Design of a Shallow Ground-Water Network to Monitor Agricultural Chemicals, Lake Wales Ridge, Central Florida

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 00–4134

Prepared in cooperation with the
FLORIDA DEPARTMENT OF AGRICULTURE AND CONSUMER SERVICES

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By A.F. Choquette *and* Agustín A. Sepúlveda

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Tallahassee, Florida
2000

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Acronyms and Abbreviations

BMP	Best Management Practices
DACS	Florida Department of Agriculture and Consumer Services
DOH	Florida Department of Health
EDB	ethylene dibromide
FDEP	Florida Department of Environmental Protection
GIS	Geographic Information System
IFAS	Institute of Food and Agricultural Services (of the University of Florida)
IWRM	Integrated Water Resources Monitoring Program (of the FDEP)
NAWQA	National Water-Quality Assessment Program (of the USGS)
PVC	polyvinylchlroride
PTFE	polytetrafluouroethylene
SFWMD	South Florida Water Management District
SWFWMD	Southwest Florida Water Management District
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VISA	Very Intense Study Areas (of the FDEP)
ft	foot
in.	inches
mi^2	square mile
mg/L	milligrams per liter
µg/L	micrograms per liter

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Executive Summary

Extensive agricultural land use and dynamic hydraulic connections between the land surface and ground-water resources render many of Florida's aquifers vulnerable to chemical contamination. In these areas, there is a need to monitor shallow ground water for agricultural chemicals to evaluate potential migration of the chemicals to the subsurface and to deeper aquifers, and to assess the effects of agricultural practices on ground-water quality. Historically, efforts to monitor water-table aquifers have been minimal compared with monitoring deeper aquifers used for municipal drinking-water supply. The Florida Department of Agriculture and Consumer Services has proposed the establishment of long-term, water-quality networks to monitor shallow ground water in agricultural areas of Florida. These networks will bridge the current information gap between local-scale short-duration field studies, which are required for pesticide licensing, and statewide monitoring of deeper ground-water resources. Laboratory (experimental) and short-term field evaluations of the transport of agricultural chemicals to the subsurface contain some degree of uncertainty due to widespread variations in environmental conditions. The proposed regional-scale shallow ground-water networks will serve as "early warning" networks to avoid contamination of ground-water resources.

The objectives of these shallow ground-water networks are to provide information for early detection of pesticides and nitrate in the subsurface, and for evaluating temporal trends in concentrations in relation to changes in land use and agricultural practices. Information on trends is important to the U.S. Environmental Protection Agency, State agencies, and agricultural managers, and is an integral part of Florida's Pesticide Management Plan, which evaluates the effectiveness of implementing "best management practices" to minimize environmental impacts.

Lake Wales Ridge in Polk and Highlands Counties has been identified by the Florida Department of Agriculture and Consumer Services as a pilot study area for implementing a regional shallow ground-water network. Information gained from designing the Lake Wales Ridge Network will be used to develop plans as similar networks are considered for other areas of Florida. Lake Wales Ridge is heavily utilized for citrus production, but the well-drained, clean sands underlying the region, coupled with a hydraulic connection with deeper karst formations, render the area extremely vulnerable to the transport and migration of agricultural chemicals within the subsurface.

The network design for Lake Wales Ridge was developed on the basis of the objectives of monitoring, factors affecting aquifer vulnerability, probability (statistical) sampling theory, and specifications regarding well construction, sampling, and laboratory analysis. The network will provide estimates of regional pesticide and nitrate concentrations in targeted ground water, monitor for trends over time, and will provide baseline, regional-scale information. The areas targeted for sampling were citrus groves located on soils classified as vulnerable to leaching of agricultural chemicals, and ground water in close proximity to the water table. The duration of monitoring is planned to be long term.

Chemicals targeted for monitoring include selected nutrients, trace elements, and pesticides used for citrus management. Standardization of field sampling and laboratory methods, and construction of a computerized data-base repository will be important for long-term utility of the data.

The proposed network design consists of existing and newly drilled wells. Existing wells were evaluated as candidates for the network based on location and well-construction specifications for water-quality monitoring. Using probability selection techniques, new well locations were selected in areas that lacked adequate existing wells. Implementation of the network will occur in phases. Quarterly sampling of 13 Phase I wells commenced in April 1999. An additional 11 Phase II wells were added to the network in April 2000. Proposed locations have been identified for 8 Phase III wells.

Future topics for study include a regional water-quality analysis, a network design evaluation, and consideration of local-scale studies needed to support regional monitoring efforts. An analysis of historical water-quality data for Lake Wales Ridge, including Phase I wells, is needed for the purpose of examining trends, providing a preliminary description of spatial and short-term variability in water quality, and evaluating the proposed network design for cost effectively meeting program objectives. Local-scale, process-oriented studies are needed to provide important information for evaluating regional water-quality data. Coordination between individuals conducting such local-scale studies and those interpreting regional sampling results will be considered as a component of the network design, and will require coordination between multiple agencies.

