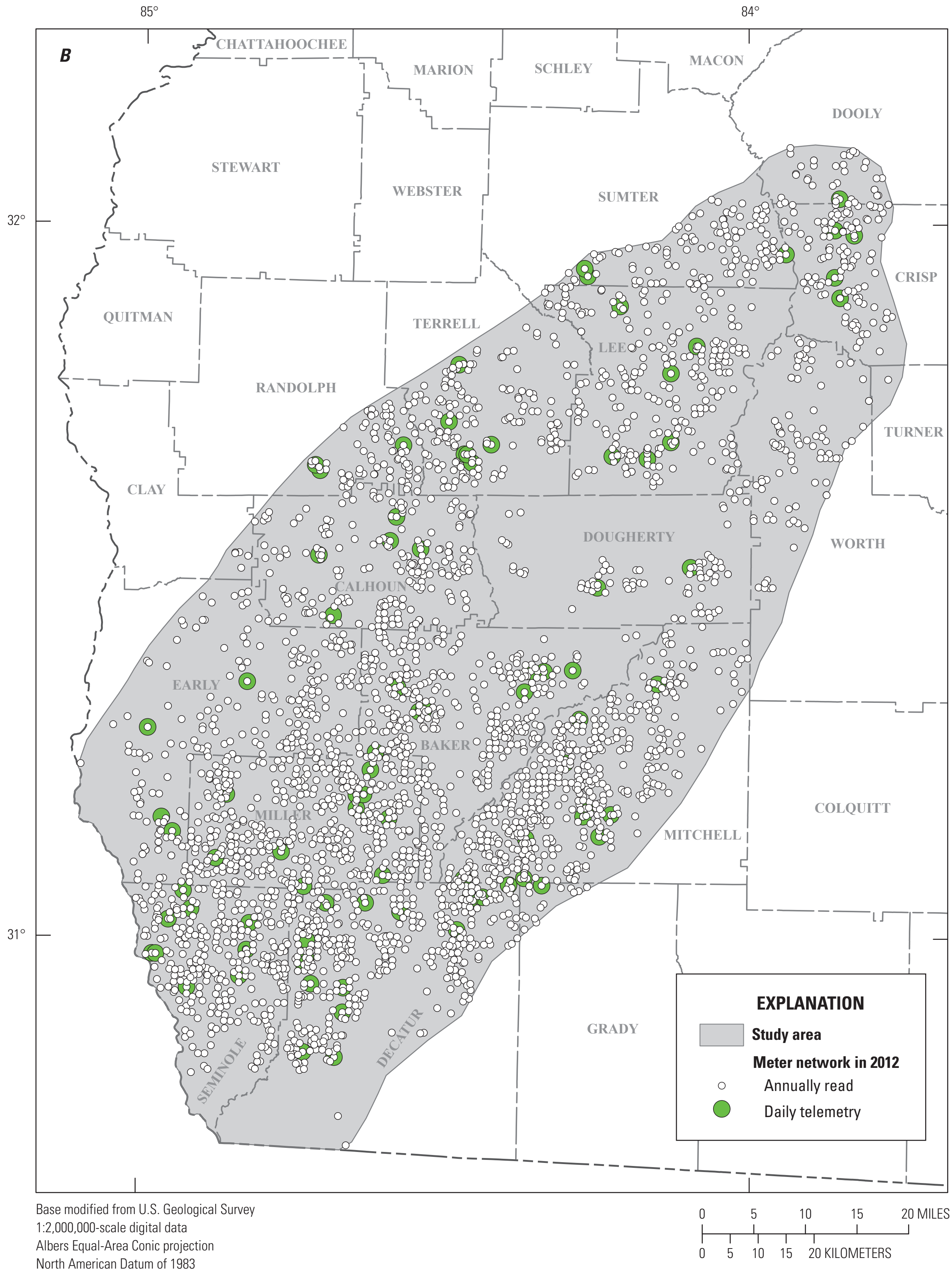

Figure 2. The metering program in the Chattahoochee-Flint River Basins of Georgia, *A*, annually read and daily telemetry network, 2007–11 growing seasons; *B*, annually read and monthly meter network, 2012 growing season.—Continued

The following tasks describe the USGS effort to evaluate irrigation-withdrawal estimates in support of the National Water Census, as contained in this report,

- Describe the crop-demand method for estimating water withdrawal;
- Evaluate geostatistical techniques applied to metered irrigation withdrawal to estimate irrigation withdrawal at non-metered locations;
- Analyze the process of using space-based Landsat images to identify where and when water is being used;
- Discuss attributes, contributions, and limitations of each estimation method;
- Compare irrigation-withdrawal estimates collectively among the three methods and with monthly meter data within the spatial extent of the study region; and
- Discuss emerging technology that would enhance the accuracy of estimation tools.

Evaluation of Methods to Estimate Irrigation Withdrawal in the ACF–FAS

Three methods were evaluated that address a critical need for the ACF–FAS to assess water availability and use by attempting to identify where, when, and how much water the agricultural community withdraws from the basin's water resources. The crop-demand method intended to answer these metrics by applying standard methods with reference parameter values and nationally available datasets to calculate irrigation requirements. Geostatistical techniques developed spatial models that interpolate between measured irrigation withdrawal values to estimate irrigation withdrawal in areas where irrigation withdrawal data do not exist. The image analysis method generated a dataset of irrigated land as a subset of agricultural land identified by Landsat imagery.

The geostatistical and image analysis methods combine to estimate irrigation withdrawal for the near term depending on the availability of irrigation withdrawal (monthly meter) data and Landsat imagery (every 16 days, unobstructed by cloud cover). The crop-demand method provides "a consistent and transparent basis for a globally valid standard for crop water requirement calculations" with minimal inputs for geographic specificity (Allen and others, 1998).

Crop-Demand Method

The crop-demand method assumes that only enough water is applied to a crop to satisfy the gross irrigation demand (GID); that is, the deficit between evapotranspiration and precipitation, plus a small amount of water lost to irrigation inefficiency because of the physical structure of the water delivery systems. This assumption relies on the economic disincentive for farmers to pump more water than required to turn a profitable harvest, thereby conserving energy (fuel) and reducing maintenance costs. It also assumes that each farmer knows the crop water deficit at any given time and irrigates accordingly. This method uses readily available, spatially distributed, reference and standardized data for weather conditions, and soil and crop characteristics.

Governing Equations

Gross irrigation demand is calculated using the following equation (Jason Bellino, U.S. Geological Survey, written commun., January 2014):

$$GID = \left[\frac{ET_{crop} - P_e}{I_{eff}}\right] \times A_{crop}\ , \qquad (1)$$

where

GID	is gross irrigation demand $[L^3/T]$;
ET_{crop}	is evapotranspiration for a given crop $[L/T]$;
P_e	is effective precipitation $[L/T]$;
I_{eff}	is the irrigation efficiency, 0.9 for all systems [dimensionless]; and
A_{crop}	is the area over which the crop is being grown $[L^2]$;

and where

L	is length; and
T	is time.

Crop evapotranspiration (ET_{crop}) incorporates into its calculation a modified Food and Agriculture Organization (FAO) Penman-Monteith standard method (FAO56; Allen and others, 1998) for reference evapotranspiration (ET_o) that provides values that are more consistent with actual crop water-use data worldwide than previous methods and creates "a consistent and transparent basis for a globally valid standard for crop water requirement calculations" (Allen and others, 1998). The crop evapotranspiration [ET_{crop}] differs distinctly from the reference evapotranspiration (ET_o) [calculated for a standard, uniform, grass surface, or reference surface] as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). In the crop coefficient approach, crop evapotranspiration is calculated by multiplying ET_o by K_c (p. 89, Allen and others, 1998),

$$ET_{crop} = ET_o \times K_c \,, \tag{2}$$

where

ET_{crop} is crop evapotranspiration $[L/T]$;
K_c is crop coefficient [dimensionless];
ET_o is reference evapotranspiration $[L/T]$, expressed as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \,,$$

where parameters and data sources for ET_o are defined in table 1.

Effective precipitation (P_e) in equation 1 is that part of rainfall available to meet consumptive needs of crops, average monthly values of which are calculated as (Martin and Gilley, 1993),

$$P_e = SF(0.710917 P_t^{0.82416})(10^{0.02426 ET_{crop}}) \,, \tag{3}$$

where

SF is the soil water storage factor [dimensionless];
P_t is average monthly precipitation as rainfall $[L]$; and,
ET_{crop} is average monthly crop evapotranspiration $[L]$.

The soil water storage factor, SF, is the total amount of water that is stored in the soil within a plant's root zone, and is described by the polynomial function,

$$SF = 0.531747 + 0.295164D - 0.057697D^2 + 0.003804D^3, \tag{4}$$

where

D is the usable soil water storage $[L]$.

The crop-demand method requires parameterization of meteorological, crop, and soil type conditions for spatial or temporal horizons related to all irrigated fields to produce accurate estimates of irrigation withdrawal, expressed as the gross irrigation demand (*GID*). Data requirements and limitations for this parameterization are discussed in the following section.

Parameterization and Data Limitations

Data that parameterize crop, soil, and meteorological characteristics were obtained from a variety of sources (table 1), which contain distinct levels of precision that (1) affect their application to irrigated fields in the ACF–FAS; and, (2) impose limitations that negatively impact estimation accuracy of the crop-demand method. Locations and types of crops being grown, thereby indicating potential areas of irrigation withdrawal (A_{crop}), were identified with raster datasets from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) hereafter CDL (U.S. Department of Agriculture, National CDL's 2008–12). The CDL datasets merge areas of distinct crop type, and all acres assigned to land associated with these specific crop types might not have been irrigated. Crop patterns generated from individual center-pivot-irrigation systems, such as irrigated by monthly meter sites, could not be discerned from the general agricultural-land classification associated with the CDL.

Non-site-specific values for agronomic and meteorological parameters introduce limitations when used in the crop-demand method to compute *GID*. Crop coefficients (K_c) obtained from publicly available sources (Allen and others, 1998; Smajstrla, 1990), and planting dates, maturation times, and rooting depths supplied from data on file at the then-USGS Florida Water Science Center Office, Tallahassee, Fla. (Jason Bellino, U.S. Geological Survey, written commun., 2014) were used to generally evaluate agricultural conditions for GID calculations. Likewise, soil water storage, *D,* was obtained from the National Resources Conservation Service (NRCS) Soil Survey Geographic database (SSURGO) (http://sdmdataaccess.nrcs.usda.gov/, accessed February 24, 2015) and used in calculating effective precipitation, P_e.

Adjustments to the above standard reference meteorological and agronomic characteristics during the growing season were made with regard to fixed crop planting and harvesting dates only; further adjustments were made using monthly precipitation and temperature data from the PRISM Climate Group (http://www.prism.oregonstate.edu/, Daly and Gibson, 2002; Daly and others, 2011) but did not account for season-specific changes in soil and meteorological conditions and crop-specific growth cycles. Meteorological and vegetation conditions are computed in PRISM using a variable that represents the coverage and health of the vegetation termed the "Greenness Vegetation Fraction" (GVF; Bell and others, 2012). Values for the GVF are computed based on a nearly 20-year-old climatology dataset obtained from the National Centers for Environmental Prediction (NCEP; Bell and others, 2012), termed "NCEP-GVF," which "remains static from year to year… [which] may not properly represent the vegetation patterns of the United

States in regions that have changed over the last two decades through urbanization, or experienced substantial deviations from climatology (e.g. droughts excessive rainfall, late/early season freezes or blooms." The NCEP–GVF dataset does not distinguish or resolve large variations in vegetation over small distances because of its coarse resolution of 0.144° (about 15 kilometers [km]). These issues affect updates to vegetation components derived from PRISM modeling that are used to calculate evapotranspiration, ET_o, and effective precipitation, P_e, in turn, used by the crop-demand method to estimate irrigation withdrawal.

Average daily values of minimum and maximum air temperature (T), dew-point temperature (used to calculate psychrometric constant, γ), and precipitation data (P_t) were obtained from PRISM data (table 1) to compute the monthly meteorological parameters for the ET_o and P_e. Further, a value of 3.3 meters per second was used for the average monthly windspeed—associated with low humidity regions, represents a constant moderate to strong wind (Allen and others; 1998)—during all months of the 2008–12 growing seasons, which is uncharacteristic of the ACF–FAS region.

The irrigation efficiency term, (I_{eff}) (Howell, 2003), accounts for the loss of water pumped from the irrigation source (groundwater or surface water) to the crop. Water losses are attributed to the type of irrigation system used such as traveler, portable pipe, drip, solid set, and center-pivot. Depending on the type of system used, irrigation efficiency ranges between 75 and 98 percent of water withdrawn (Howell, 2003). Center-pivot irrigation comprises at least 75 percent of the total irrigation systems in the ACF–FAS; most of these pivots had improved energy and application efficiency sprinkler packages (Harrison and Hook, 2005); therefore, a constant irrigation efficiency of 90 percent (0.9) was used for I_{eff} in the ACF–FAS.

Table 1. Data parameters and sources for crop-demand method governing equations.

Parameter	Definition
	National Cropland data layer[1]
A_{crop}	Area over which the crop is being grown
	Publicly available sources[2]
K_c	Crop coefficient (incorporates planting dates, maturation times, and rooting depths)
	ET_o Functional Dependence FAO56 standard reference values
R_n	Net radiation
G	Soil heat flux density
e_s	Saturation vapor pressure
e_a	Saturation vapor pressure deficit
Δ	Slope vapor pressure curve
γ	Psychrometric constant
	PRISM data[3]
P_t	Average precipitation
T	Air temperature, minimum and maximum
	SSURGO[4]
D	Usable soil water storage
	Assumed constants
I_{eff}	Irrigation efficiency, 0.9 for all systems
U_2	Mean monthly windspeed, 3.3 meters per second

[1] http://www.nass.usda.gov/research/Cropland/Release/index.htm.

[2] Allen and others, 1998; Smajstrla, 1990; Jason Bellino, U.S. Geological Survey, written commun., 2014.

[3] http://www.prism.oregonstate.edu/.

[4] https://gdg.sc.egov.usda.gov/.

Data Integration and Geographic Information System Processing

Estimation of irrigation withdrawal occurred within a geographic information system (GIS) through a series of Python scripts (Van Rossum, 2009) to solve equations 1–4. Identification of where irrigation occurred was determined from the CDL data using an algorithm that grouped together adjacent pixels having the same crop code and at least 5 acres in cumulative area. These grouped pixels were converted to a vector polygon feature class representing potential areas of irrigation withdrawal. The feature class was intersected with the PRISM and SSURGO raster datasets (fig. 3) to extract the meteorological and soil attributes at each area of potential irrigation withdrawal for subsequent GID calculations.

Geostatistical Techniques

Spatial correlation and estimation of monthly irrigation depth was calculated in a framework of geostatistical techniques involving structural analysis, variogram development (or variography), interpolation (kriging), and conditional simulation (Journel and Huijbregts, 1989). These techniques represent a second method of estimating irrigation evaluated for the ACF–FAS.

Geostatistical techniques used monthly recorded water-use data from a metering program in southwestern Georgia to estimate monthly irrigation at annually reported (metered) and unmetered irrigation sites. Values of irrigation depth (in inches), or the volume of irrigated water applied per acre (in acre-inches), were estimated for the ACF–FAS with

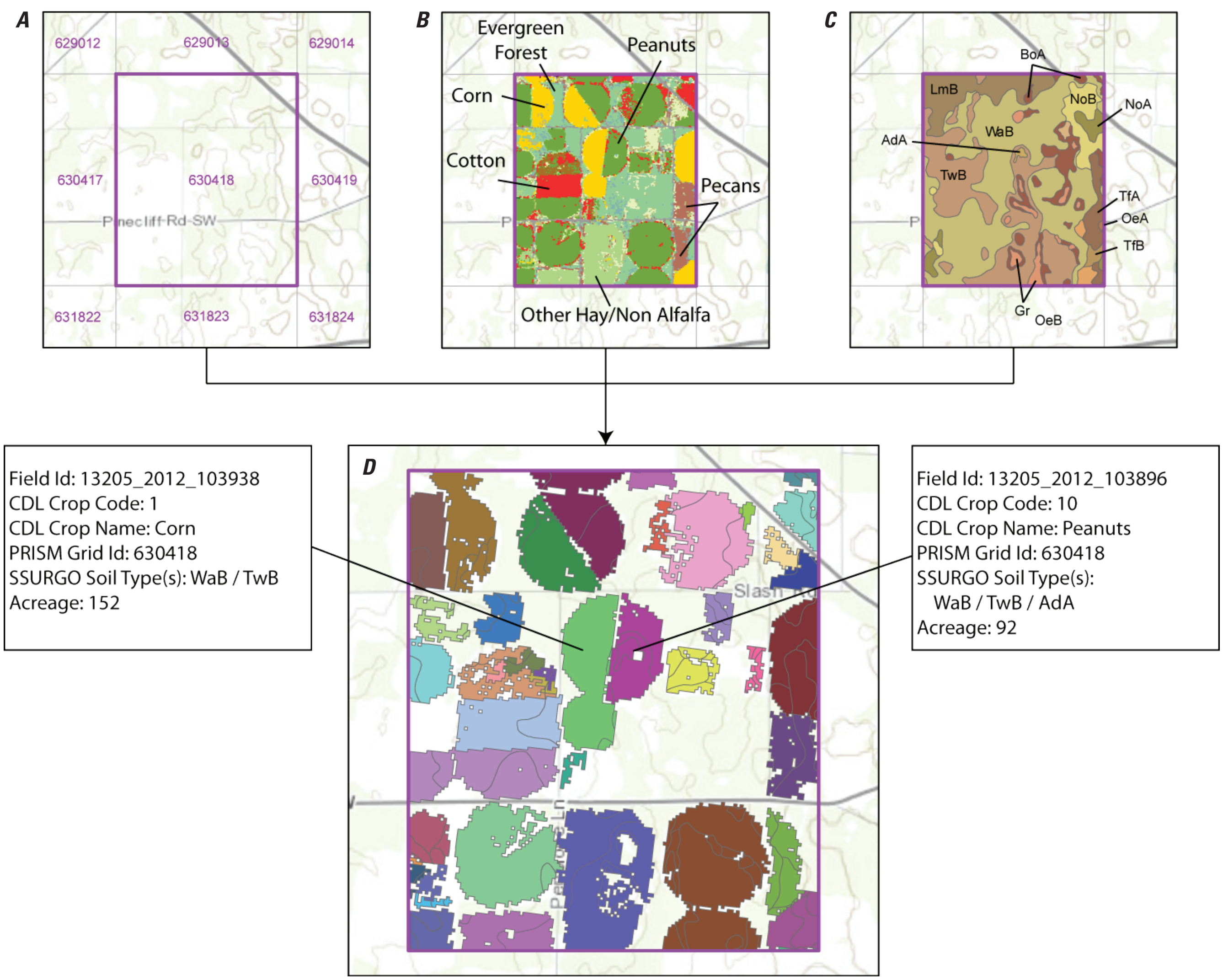

Figure 3. Geographic information system data processing steps for the crop-demand method to combine *A*, PRISM monthly precipitation and temperature data *B*, CDL crop acreage, and *C*, SSURGO soils data. The resulting polygon features in diagram D, potential areas of irrigation withdrawal for which gross irrigation demand were calculated. (U.S. Department of Agriculture, National CDL's 2008–12; http://www.prism.oregonstate.edu/; http://sdmdataaccess.nrcs.usda.gov/)

geostatistical modeling. The GSWCC provided information on irrigated acres associated with meter data for each month of the growing season (March–October) and for the annually read meters (one value for total withdrawal during growing season) to facilitate irrigation-depth calculations.

Description

Geostatistical techniques to estimate irrigation depth used the sequential, or staged approach outlined by Torak and Painter (2011, 2013), culminating with the development of a spatially correlated distribution of irrigation depth for the ACF–FAS region. Monthly metered irrigation withdrawal was normalized to irrigation depth to eliminate from the irrigation estimation any spatial bias associated with the size of each agricultural field. The initial stage of structural analysis evaluated the first two statistical moments of the data, namely the mean and covariance (semivariance, or the semivariogram) (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990) of irrigation depth. Subsequent stages of the analysis identified spatial correlations among annual and monthly meter data.

Semivariance, $\gamma(h)$, provides a measure of spatial correlation based on the difference in meter values between data pairs located within specific distance-class intervals and is expressed as

$$\gamma(h) = \frac{\sum_{i=1}^{n} (z_i - z_{i+h})^2}{2N(h)} , \qquad (5)$$

where

h is the separation distance for the distance-class interval $[L]$;

$N(h)$ is total data pairs; and,

z_i, z_{i+h} are metered irrigation values $[L^3/T]$.

An experimental variogram (see symbols on “Structural Analysis” graph, plotted in fig. 4) graphically represents the spatial correlation of one month’s meter data with distance. Structural analysis was completed by fitting a simple mathematical function (exponential curve on “Variography” graph in fig. 4) to each monthly experimental semivariogram to produce variogram models for the next stage of the analysis. Variogram modeling (or variography) (Journel and Huijbregts, 1989) associates a mathematical function (such as exponential, Gaussian, or linear functions, for example) with the correlation structure inherent to the irrigation-depth data, and integrates the geospatial characteristics of meter-data locations into an estimation process for irrigation depth that involves interpolation at locations where data do not exist.

Monthly variogram models of irrigation depth were used in a coupled linear-interpolation and modeling process consisting of kriging and conditional simulation to estimate irrigation depth at unmetered agricultural fields in the ACF–FAS. Kriging provided unbiased estimates for the expected values of irrigation depth, expressed as a weighted sum of the monthly meter data having minimum estimation variance (American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990). Conditional simulation used the spatial correlation structure expressed in the variogram models and honored (or preserved) the monthly meter data at each site in the interpolation process to estimate irrigation depth for unmetered irrigated fields. Unlike kriging, which smooths out local variations in irrigation depth by calculating the average, or expected values, conditional simulation incorporates actual meter data and its spatial correlation structure into the estimation process, thereby using the spatial complexity and heterogeneity of the irrigation-depth data in estimates of irrigation withdrawal across multiple scales of correlation distances, as defined by the variogram (fig. 4).

Conditional simulation of irrigation depth based on variogram models of monthly meter data from sparse meter networks yielded large estimation variances, or errors, that proved inadequate for representing the spatial variability of irrigation withdrawal at unmetered agricultural fields during most months of the growing season. To improve the geostatistical estimation process, a method was developed that associated the monthly irrigation characteristics defined by the sparse monthly meter data to the larger distribution of annual meter sites by considering the temporal distribution of irrigation defined by the monthly meter data.

Geostatistical techniques of structural analysis, variogram development, kriging, and conditional simulation were applied to spatial distributions of monthly percentages of total annual irrigation derived from the monthly meter data and were used to represent monthly percentages of total annual irrigation at the annual meter sites. Monthly percentages of total annual irrigation estimated from conditional simulation of monthly meter data were assigned to annual meter sites based on their spatial correlation with the monthly meter data. Monthly irrigation volume and depth were then calculated for annual meter sites by applying the assigned monthly percentages to the metered values of total annual irrigation. The resulting variogram models of monthly irrigation depth developed for the annual meter sites indicated high spatial correlation and few outliers, and produced kriging estimation variances that were consistent with estimation variances associated with variogram models of monthly percentages of total annual irrigation derived from monthly meter data. That is, the validity of using monthly meter data as a representative sample of monthly irrigation at the annual meter sites was confirmed by the consistency of the resulting spatial correlations of geostatistical models that estimated monthly irrigation depth at the annual meter sites from similar spatial correlations of independent geostatistical models that estimated percentages of total annual irrigation with the monthly meter data.

Estimates of monthly irrigation depth at the annual meter sites obtained from geostatistical models representing percentages of total annual irrigation withdrawal were derived from monthly meter data. These data constitute a sample size of more than 4,000 annual meter sites from which variogram

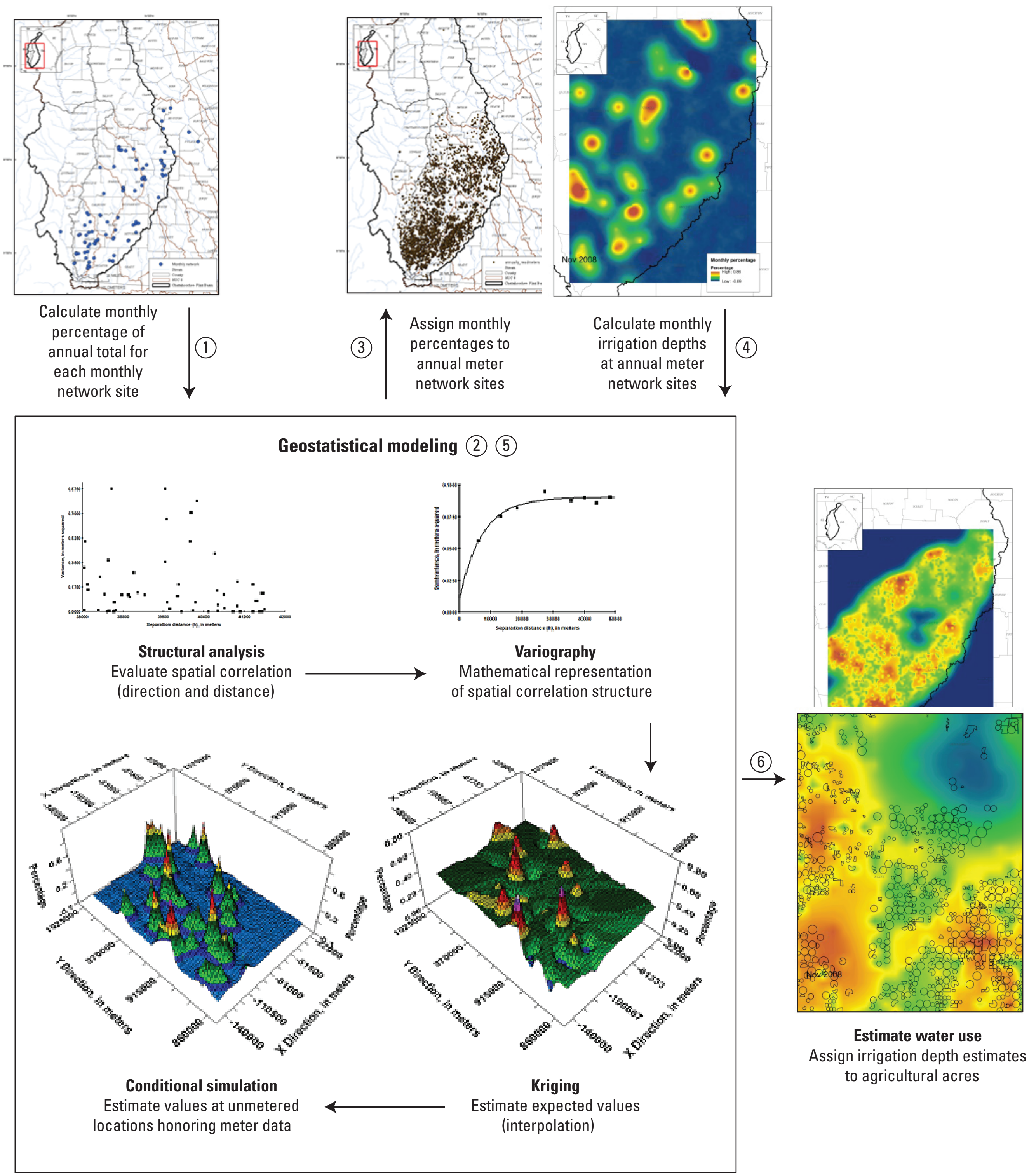

Figure 4. Geostatistical techniques used to estimate irrigation depth.

models have identified spatial correlation structures for the final stage of geostatistical applications to estimate irrigation depth at unmetered irrigated fields. Monthly variogram models of irrigation depth at the annual meter sites were then used in a coupled kriging-conditional simulation process to estimate irrigation depth at unmetered sites in the ACF–FAS (see “Conditional Simulation” graph and “Kriging” graph on fig. 4).

Geostatistical techniques provided irrigation-depth estimates for the ACF–FAS that can be applied indiscriminately to any distribution of irrigated agricultural land (or non-agricultural land); therefore, accurate identification of spatial and temporal distributions of irrigated acres during the growing season is critical for accurately estimating irrigation withdrawal from the geostatistically derived distributions of irrigation depth. Irrigated acres not assigned to a meter represented areas where geostatistical models were required to estimate irrigation depth, values of which were then combined with monthly distributions of irrigated acres to estimate irrigation volume for the withdrawal evaluation.

Distributions of agricultural land, from which irrigation depths were estimated using geostatistical techniques, were provided by a dataset from the Georgia Department of Natural Resources, termed “GaDNR Agricultural Lands,” (Danna Betts, Georgia Department of Natural Resources, written commun., May 2012). This dataset represents a distribution of metered and unmetered agricultural acres in southwestern Georgia that is associated with water-use permits and that identifies potential irrigated acres catalogued previously by the GSWCC to support the metering program. The GaDNR Agricultural Lands dataset is a static representation of agricultural acres developed from previous growing season data.