INTRODUCTION

Ground water in many areas of Florida is susceptible to contamination by pesticides and nitrates due to a combination of land use, soils, and hydrogeology. Agriculture is widespread and commonly situated on well-drained sandy soils having low organic content and a limited capacity for filtering contaminants from waters recharging underlying aquifers. In addition, many of the primary drinking-water aquifers have direct hydraulic connections with the land surface, which in many areas is the result of karst development and associated subsurface solution of underlying limestone formations.

The Florida Department of Agriculture and Consumer Services (DACS) is charged with managing the use of agricultural chemicals in the State of Florida. In support of this mandate and as part of the State's Pesticide Management Plan to protect ground-water resources, DACS is interested in evaluating the potential transport of chemicals from agricultural lands to the subsurface environment. DACS has implemented a registration review system to evaluate the leaching potential of specific pesticides. This review system includes detailed monitoring of subsurface water at selected field sites (Florida Department of Agriculture and Consumer Services, 1995). Because these field studies must be limited in duration and areal extent, a long-term regional network focused on shallow ground water can provide important additional information, especially for vulnerable areas of the State. Traditionally, long-term regional monitoring of ground-water quality has focused primarily on deeper aquifers tapped for public-water supplies as opposed to shallower water-table aquifers that are more susceptible to contamination.

The Florida Department of Agriculture and Consumer Services is interested in establishing monitoring networks that will focus on water quality in shallow aquifers to bridge the knowledge gap that currently exists between short-term site-specific studies and long-term regional monitoring of public-supply aquifers. As conceived, these planned networks will be located in selected areas statewide and will serve as "early warning" for potential pesticide and fertilizer (nitrate) contamination, as well as will provide information on the current status of shallow ground-water conditions subjected to changes in agricultural practices. Information from the networks will assist DACS to register pesticides and control their usage; design the Pesticide Management Plans as mandated in a rulemaking proposal by the U.S. Environmental Protection Agency (USEPA) (George Wiegand, DACS, written commun., 1999); and implement nutrient and irrigation practices adopted as "best management practices" by the DACS nitrogen and pesticide Best Management Practices Program. The information on trends is important to the USEPA, State agencies, and agricultural managers for evaluating the effectiveness of implementing "best management practices" to minimize environmental impacts.

Lake Wales Ridge, a physiographic feature in central Florida, was selected as the first area for implementing the DACS early warning networks. The Ridge is one of the most intensively cultivated citrus regions of the State, and is underlain by soils that are highly susceptible to leaching of contaminants. Ground water is the principal source of water supply in the area, typical of most regions in Florida. A number of government agencies have constructed ground-water monitoring wells in the vicinity of the Ridge. However, there is presently no integrated regional network focused on long-term sampling for nitrates and pesticides in the shallow ground water.

Results of a national survey indicate that pesticides, particularly herbicides and insecticides, are applied more heavily in citrus areas than in many other types of agriculture (Brandt, 1995). In this survey, citrus was ranked first out of 37 classes of treated crops and turf grasses in herbicide application in terms of pounds of active ingredient per acre (710 pounds per acre annually). This evaluation also indicated that nationwide about 86 percent of citrus cropland is treated with herbicides; citrus ranked 3rd of 33 in annual insecticide use, and 16th of 30 in fungicide use (Brandt, 1995; Barbash and Resek, 1996). However, the amounts of pesticides applied in citrus groves can vary greatly depending on geographic region, fruit variety, and intended market.

A summary of agricultural pesticide usage and crop acreage in Florida was compiled by Shahane (1999). Florida produces 70 percent of the Nation's citrus, 25 percent of the sugar, and nearly 10 percent of the vegetables. In 1998, a total of 800,000 acres of bearing citrus groves existed in Florida (Shahane, 1999).

The Florida Department of Environmental Protection (FDEP) has documented the occurrence of pesticides and high nitrate levels in ground water in the area of Lake Wales Ridge, both in the surficial aquifer system and in the underlying intermediate and Upper Floridan aquifer systems (Ouellette and others, 1998). To date (2000), State and local governments in Florida have allocated substantial resources in response to existing or potential contamination of ground water by agricultural chemicals. In the vicinity of Lake Wales Ridge, millions of dollars have been spent on remedial measures addressing ground-water contamination from the pesticide 1,2-dibromoethane (EDB, ethylene dibromide), banned from agricultural use in 1983. These measures have included the placement of filter systems on private supply wells, long-term monitoring of public and private supply wells, and, in some areas, extending public-water-supply lines to homes previously supplied by private wells. The DACS and FDEP have taken a number of actions to protect ground-water quality in agricultural areas, including the institution of voluntary best management practices for citrus land management; prohibitions, rate reductions, and seasonal restrictions on applications of specific pesticides in designated areas; and restrictions on the application of some pesticides near drinking-water wells.