Application Limitations

Limitations in the application of geostatistical techniques to estimate irrigation withdrawal in the ACF–FAS center on the ability of meter-network data to document monthly spatial correlations for (1) evaluation by variogram models; and, (2) estimation and simulation processes to fulfil water assessment and use objectives. Structural analysis, variography, and the coupled kriging-conditional simulation modeling approach work in concert to estimate values for regionalized variables of interest (irrigation volume, irrigation depth, and percent of total annual irrigation) using advanced, directional-interpolation methodology. The inability to obtain accurate spatial and temporal distributions of irrigated acres or metered irrigation volume for analysis using geostatistical techniques presents severe limitations on estimation of irrigation withdrawal at metered and unmetered irrigation sites using these techniques.

A critical limitation of these geostatistical techniques and of interpolation methods in general exists where meter-network data do not completely envelop the area where interpolation is required to estimate the regionalized variable. During conditional simulation, sparse data at the edge of the ACF–FAS from the meter network limited the amount of, and direction from which, data were used in interpolations to estimate irrigation depth. Conditional simulation uses a multiscale and multidirectional interpolation process that integrates neighboring data and the variogram structure into a form of stochastic simulation in which measured data values are honored at their locations (Robertson, 2008). The sparse data along the edges of the ACF–FAS can cause spatial bias, relatively large estimation variances, and poor estimates.

Image Analysis

A third method to estimate irrigation withdrawal for the ACF–FAS analyzed moderate spatial-resolution satellite imagery and commonly available meteorological data to identify irrigated land at specific times during the growing season. Resulting datasets of irrigated land were prepared on near-term horizons that correspond with satellite data repeat frequencies of imagery to provide water managers with meaningful datasets to assess then-current conditions of irrigation withdrawal.

Process

The overall process integrated two types of mathematical models into an imagery analysis to develop an irrigated-land dataset (fig. 5). The first model identified pixels in Landsat 5 satellite imagery that indicated unusually cool land-surface temperature because of high evapotranspiration (ET) relative to pixels that represented a relatively warm land surface associated with known non-irrigated land. The resulting image-pixel modeling produced estimates of three image classes: (1) “Irrigated Emergent Crop”; (2) “Irrigated Soil”; and, (3) “Non-irrigated cropland” (fig. 5). The second model combined monthly maps generated from multiple Landsat 5 satellite images into a single image, from which monthly estimates were developed for the three irrigation classes identified by the first model. Spatial models portraying these irrigation classes were created for each month during the growing season in a GIS environment that used ArcMap (Esri, Inc., 2013) to account for differences in availability across Landsat 5 image paths/rows.

Data Requirements

Public domain, spatially referenced imagery and datasets were input to the image analysis process. Meteorological data required to compute evapotranspiration was obtained from National Oceanic and Atmospheric Administration climatological stations (National Oceanic and Atmospheric Administration, 2015) and the Georgia Environmental Monitoring Network (Georgia Automated Environmental Monitoring Network, 2015). Data identifying agricultural and non-agricultural land was supplied by the 2011 National Land Cover Database

(NLCD) (Homer and others, 2015). The Landsat 5 satellite provided thermal data in the form of apparent temperature, calibrated to a “top of atmosphere” value, and the provisional Landsat Surface Reflectance Product, termed “L5LSRP,” for Landsat 5 image paths and rows that cover the area of interest (http://landsat.usgs.gov/documents/cdr_sr_product_guide.pdf). Imagery from the newer Landsat 7 satellite suffered a partial loss of imaging capacity during May 2003, making it unsuitable for the study. Satellite imagery from Landsat 8, launched on February 11, 2013, post-dated the study period, 2008–12. Separation of image pixels into “Irrigated Emergent Crop” and “Irrigated Soil” classes was based on classification of a vegetation index derived from the satellite data (fig. 5).

Limitations

Data availability of satellite imagery presents a major limitation for the image analysis method to accurately estimate locations where irrigation occurred in the ACF–FAS during the growing season. Haze, clouds, and cloud shadows created non-clear sky conditions and confounded optical satellite-image processing and analysis. Weather and satellite-system limitations resulted in a nominal scene-area repeat period of 16 days. The lack of clear sky over some regions caused a longer repeat period of 32 days or longer, which rendered the image analysis method unreliable for accurately estimating locations of irrigation withdrawal on a monthly time horizon.

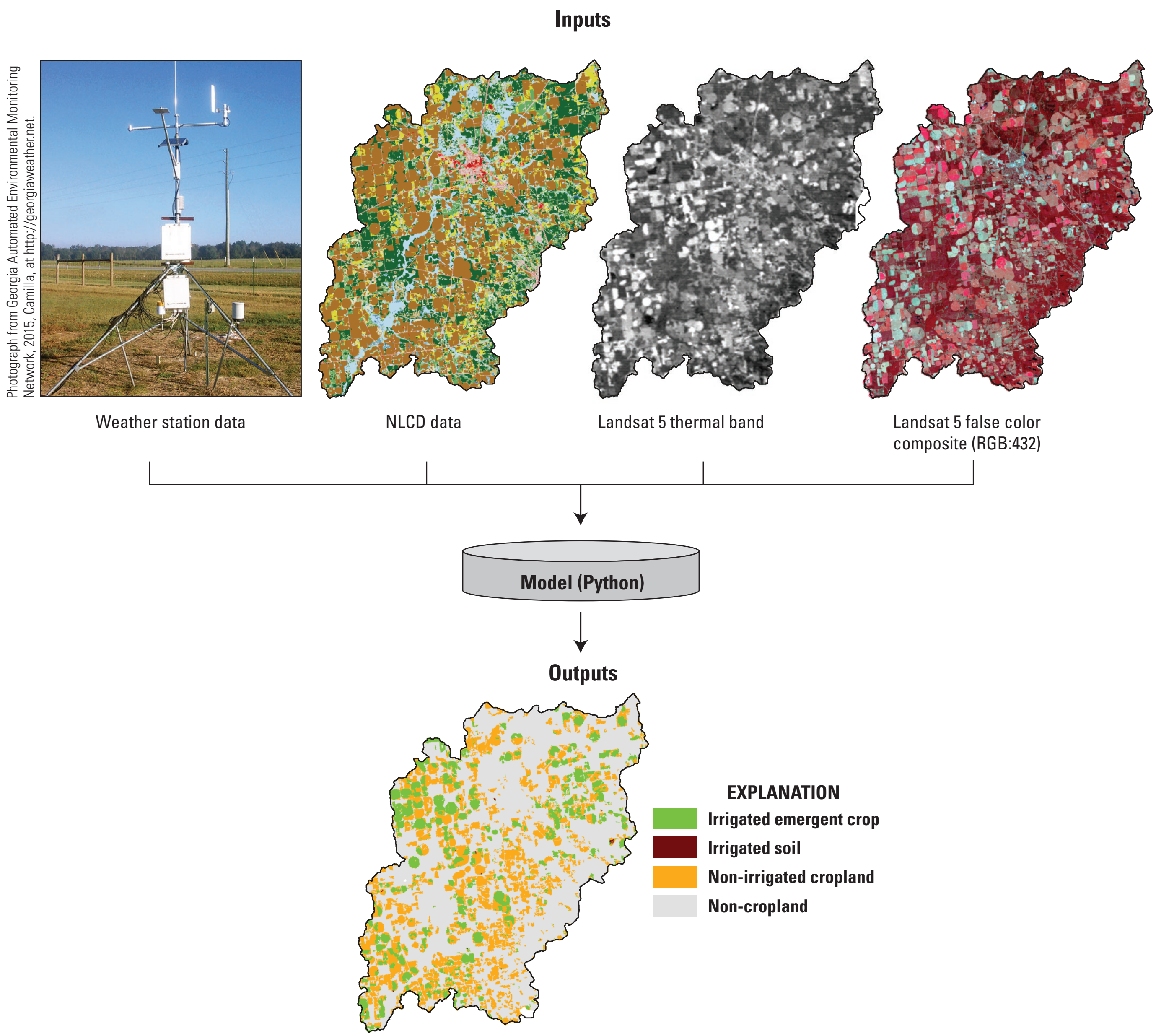

Figure 5. Image analysis process. (National Oceanic and Atmospheric Administration, 2015; Georgia Automated Environmental Monitoring Network, 2015; National Land Cover Database (NLCD), Homer and others, 2015)

Also, thermal infrared data used for this analysis were corrected only for sensor calibration drift, not atmospheric effects. Temperature differences caused by clouds and cloud shadows were largely removed through the cloud-shadow masking process; however, it is possible that some within-scene variations in apparent surface temperature were attributed to differences in atmospheric conditions rather than evapotranspiration of irrigation water. These temperature variations could lead to over- or underestimation of irrigated acres.

Another limitation of image analysis centered on using agricultural land from the 2011 NLCD as the population of potentially irrigated land from which image analysis identified irrigation patterns for the study period of 2008–12. This process excluded actual irrigated land during 2008–10 and 2012 that was not designated as agricultural in the 2011 NLCD; these “missing agricultural acres” were identified as irrigated through meter data. That is, areas where land cover was designated as agricultural before and after 2011 were excluded from the image analysis process even though the meter data identified these acres as agricultural and irrigated.

Comparison of Methods to Estimate Irrigation Withdrawal

This comparison collectively assesses the estimation methods in the context of data availability, which affected the resulting time and spatial horizons for which the estimations were produced. Each method required meteorological, agronomic, remotely sensed, or physically metered or observed data by varying degrees throughout the ACF–FAS and for varying time horizons coincident with data acquisition. The inability to obtain complete parameterization because of incompleteness in these unique datasets posed limitations in the estimation process by each method, as previously discussed in the Parameterization and Data Limitations, Application Limitations, and Limitations sections. These limitations also affected the extent of method-by-method comparisons of estimation accuracy and completeness of a singular estimation process. Additional comparisons were done at meter sites during the 2010 and 2012 growing seasons between (1) metered irrigation withdrawal and estimates provided by the crop-demand method; and, (2) between irrigated acres associated with meters and irrigated acres estimated through image analysis.

Of the three estimation methods developed for the ACF–FAS, only the crop-demand method provided estimates of where irrigation was applied, when it was being used, and how much was used during each month of the study period (2008–12). By comparison, monthly meter data were absent during the 2009 growing season and the first 3 months of the 2010 growing season (March–May), preventing use of geostatistical techniques to estimate irrigation depth for this period as described in the geostatistical techniques section. Additionally, the image analysis method was unable to identify irrigated acres during those months of the growing season when atmospheric effects (haze, clouds, and cloud shadows) obscured land surface and prevented the collection of usable imagery.

Assessments at a Regional Spatial Extent

Estimates of irrigation withdrawal (million gallons per day) and irrigated areas (acres) were compared collectively at a study area, or regional, spatial extent (fig. 1) to assess similarities and differences in results produced by each estimation method. Irrigation-withdrawal estimates from the crop-demand method and geostatistical techniques were comparable for 26 months of the 40-month study period because of the limitations presented previously in the Parameterization and Data Limitations, Application Limitations, and Limitations sections (fig. 6). The crop-demand method produced higher estimates of irrigation withdrawal than geostatistical techniques for 17 of the 26 months used in the comparison. The largest difference in monthly irrigation withdrawal estimated by these methods occurred for October 2012, when the crop-demand method estimated irrigation withdrawal that was about 12 times higher than withdrawal estimated using geostatistical techniques. Irrigation water use of nearly 1.2 billion gallons a day estimated during October 2012 using the crop-demand method conflicts drastically with irrigation withdrawal determined with geostatistical techniques on monthly meter data and is uncharacteristic of irrigation during the month of October in this region (fig. 7). According to monthly meter-network irrigation data, the least amount of water withdrawn for irrigation typically occurs during October (fig. 7) of each year; however, the crop-demand method for October 2012 produced the third largest irrigation withdrawal estimate during the study period (fig. 6). In contrast, the crop-demand method computed zero water use in October 2008 (fig. 6), when the metered data indicated irrigation (fig. 7).

In general, the primary growing season months of May–July exhibited the largest discrepancy between irrigation-withdrawal estimated with the crop-demand method and geostatistical techniques, discounting from this comparison the October 2012 irrigation-estimation abnormality (fig. 6). The month with the highest water-use estimate varied by growing season; however, the two methods never coincided to estimate maximum irrigation withdrawal in the same month.

The large disparity between irrigation withdrawal estimated with the crop-demand method and irrigation withdrawal documented by monthly meter data demonstrated a major limitation of the crop-demand method related to evaluation of meteorological and agronomic parameters used to compute *GID*. That is, the use of standard reference values in the governing equations for *GID* did not accurately account for site-specific meteorological and agronomic conditions of irrigated areas. As previously mentioned in the Parameterization and Limitations section, maintaining a constant wind speed and constant crop coefficients, and the use of average meteorological conditions in the *GID* equations that do not match actual field conditions, can result in gross overestimation of values for *GID* and in equally large estimates of the water needed to irrigate a crop, as evidenced by the large (nearly 12-fold) discrepancy between

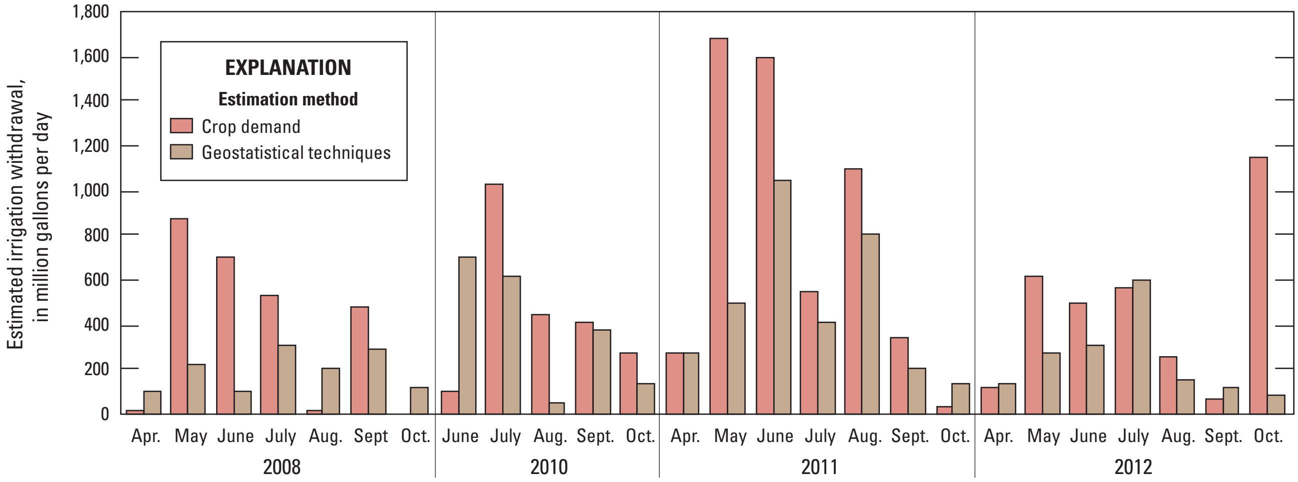

Figure 6. Irrigation withdrawal estimates for each month of the study period. (If a month is not shown, the Georgia Soil and Water Conservation Commission metering program data are missing.)

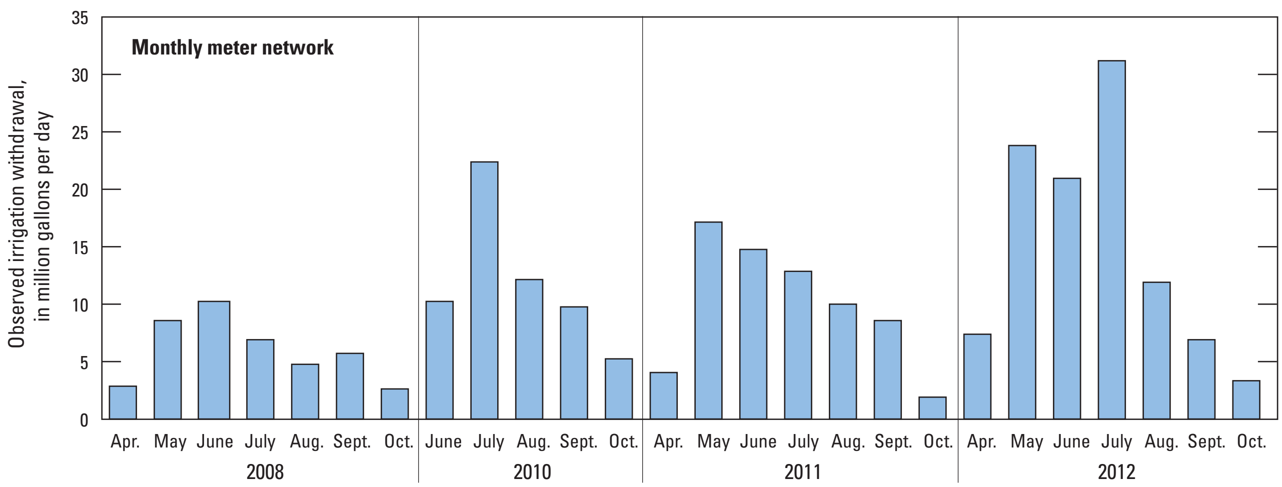

Figure 7. Monthly meter network irrigation withdrawals for the study period.

irrigation withdrawal estimated by the crop-demand method and metered irrigation during October 2012.

Another assessment used monthly irrigation-depth distributions estimated with geostatistical techniques to identify the sensitivity of irrigation-withdrawal estimates to the distributions of irrigated acres defined by (1) the GaDNR Agricultural Lands dataset and, (2) image analysis (fig. 8). The irrigation-depth distributions for the ACF–FAS obtained from geostatistical techniques provided the control for this assessment; that is, irrigated acres from the above datasets (1 and 2) were associated with identical monthly irrigation-depth distributions derived from geostatistical techniques, and the effects on irrigation-withdrawal estimates of each dataset were compared.

Monthly differences between total irrigation-withdrawal estimates derived from the two irrigated acres datasets (fig. 8) were more consistent during 2008 than during 2010. Total irrigation withdrawal during May–July 2008 estimated using the GaDNR Agricultural Lands dataset exceeded that using image analysis by approximately 53 percent. During June 2010, irrigation-withdrawal estimates derived from the image analysis dataset of irrigated acres constituted only 31 percent of that estimated using the GaDNR Agricultural Lands dataset. In the following month, however, irrigation-withdrawal estimates derived from image analysis dataset contributed 83 percent of the estimated irrigation withdrawal derived from the GaDNR Agricultural Lands dataset, demonstrating the critical importance of accurately identifying spatial and temporal distributions of irrigated acres to irrigation-withdrawal estimates.

Another assessment of each method to estimate monthly irrigation compared the amount and location of irrigated acres

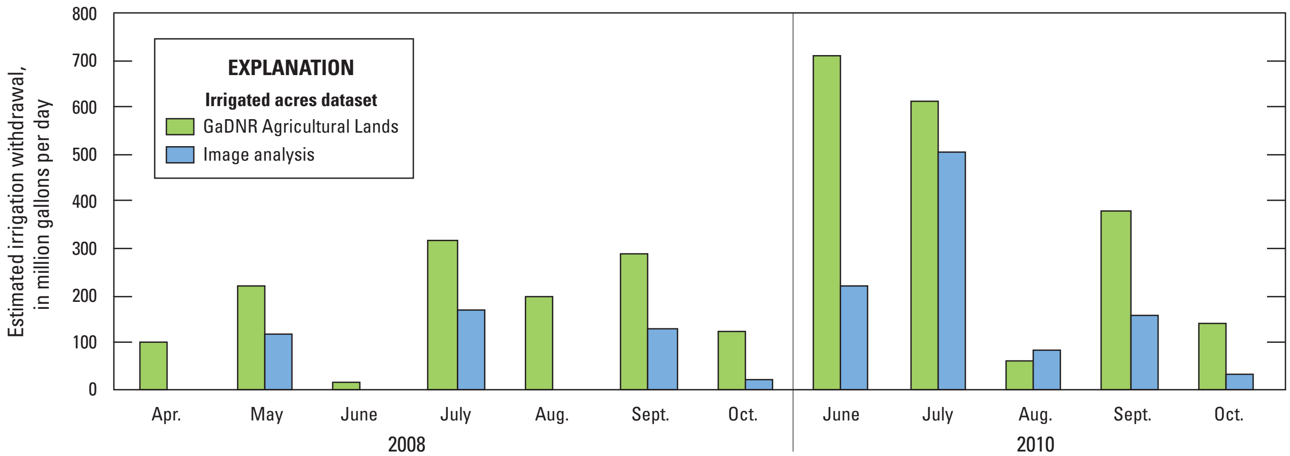

Figure 8. Irrigation-withdrawal estimates using irrigated acres identified by the Georgia Department of Natural Resources Agricultural Lands dataset (Danna Betts, Georgia Department of Natural Resources, written commun., May 2012) and image analysis associated with identical monthly irrigation-depth distributions derived from geostatistical techniques during months of available meter data and Landsat 5 imagery. (Zero irrigation withdrawal for image analysis indicates that Landsat 5 imagery were missing or unusable.)

with acres associated with identical monthly irrigation-depth distributions derived from geostatistical techniques. Irrigated-acres distributions from the GaDNR Agricultural Lands dataset and image analysis were compared with irrigated acres defined by the crop-demand method (fig. 9). The total number of acres identified as irrigated varied from month to month, and no one method consistently estimated the largest number of irrigated acres among the three methods. Likewise, no one method consistently over or under-reported irrigated acres, compared with the irrigated acres associated with the monthly meter data. A large discrepancy among irrigated acres represented by each estimation method existed during August 2008, where irrigated acres represented by the crop-demand method estimated 94 percent less than the irrigated acres represented by geostatistical techniques. Zero irrigated acres were estimated by the crop-demand method during October 2008; whereas irrigated acres identified by image analysis and geostatistical techniques (monthly meter data) documented the occurrence of irrigation. The closest agreement of irrigated acres identified with the estimation methods occurred during July 2010, compared with any other month during the quantitative assessment of irrigation for the ACF–FAS. The crop-demand method and geostatistical techniques yielded irrigated acres estimates of 578,649 acres and 445,263 acres from the GaDNR Agricultural Lands dataset, respectively; irrigated land identified with image analysis totaled 448,567 acres.

The crop-demand method tended to underestimate irrigated acres during the last four months of the growing season (July–October) and overestimate irrigated acres during May and June, compared with irrigated acres derived from monthly meter data and used by geostatistical techniques (fig. 9). This finding indicates that farmers do not irrigate completely according to estimated crop planting, maturity, and harvesting dates, which are used in the crop-demand method, and that these dates do not necessarily coincide with irrigation schedules documented by the monthly meter data. In addition, meter data also indicate that water is applied to fields at the beginning and end of the growing season to prepare for planting and cultivating the crops, and to prepare the fields for the next season. Irrigated acres derived from monthly meter data and associated with geostatistical techniques exceed irrigated acres estimates used in the crop-demand method at the beginning and end of the growing season.

In a spatial context, the occurrence, identification, and coincidence of irrigated acres used by each method were evaluated to compare the consistency of information used to estimate irrigation withdrawal. In general, none of the methods accounted for all of the irrigated acres in any given month. For example, a representative sub-region of the study area indicated that not all acres identified by image analysis or the crop-demand method were listed in the GaDNR Agricultural Lands dataset (figs. 10*A, B*). Additionally, the crop-demand method and image analysis representation of irrigated acres have minimal agreement for any given month (fig. 10*C*).

A summary of irrigated acres identified as irrigated land by image analysis and the crop-demand method during the 2010 growing season indicates that the GaDNR Agricultural Lands dataset could be under-reporting agricultural acres by 22,508 to 253,797 acres, depending on the growing season month (table 2). The acres identified as irrigated land by image analysis and the crop-demand method that do not intersect agricultural field polygons in the GaDNR Agricultural Lands dataset (figs. 10*A*, *B*), would add to the GaDNR dataset to give a more complete assessment of agricultural land. This is evidenced by comparing the potential agricultural fields identified by the GaDNR (544,235 acres) with agricultural fields identified by the CDL dataset (crop-demand method)

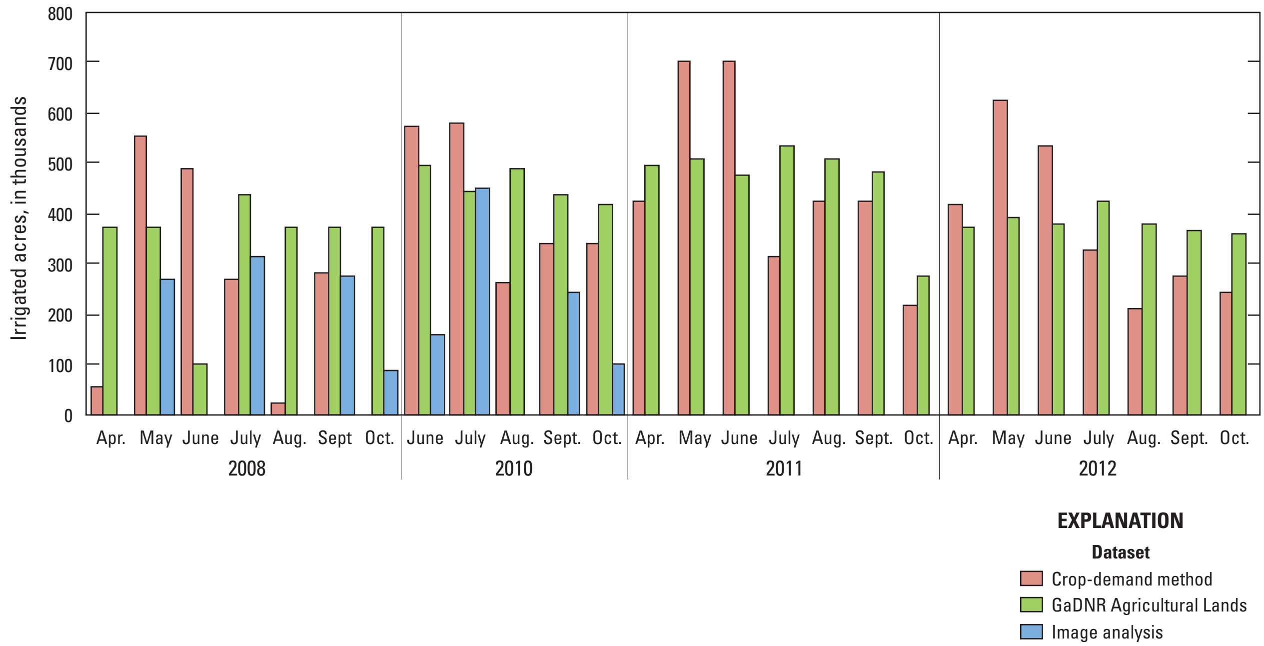

Figure 9. Estimates of irrigated acres from the crop-demand method, and from the Georgia Department of Natural Resources Agricultural Lands dataset (Danna Betts, Georgia Department of Natural Resources, written commun., May 2012) and image analysis, associated with identical monthly irrigation-depth distributions derived from geostatistical techniques during months of available meter data and Landsat 5 imagery. (Zero irrigation withdrawal for image analysis indicates that Landsat 5 imagery were missing or unusable.)

(718,848 acres) and cultivated cropland identified by the 2006 NLCD (image analysis) (825,317 acres).

Spatial comparisons between irrigated acres obtained from the crop-demand method and geostatistical techniques, and the previous discussion of limitations of the latter estimation method, indicate inaccuracies in irrigation-depth estimates at the geographic limits of the meter data (fig. 11*A*). Geostatistical techniques yielded erroneous zero-valued estimates of irrigation depth along the edges of the ACF–FAS region during 2008–11, but correctly and automatically estimated irrigation depth at unmetered fields encompassed by monthly meter data as part of the interpolation process. Appropriate redesign of the meter network, such as the network used for the 2012 growing season, eliminated interpolation errors by encompassing the ACF–FAS region with data, which allowed geostatistical techniques to provide accurate estimates of irrigation depth along the ACF–FAS boundary (fig. 11*B*). In contrast, the crop-demand method estimated non-zero values of irrigation depth at fields located along the edges of the ACF–FAS region. The standard reference and assumed constant conditions used to evaluate meteorological and agronomic parameters contained in crop-demand calculations, however, could compromise the accuracy of irrigation-withdrawal estimates at all fields located in the ACF–FAS regardless of proximity to region boundaries. The ability of geostatistical techniques to provide complete spatial distributions of irrigation depth in the ACF–FAS demonstrates the robustness of geostatistical techniques to estimate irrigation depth at non-network (unmetered) fields, without additional calculations, data collection, or parameterization.

Assessment of Results with Data from Monthly Meter Sites

Monthly meter-network data provided a sample of known irrigation withdrawal for comparison with estimates derived from the crop-demand method and for comparison with the image-analysis designation of irrigated acres. Irrigation-depth estimates at the monthly meter-data sites derived from geostatistical techniques were not compared because conditional simulation honors the monthly meter data and interpolates at unmetered locations in the ACF–FAS. That is, by design, conditional simulation (geostatistical techniques) identically "estimates" the monthly meter data at the meter sites. In addition, a subset of meter sites where crop identification information was available provided the basis for an assessment of crop identification accuracy, a driving factor for determining crop-demand estimates. The 2010 and 2012 growing seasons were selected for use in these comparisons because (1) the distribution (network) of monthly meters was redesigned for the 2012 growing season from the network used during the 2007–11 growing seasons, which allowed irrigation-depth estimates

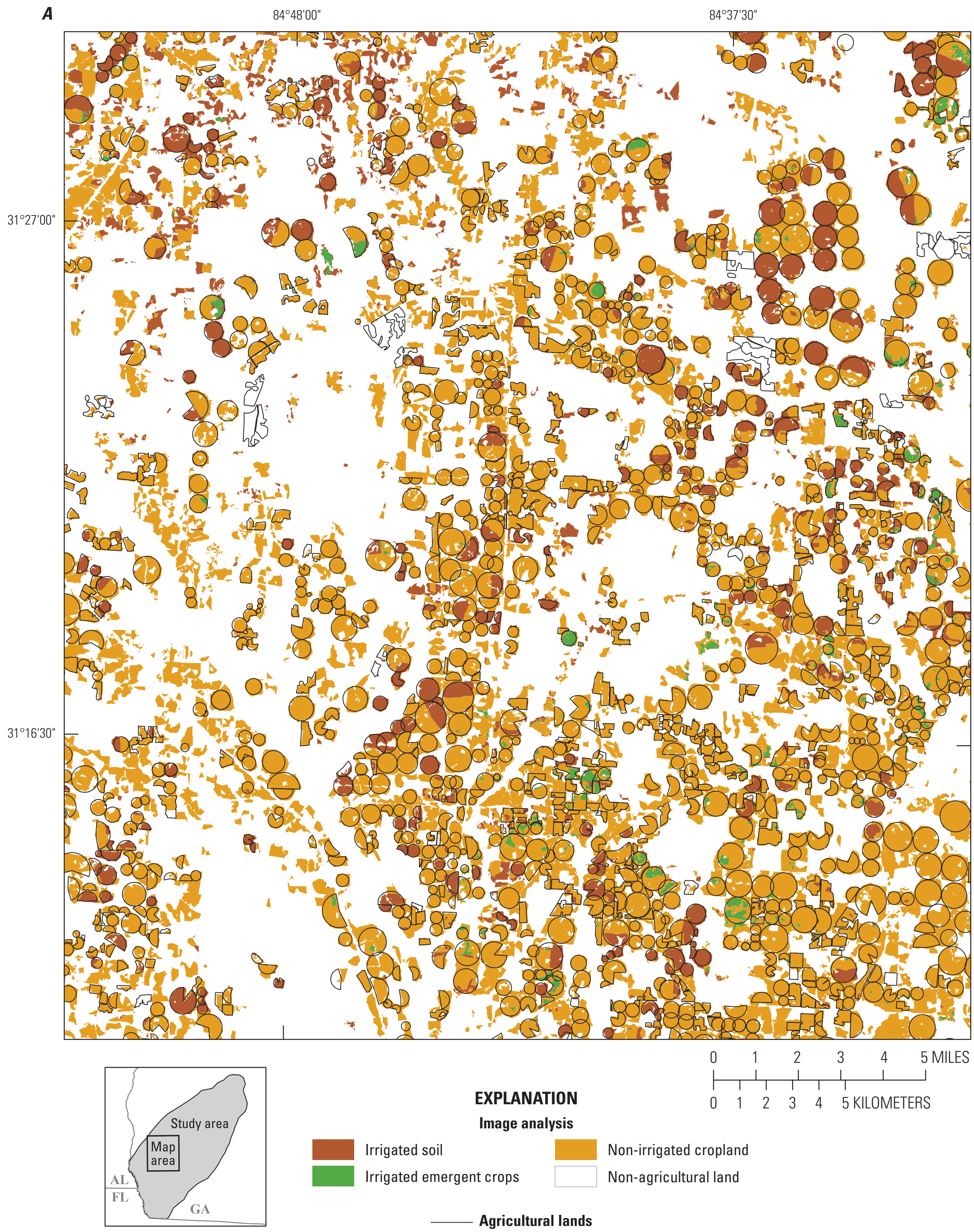

Figure 10. Sub-region of National Water Census focus area study of the Apalachicola-Chattahoochee-Flint River Basin (ACF–FAS) depicting conflicting irrigated lands by comparing *A*, image analysis and the Georgia Department of Natural Resources (GaDNR) Agricultural Lands dataset; *B*, crop-demand method and the GaDNR Agricultural Lands dataset; and *C*, crop-demand method and image analysis. (Georgia Department of Natural Resources Agricultural Lands dataset from Danna Betts, Georgia Department of Natural Resources, written commun., May 2012.)

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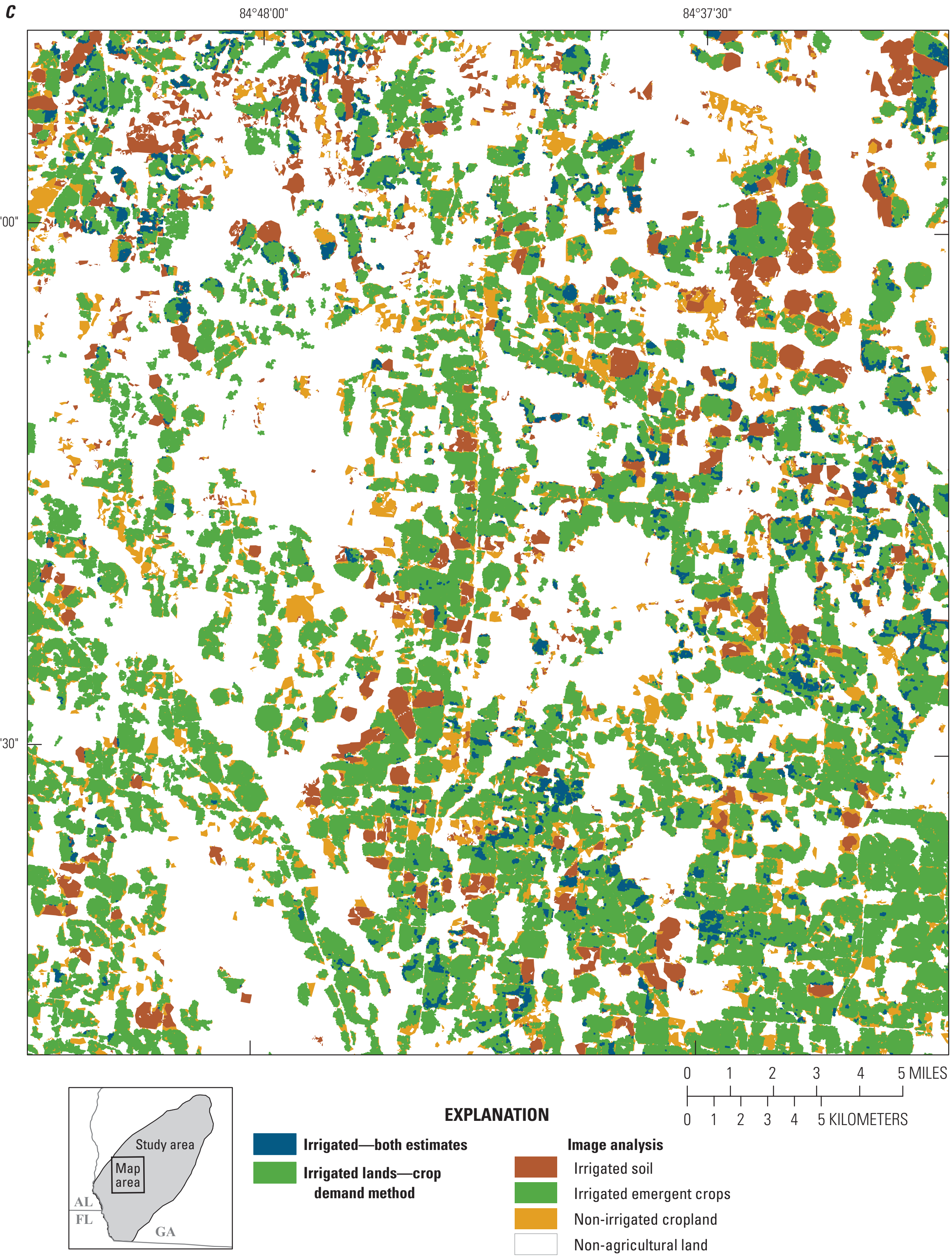

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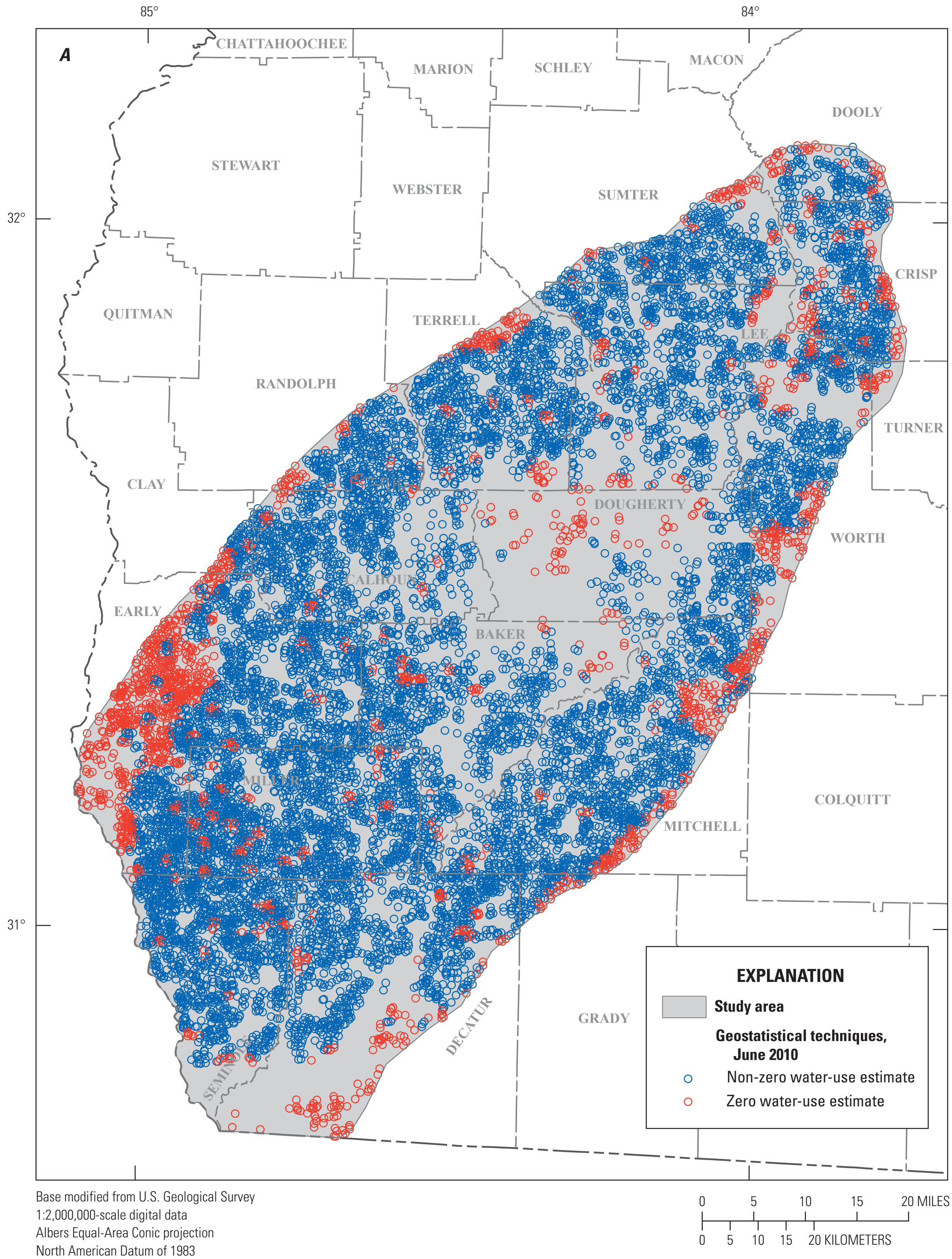

Figure 11. *A*, Estimation of zero irrigation depth (geostatistical techniques) along the perimeter of the National Water Census focus area study of the Apalachicola-Chattahoochee-Flint River Basin (ACF–FAS) region compared to the crop-demand estimates of nonzero irrigation for 2010 and *B*, 2012 estimates of irrigation depth (geostatistical techniques) showing nonzero estimates of irrigation depth along the ACF–FAS boundary.

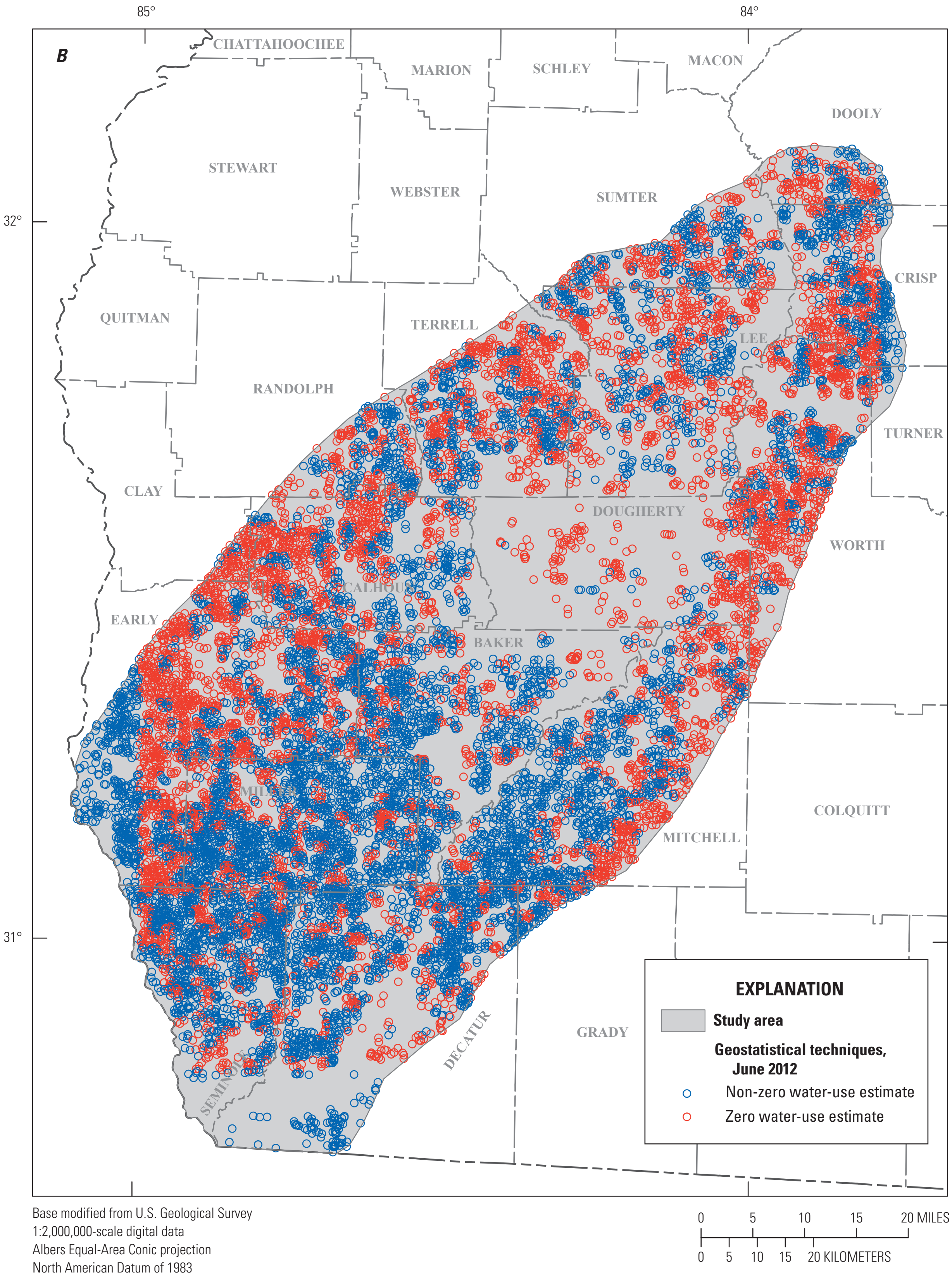

Figure 11. *A*, Estimation of zero irrigation depth (geostatistical techniques) along the perimeter of the National Water Census focus area study of the Apalachicola-Chattahoochee-Flint River Basin (ACF–FAS) region compared to the crop-demand estimates of nonzero irrigation for 2010 and *B*, 2012 estimates of irrigation depth (geostatistical techniques) showing nonzero estimates of irrigation depth along the ACF–FAS boundary.—Continued

Table 2. Irrigated lands identified exclusively by the crop-demand and image analysis methods. These estimates are not represented in the GaDNR Agricultural Lands dataset, which includes 544,235 acres for every month of the 2010 growing season.

[Georgia Department of Natural Resources (GaDNR) Agricultural Lands dataset (Danna Betts, Georgia Department of Natural Resources, written commun., May 2012); —, no data]

Estimation method	Identified irrigated acres				
	June 2010	July 2010	August 2010	September 2010	October 2010
Crop demand	253,797	242,263	91,680	103,881	104,472
Image analysis	54,393	139,499	—	69,731	22,508

to be compared against two distinct sets of known irrigation withdrawal represented by the monthly meter networks; (2) the monthly meter data for these years contained crop identification information; and, (3) the image-analysis estimates were available for 2010.

The distinction between the monthly meter networks used for the 2010 and 2012 growing seasons resulted in varying amounts of meter data used to compare with estimates of irrigation withdrawal by the crop-demand method and geostatistical techniques. During the 2010 growing season, the monthly meter network yielded actual withdrawal data from 30 sites during October; 40 sites each during June and September; and 48 sites each during July and August. Meter data were not available during March–May 2010, as described previously in the Comparison of Methods to Estimate Irrigation Withdrawal section. During the 2012 growing season, the new monthly meter-network design resulted in a larger and more consistent number of monthly meter data by month (number of meter data in parentheses): March–May (90), June (86), July (87), August (88), September (84), and October (85).

Direct comparison of irrigation-withdrawal estimates to meter data was made in a GIS environment where field areas associated with meter sites were spatially joined to overlapping (coincident) irrigated areas identified with the crop-demand method and image analysis. The exact number of irrigated acres associated with monthly meter sites could not be compared with the spatially joined irrigated acres associated with the crop-demand method and image analysis method because of the limitations discussed previously in the Parameterization and Limitations and the Limitations sections. Specifically, the limitations related to the identification of agricultural lands using the NLCD and CDL datasets. Therefore, only designated fields from the crop-demand method and image analysis that overlap with the meter-identified fields were used as comparable acres in the analysis.

Comparison of irrigated acres associated with metered sites and image analysis indicates that image analysis under-identified irrigated fields that were defined with meter data as being irrigated (see example in fig. 12*A*). The previously discussed limitations of the image analysis method in the Limitations section, namely the irregular and long 16-day repeat interval for imagery and the meteorological interference of clear-sky conditions, adversely affected the ability of satellite imagery to identify irrigated land on a monthly basis.

Assignment of constant values of irrigated acres to specific meters during the growing season could contribute toward differences in the identification of irrigated acres by image analysis and meter data (fig. 12*B*). Image analysis provided a temporal distribution of irrigated acres during the growing season, whereas acres assigned to specific meters were held constant throughout the growing season, although crop patterns and irrigated acres could change during the growing season. For example, double-cropping of corn followed by cotton or peanut on some of the previously irrigated acres (for corn) would not be represented in the irrigated acres assigned to the meter data.

Comparisons of irrigation-withdrawal estimates from the crop-demand method with the monthly meter data for selected months during the 2010 and 2012 growing seasons show marginal similarities (fig. 13). For example, in October 2012, the GID calculated using the crop-demand method was a poor match for the metered amount of water applied to the fields. Limitations related to using standard reference and constant values for agronomic and meteorological parameters in GID calculations most likely resulted in withdrawal estimates from the crop-demand method showing little or no relation to meter values over the entire range of values for metered withdrawal.

Irrigated acres used to calculate GID differ from irrigated acres assigned to meter data, limiting comparisons of irrigation withdrawal calculations by the crop-demand method with that documented by monthly meter data (fig. 14). Irrigated acres estimated by the crop-demand method encompass multiple meters; the acres of these additional meters may or may not be incorporated in the CDL datasets for calculations of GID. These meters were not part of the monthly meter dataset, but were read annually.

Incongruities in agricultural acres designations by the CDL datasets and meter data contribute toward over- or under-estimation of GID by the crop-demand method. Additional acres contained in the CDL datasets that are neither identified by annual nor monthly meters contribute toward over-estimation of GID. The resulting disagreement of actual irrigation withdrawal (and acres) represented by the monthly meter data and that which should be used for comparison with

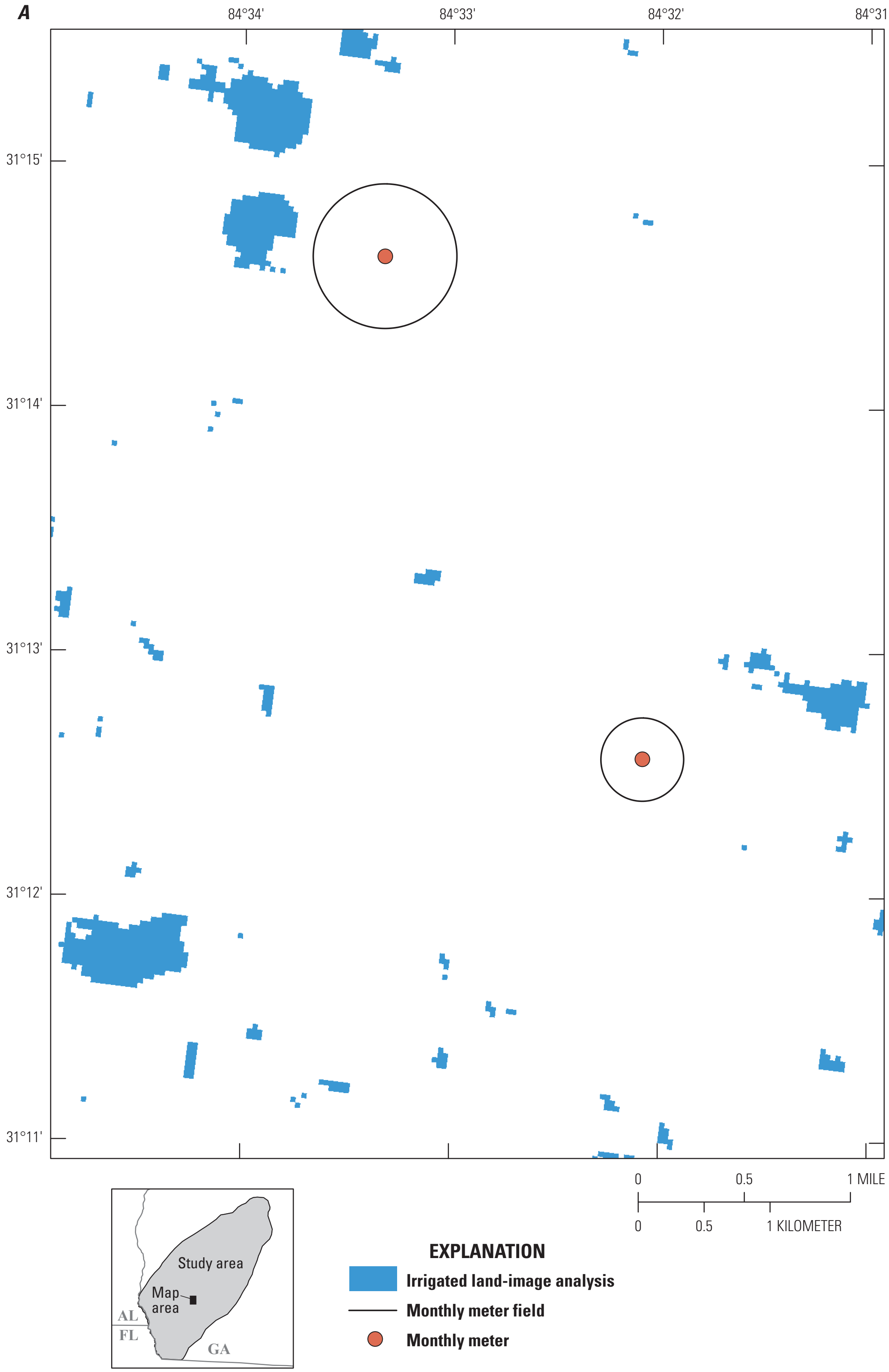

Figure 12. Irrigated land identified by image analysis for *A*, under-identified irrigated acres where meter data recorded irrigation, and *B*, comparison with constant assignment of irrigated acres to metered withdrawal.

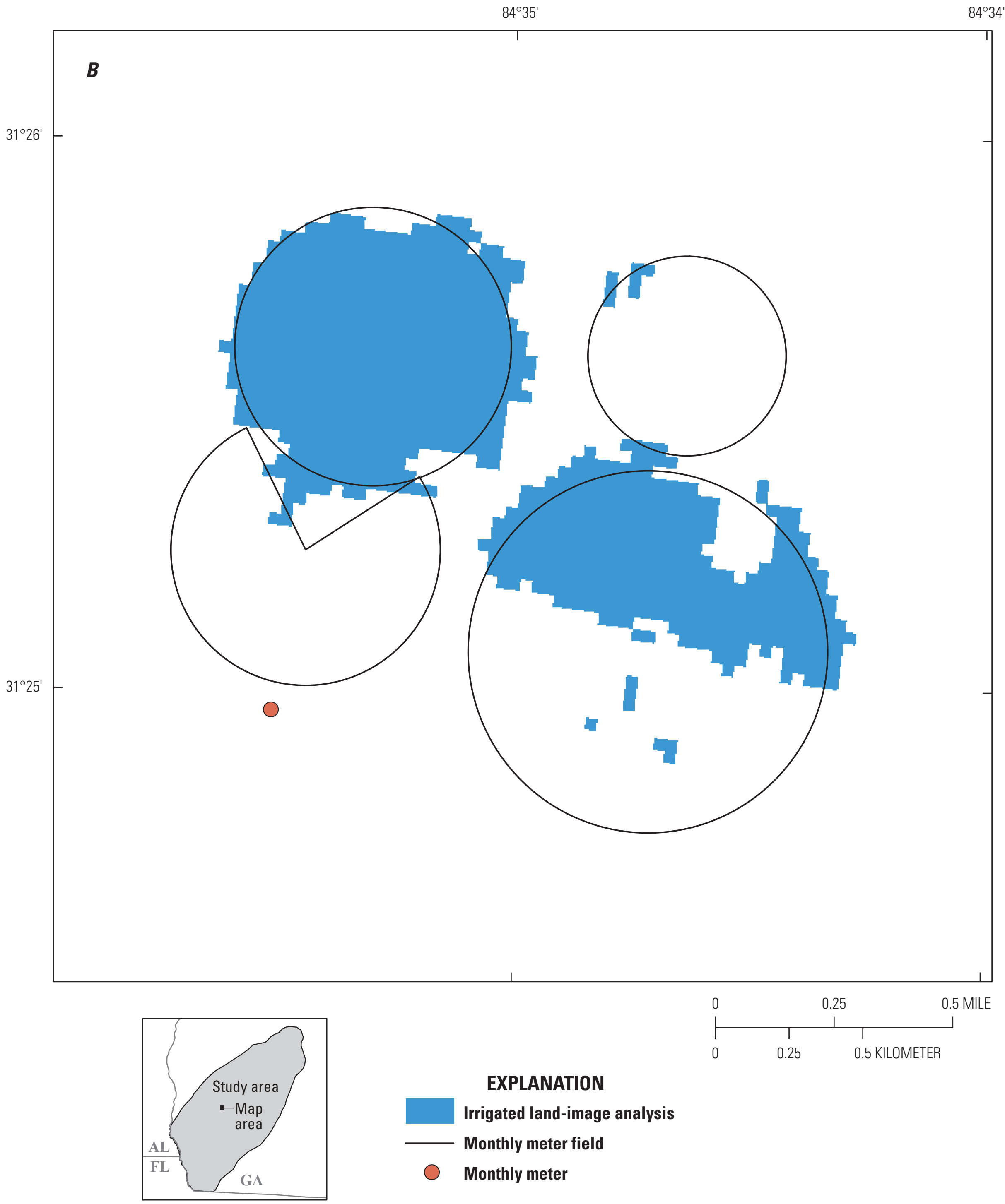

Figure 12. Irrigated land identified by image analysis for *A*, under-identified irrigated acres where meter data recorded irrigation, and *B*, comparison with constant assignment of irrigated acres to metered withdrawal.—Continued

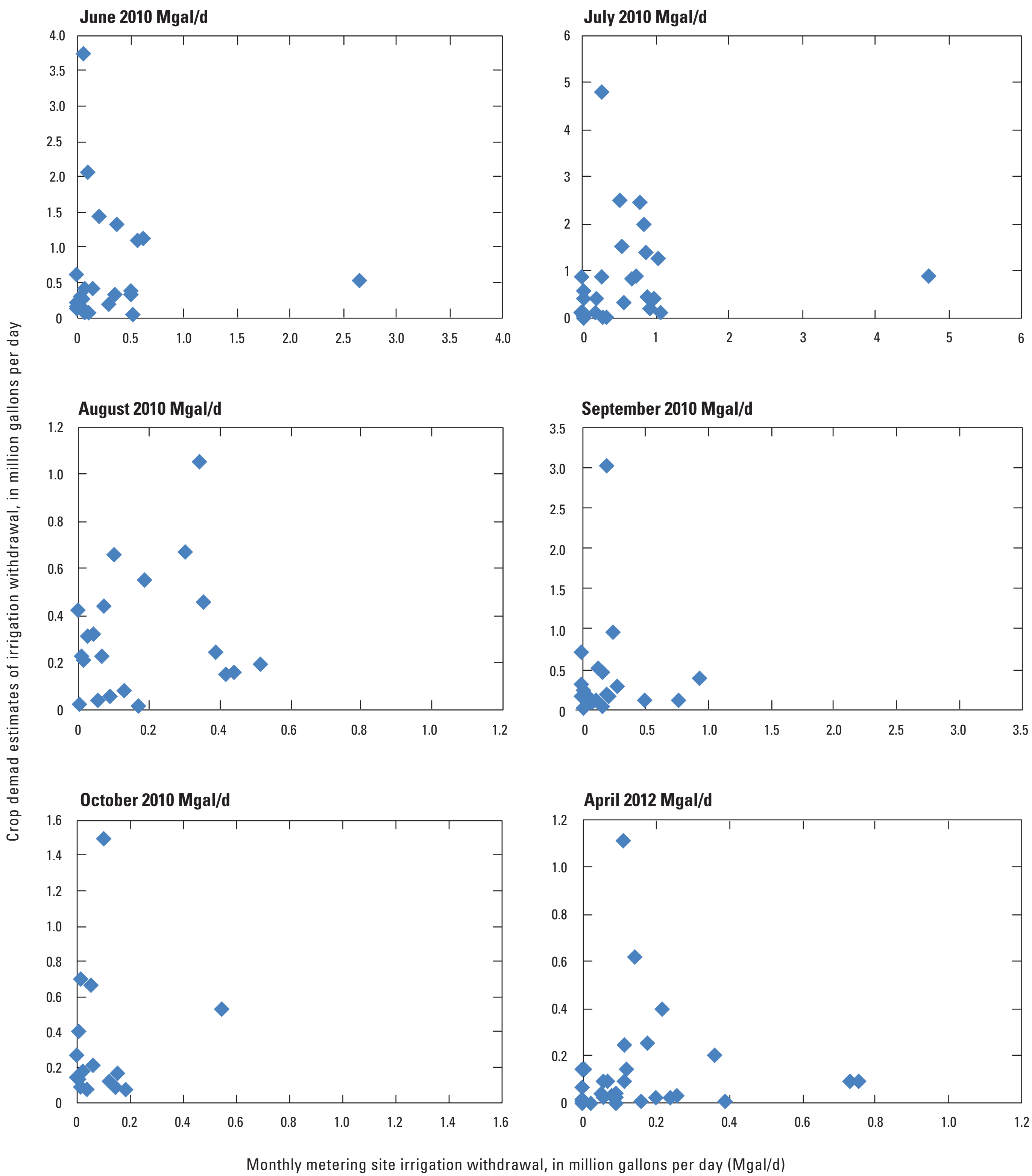

Figure 13. Crop-demand estimates of irrigation withdrawal in million gallons per day compared to corresponding monthly metering site irrigation withdrawal.

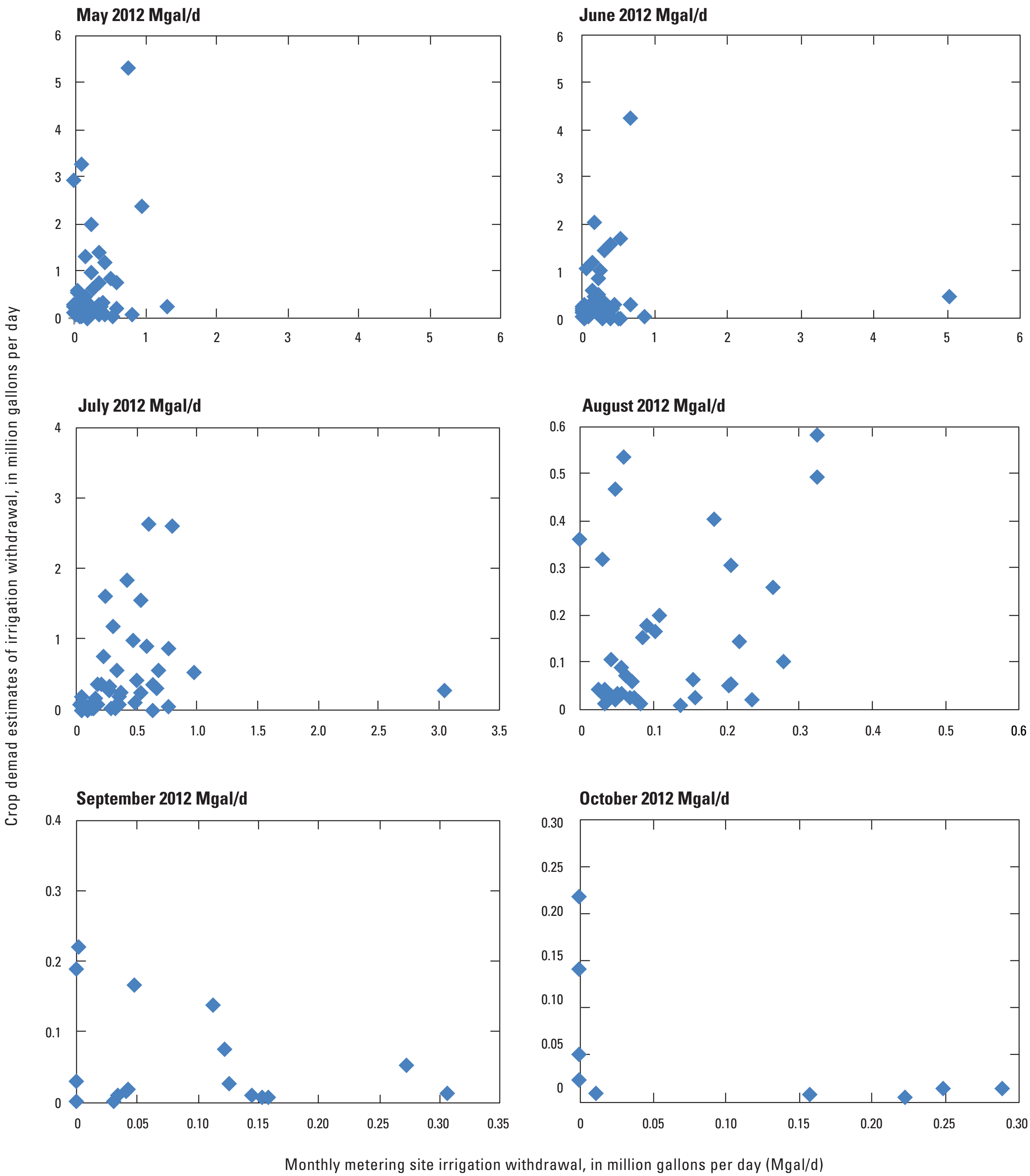

Figure 13. Crop-demand estimates of irrigation withdrawal in million gallons per day compared to corresponding monthly metering site irrigation withdrawal.—Continued

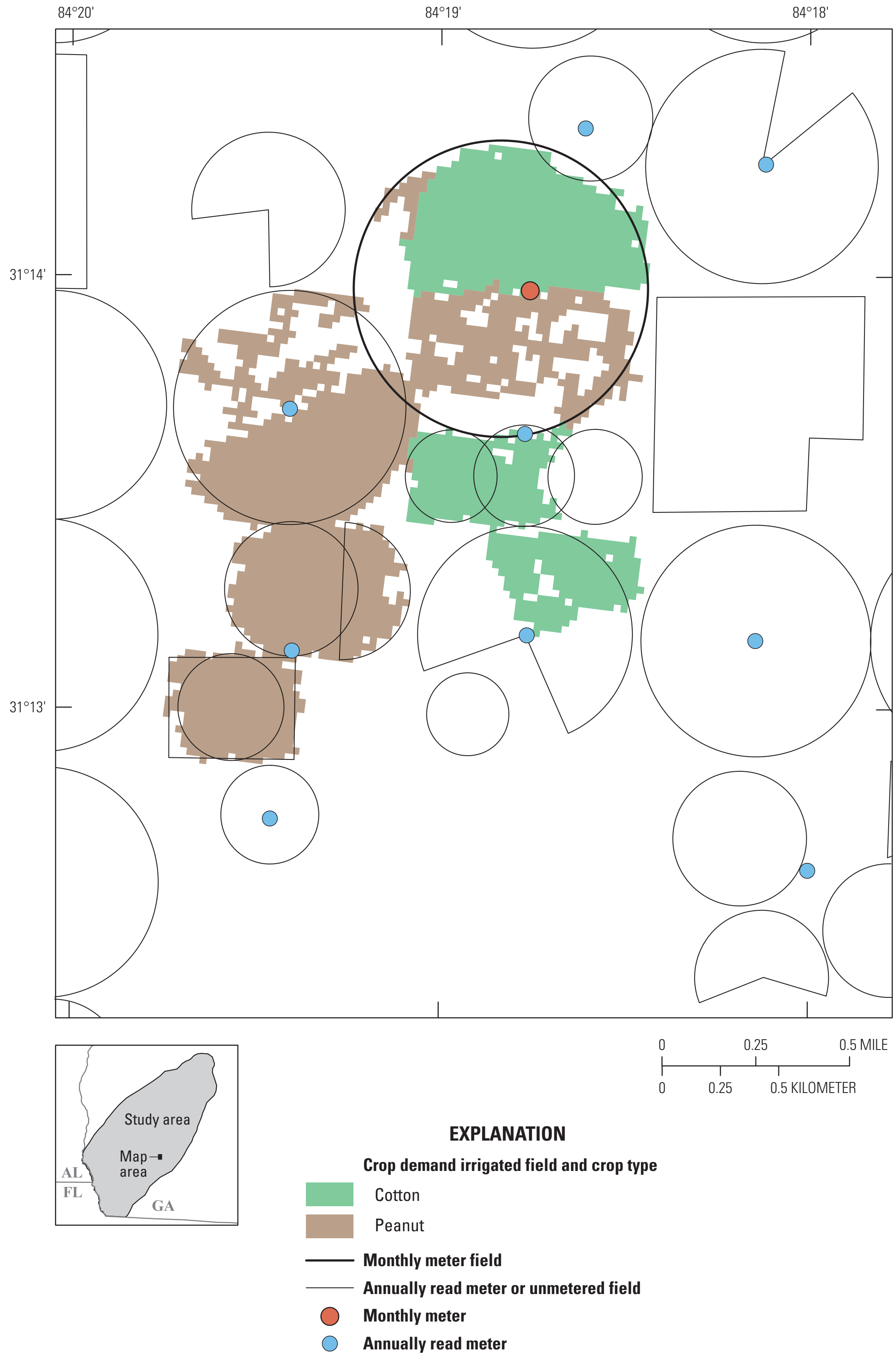

Figure 14. Identified irrigated acres and crop type by the crop-demand method used in the GID calculation at meter sites.

GID calculations (which could include acres associated with annually read meters) with the crop-demand method prohibits direct comparison of the accuracy of the GID at monthly meter sites (fig. 13).

Crop types from the CDL datasets that were used in the development of the crop-demand estimates share little commonality with crop types identified in the meter-network data. Many annual meter sites listed crop-identification information for 2010 and 2012, which was compared with spatially coincident crop information identified by CDL datasets, upon which the crop-demand method relied for crop identification and evaluation of associated parameters for GID calculations. Not all of the meters provided a crop designation; therefore, only a subset of monthly meters containing crop-identification information was included in the assessment of estimation methods. Furthermore, crop-identification information associated with annual meter sites introduced uncertainty into the associations of crop(s) with the monthly meter data, as double or triple cropping during the growing season could not be discerned from crop information at the annual meter sites. Image analysis and meter data confirmed irrigation at some metered fields where crop identification is missing; however, the specific crop or purpose of the irrigation (such as preparation to cultivate or to test irrigation equipment) was unknown. Likewise, the CDL dataset does not provide information on crop changes throughout the year, such as multiple cropping, whereas the crop-demand method relies on crop identification to apply standard crop planting, maturity, and harvesting schedules to determine when to irrigate during the growing season, independent of actual soil or meteorological attributes associated with the field and independent of additional dates for double- or triple-crop planting and harvesting.

Enhancement of Data Requirements for Estimating Irrigation Withdrawal

Enhanced data collection that accurately represents site-specific characteristics of crops, soil, weather, field size, and irrigation systems could improve the accuracy of irrigation-withdrawal estimates by each method. Though these enhancements can improve the consistency and dependability of irrigation-withdrawal estimates by each method, they should be weighed against the data collection effort required by each method to support meaningful water availability and use assessments. Gauging enhanced data collection in the context of the effort required by each method to produce equally meaningful water availability and use assessments will culminate in the selection of methods that provide dependable results with less parameterization (and data requirements) than other methods.

Each of the three methods to estimate irrigation withdrawal in the ACF–FAS described herein depended on accurate identification of one critical parameter—irrigated acres—to estimate irrigation withdrawal. Accurate identification of irrigated acres would, in turn, improve the accuracy of irrigation-withdrawal estimates using the crop-demand method and geostatistical techniques. Accurate estimation of irrigated acres using image analysis could identically and solely enhance estimates of monthly irrigation withdrawal by either geostatistical techniques or the crop-demand method; therefore, enhanced identification of irrigated acres using image analysis would also improve the accuracy of irrigation-withdrawal estimates.

Enhanced identification of irrigated acres through image analysis of National Aeronautical and Space Administration (NASA) Earth observation satellite data, available since this study began in 2011, would provide the single-most-valuable improvement to parameterization of irrigation-withdrawal estimates. Techniques to infill areas obscured by clouds using combinations of Landsat datasets (for example, Landsat 5 and Landsat 7, for retrospective study, and Landsat 7 and Landsat 8, launched on February 11, 2013) could improve understanding of irrigation dynamics and better identify irrigated acres than current image analysis that uses only Landsat 5 data. The Landsat 8 operational land imager (OLI) includes a cirrus band (band 9: 1.360–1.390 micrometers [μm]) to provide better detection and subsequent filtering of high-altitude clouds that could enhance image analysis and the identification of irrigated acres, compared with cloud detection and filtering used on Landsat 5 imagery.

Landsat 8 contains instrumentation for detecting land surface temperature to provide important information about irrigation withdrawal that can inform irrigated acres identification. The Thermal Infrared Sensor (TIRS) measures radiation emitted in two thermal bands of the electromagnetic spectrum. Similar to Landsat 5 120-meter resolution and Landsat 7 60-meter resolution thermal data, the TIRS's 100-meter resolution allows monitoring on a field-by-field basis for agriculture, which is vital for water managers (National Aeronautical and Space Administration Features Web site, accessed at http://www.nasa.gov/topics/technology/features/tirs-thermal.html, on June 18, 2015). A well-callibrated Landsat 8-derived land-surface temperature product, similar to surface reflectance available from Landsat 5, would improve evapotranspiration calculations by reducing error caused by atmospheric effects on the thermal bands.

Enhanced meteorological data to support improved estimation of irrigation withdrawal requires spatial and temporal resolution of crop patterns and climatology that affects evapotranspiration calculations as used in the crop-demand method and image analysis. The NASA Short-term Prediction Research and Transition (SPoRT) Center (National Aeronautic and Space Administration Short-term Prediction Research and Transition Center web site accessed at http://weather.msfc.nasa.gov/sport/, on June 18, 2015) provides a real-time, high-resolution, daily version of the greenness vegetation fraction (GVF), termed "SPoRT-GVF" (Bell and others, 2012), which has the capability to reduce spatial and temporal bias and improve the evaluation of GVF for PRISM modeling. Daily SPoRT-GVF datasets have been produced since June 2010, and are projected on a 0.01° (approximately 1-km) grid, compared with the monthly estimates used in PRISM modeling that are derived from 20-year old climatology at a 15-km resolution. Although SPoRT-GVF can improve evapotranspiration calculations, additional data enhancements to crop- and soil-specific characteristics would further reduce spatial and temporal bias, which affects the accuracy of irrigation withdrawal.

Integration of results from NASA's soil moisture active passive (SMAP) satellite mission with Landsat 8 OLI and TIRS data products could provide detailed analysis of irrigated acres in the ACF–FAS, essential for consistent and dependable assessment of agricultural water availability and use, while informing farmers on the efficient use of water and energy to enhance agricultural production and increase the Nation's and world's food supply (NASA SMAP Mission Description, accessed on March 12, 2015, at http://smap.jpl.nasa.gov/mission/description/). The SMAP satellite mission, launched on January 30, 2015, can provide soil moisture data within 30 centimeters of land surface every 2–3 days on a 3-km grid that can be used to identify irrigated acres.

Detailed analysis of SMAP data through a downscaling process involving thermal infrared (TIR) imagery acquired from low-altitude flights by unmanned aircraft systems (UAS) holds the potential to identify irrigated acres in the ACF–FAS. Research on methods to downscale SMAP soil moisture data to the agricultural field level by using geostatistical techniques applied to UAS-TIR data is expected to identify over- or under-irrigated agricultural land in the lower Chattahoochee-Flint River Basin as part of NASA's SMAP Early Adopter Program to analyze pre-launch SMAP data (Moran and others, 2015).

Summary and Conclusions

The summary and conclusions address the findings of the evaluation and comparison of methods to estimate irrigation withdrawal for the National Water Census focus area study of the Apalachicola-Chattahoochee-Flint River Basin in southwestern Georgia. The focus area study identified methods for the consistent collection and analysis of water supply and use information, which is essential for providing a uniform and dependable national assessment of water availability and use. In this study, gathering and analyzing water supply and use information centered on describing three methods to estimate irrigation withdrawal as prototypes for future adaptation to the National Water Census. Each of the estimation methods were evaluated individually, and compared collectively, in the context of data availability and parameterization, and in the level of technical complexity and scope of data required to meet the goals of the National Water Census program. The evaluation identified time and spatial horizons for data collection that would influence the feasibility of incorporating any of the methods into the national program.

In general, none of the three methods described herein—the crop-demand method, geostatistical techniques, or image analysis—represent a complete turnkey procedure for estimating irrigation withdrawal on any spatial (local or regional) or temporal (monthly or annual) extent. That is, each method would require additional information on agricultural practices during the growing season to constitute a complete process to assess agricultural water availability and use. The evaluation and comparison of these methods for the ACF–FAS are summarized in the following sections and resulted in the conclusions as described herein.

Crop-Demand Method

Accurate estimates of irrigation withdrawal, expressed as the gross irrigation demand (GID) by the crop-demand method requires parameterization of meteorological, crop, and soil type conditions for current or anticipated spatial or temporal horizons that are uniquely suited to each irrigated field. Acquiring such site-specific data represents a time-, labor-, and cost-intensive effort. To alleviate this intractable task of data collection, standard reference values for meteorological and agronomic parameters were used to produce only general estimates of GID. Accurate estimates of irrigation withdrawal would require site-specific evaluation of these parameters throughout the growing season.

Standard reference conditions for calculating GID rarely exist in nature; however, estimation of GID by using standard methods was assessed for the National Water Census to determine the value of irrigation-withdrawal estimates calculated by the crop-demand method with readily available, non-site-specific meteorological and agronomic data. Moreover, it is because of the extreme meteorological conditions and agronomic diversity in soils and crop patterns present in the ACF–FAS that this pilot study for the National Water Census was completed; that is, to further identify methods that accurately estimate crop water demand and irrigation withdrawal beyond the general estimates provided by standard reference methods.

Use of standard reference values for parameters that govern GID calculations prevents the crop-demand method from providing a dependable assessment of agricultural water availability and use in the ACF–FAS or in the National Water Census. The value of these general estimates of GID lies in their ability to be compared universally with GID estimates that are calculated for similar agricultural practices worldwide. The crop-demand method is best applied during a post-agricultural, seasonal determination of irrigation withdrawal, compared with potential applications of the method that would provide near-term (real-time) estimation of irrigation withdrawal throughout the growing season.

Geostatistical Techniques

Geostatistical techniques were used to estimate irrigation withdrawal with minimal parameterization—only data defining the volume of applied irrigation and corresponding irrigated acres were required for estimating irrigation withdrawal. The ability of geostatistical techniques to generate consistent and dependable agricultural water availability and use in the ACF-FAS depended largely on accurate and complete temporal distributions of metered irrigation volume and irrigated acres associated with metered and non-metered agricultural fields. Judicious selection of irrigation sites for a monitor (or meter) network, based on the application of geostatistical techniques, would yield accurate, spatially and temporally relevant irrigation withdrawal data, and provide the basis for geospatial models to estimate irrigation withdrawal in a dependable national assessment of agricultural water availability and use for the ACF–FAS and the National Water Census.

Knowledge of the patterning and amount of irrigation withdrawal from a spatially and temporally representative monitor network, made possible through geostatistical analysis, can contribute valuable insight toward creating a uniform and dependable national assessment of agricultural water availability and use, and can assist water managers and scientists alike in developing future resource development and conservation strategies. Geostatistical techniques contain the analytics to design spatially and temporally relevant monitor networks that integrate correlation structures of data sites into a network for collecting unbiased, irrigation volume and acres information. Similarly, network data are analyzed in a geostatistical framework consistent with the techniques used in network design; that is, conditional simulation and variance analysis, thereby producing a consistent and uniform process to assess water availability and use, and to evaluate estimation accuracy in a spatial and temporal context.

Image Analysis

Image analysis integrated public domain, spatially and temporally referenced, Landsat 5 imagery and meteorological data into a multistep process of mathematical modeling that yielded representations of irrigated land for assessing irrigation withdrawal for the ACF-FAS. Inconsistencies in spatial and temporal Landsat 5 imagery, caused by atmospheric interference and limitations related to satellite image acquisition, limited the image analysis method to produce accurate and dependable estimates of irrigation withdrawal to meet the goals established for the National Water Census.

Emerging satellite-data products, such as Landsat 8 and SMAP, and techniques for data analysis, such as NASA's SPoRT-GVF, have the potential to generate high spatial-resolution distributions of irrigated-acres at temporal frequencies compatible with the goals of the National Water Census. Advancements in image analysis such as these have the potential to alleviate current hindrances to optical imaging caused by haze and clouds, and to provide valuable insight regarding detailed recognition of the spatial variability of irrigation in the midst of varying climatic conditions.

References Cited

Allen, R.G., Periera, L.S., Raes, D., Smith, M., 1998, Crop evapotranspiration—Guidelines for computing crop requirements: Rome, Italy, FAO, Irrigation and Drainage Paper No. 56, 300 p.

American Society of Civil Engineers Task Committee on Geostatistical Techniques in Geohydrology, 1990, Review of geostatistics in geohydrology—I. Basic concepts: Journal of Hydraulic Engineering, v. 116, no. 5, p. 612–632.

Bell, J.R, Case, J.L., LaFountaine, F.J., and Kumar, S.V., 2012, Evaluating the impacts of NASA/SPoRT daily greenness vegetation fraction on land surface model and numerical weather forecasts: 16th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, New Orleans, La., p. 22–26.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground water development of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–C, 80 p.

Daly, Christopher, and Gibson, W., 2002, 103-Year high-resolution precipitation climate data set for the conterminous United States: Corvallis, Ore., The PRISM Climate Group, accessed March 11, 2015, at http://prism.oregonstate.edu.

Daly, Christopher, Gibson, W., Doggett, M., and Smith, J., 2011, Near-real-time monthly high-resolution precipitation climate data set for the conterminous United States: Corvallis, Ore., The PRISM Climate Group, accessed March 11, 2015, at http://prism.oregonstate.edu.

Esri, Inc., 2013, Environmental Systems Research Institute, Inc., release 10.2, accessed March 11, 2015, at http://www.esri.com.

Fanning, J.L., 2007, Consumptive water use—A critical component of Georgia's comprehensive statewide water-management plan—Proceedings of the 2007 Georgia Water Resources Conference, March 27–29, 2007, The University of Georgia, Athens, Georgia.

Georgia Automated Environmental Monitoring Network, Monitoring Network Historical Data, 2015: accessed February 24, 2015, at http://georgiaweather.net.

Georgia General Assembly, 2003, House Bill 579 (as passed House and Senate), accessed September 8, 2015, at http://www.legis.ga.gov/Legislation/20032004/27094.pdf.

Harrison, K.A., and Hook, J., 2005, Status of Georgia's Irrigation System Infrastructure—Proceedings of the 2005 Georgia Water Resources Conference, April 25–27, 2005: University of Georgia, Athens, Georgia.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345–354, accessed March 11, 2015, at http://www.mrlc.gov/.

Howell, Terry A., 2003, Irrigation efficiency, *in* Stewart, B.A and Howell, T.A., eds., New York, N.Y., Marcel-Dekker, Inc., Encyclopedia of Water Science, p. 467–472.

Jones, L.E., and, Torak, L.J., 2006, Simulated effects of seasonal groundwater pumpage for irrigation on hydrologic conditions in the lower Apalachicola–Chattahoochee–Flint River Basin, southwestern Georgia and parts of Alabama and Florida, 1999–2002: U.S. Geological Survey Scientific Investigations Report 2006–5234, 83 p.

Journel, A.J., and Huijbregts, C.J., 1989, Mining geostatistics: New York, N.Y., Academic Press, 600 p.

Matheron, Georges, 1971, The theory of regionalized variables and its applications: Paris, France, École Nationale Supérieure des Mines de Paris, no. 5, 211 p.

Martin, D.L., and Gilley, J.R., 1993, National Engineering Handbook, Part 623, Chapter 2: Irrigation Water Requirements, 302 p.

Moran, S.M., Doorn, Bradley, Escobar, Vanessa, and Brown, Molly, E., 2015, Connecting NASA science and engineering with earth science applications, Journal of Hydrometeorology, v. 16, p. 473–483, accessed March 11, 2015, at http://journals.ametsoc.org/doi/pdf/10.1175/JHM-D-14-0093.1.

National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2015: Climate Data Online database: accessed February 24, 2015, at http://www.ncdc.noaa.gov/cdo-web.

Patwardhan, A.S., J.L. Nieber, and E.L. Johns, 1990, Evaluation of effective rainfall estimation methods: Journal of Irrigation and Drainage, American Society of Civil Engineers, v. 116, no. 2, p. 182–193.

Robertson, G.P, 2008, GS+: GeoStatistics for the Environmental Sciences, Version 9: Plainwell, Mich., Gamma Design Software, LLC, 179 p.

Smajstrla, A.G., 1990, Technical Manual: Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) Model, Version 5.5: St. Johns River Water Management District Special Publication SJ2008-SP17.

Torak, L.J., and Painter, J.A., 2006, Geohydrology of the lower Apalachicola-Chattahoochee-Flint River Basin, southwestern Georgia, northwestern Florida, and southeastern Alabama: U.S. Geological Survey Scientific Investigations Report, 2006–5070, 80 p.

Torak, L.J., and Painter, J.A., 2011, Summary of the Georgia Agricultural Water Conservation and Metering Program and evaluation of methods used to collect and analyze irrigation data in the middle and lower Chattahoochee and Flint River basins, 2004-2010: U.S. Geological Survey Scientific Investigations Report 2011–5126, 35p.

Torak, L.J., and Painter, J.A., 2013, Geostatistical estimation of growing season irrigation rates using monthly metered data, middle-to-lower Chattahoochee-Flint River Basin, Southwestern Georgia., *in* Clarke and Dalton (compilers), Hydrologic monitoring and selected hydrologic and environmental studies by the U.S. Geological survey in Georgia, 2011-2013: U.S. Geological Survey Open-File Report 2013–1278, p. 63–68.

U.S. Department of Agriculture, National Agricultural Statistics Service, Cropland Data Layer, National CDL's for years 2008, 2009, 2010, 2011, and 2012: accessed February 24, 2015, at http://www.nass.usda.gov/research/Cropland/Release/index.htm.

United States Department of Agriculture, Soil Conservation Service, 1970, Irrigation water Requirements: Technical Release No. 21, (revised 1970) 88 p.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, Soil Survey Geographic (SSURGO) Database: accessed February 24, 2015, at http://sdmdataaccess.nrcs.usda.gov/.

Van Rossum, G., 2009, The Python Language Reference, Release 2.6.3: Python Software Foundation, 111 p. [Also available at https://docs.python.org/2/reference/.]

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