The Lake Wales Ridge Network will provide information for early response in managing agricultural chemicals locally and throughout Florida, by focusing on shallow ground-water quality in one of the most highly susceptible areas of the State. In addition, in much of the study area the surficial aquifer system is used for private domestic drinking water, and is hydraulically connected with underlying aquifers used for public drinking-water supply. Therefore, water-quality data from the network will also be used to address human health concerns.

Purpose, Scope, and Approach

The purpose of this report is to describe the design framework for the DACS Lake Wales Ridge Network, including considerations for future network development. The approach includes identifying existing water-quality monitoring wells in the study area, determining which of these candidate wells meet specifications for the shallow ground-water network, and locating sites where additional wells are needed. General guidelines for new well construction and data collection are included; however, quality-assurance and quality-control protocols for well drilling and for subsequent water-quality sampling activities will be documented in separate reports.

This study was limited to the surficial aquifer system underlying Lake Wales Ridge in Polk and Highlands Counties (fig. 1). Sampling focused on the zone of water near the water table and areas where the water table is close to land surface to provide information on the early detection of agricultural chemicals entering the aquifer. Existing information on hydrogeology, soils, and land use was used to identify potential sources of nitrate and pesticide contamination. Broad spatial distribution of wells was important to capture the regional variability of factors that potentially influence ground-water quality, such as agricultural management practices (fertilizer and pesticide application, irrigation), soil types, and hydrogeological settings.

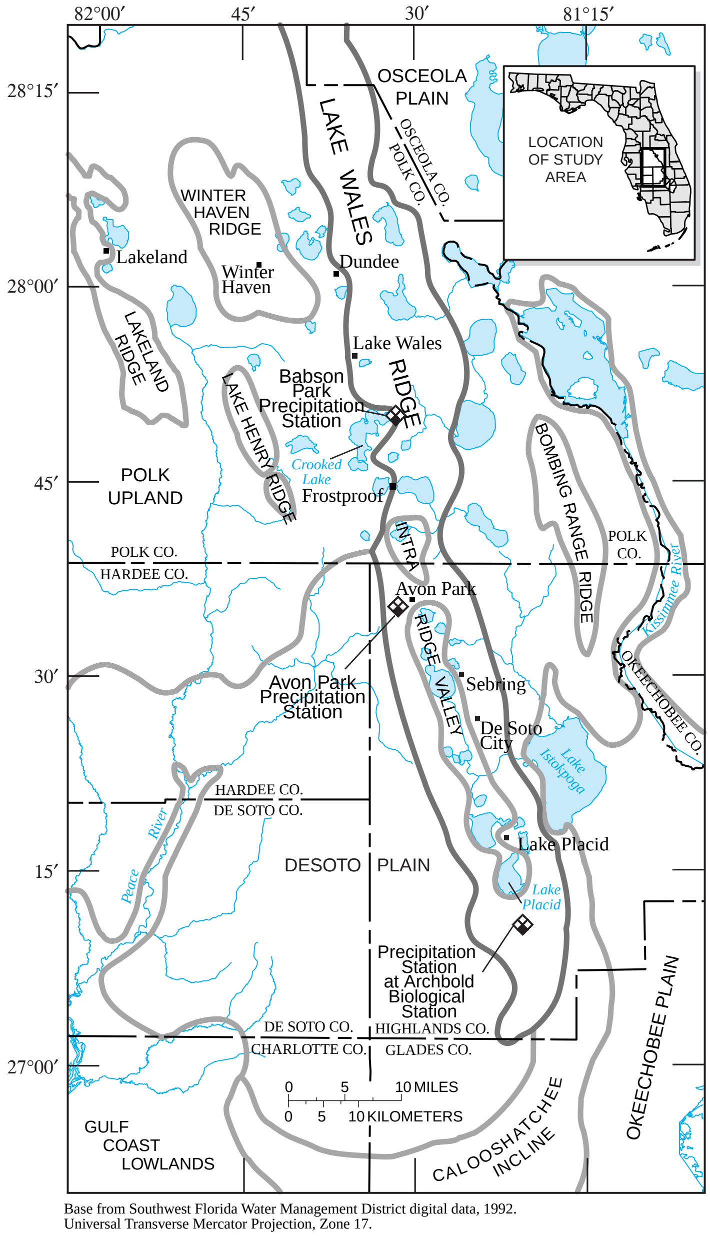

Figure 1. Location and physiography of Lake Wales Ridge and nearby areas. (Adapted from Yobbi, 1996.)

Previous Studies

Ground-water flow and ground-water quality in the vicinity of Lake Wales Ridge have been the focus of several previous studies. These previous investigations include studying the hydraulic connection between underlying aquifers, ground-water flow in the vicinity of the numerous lakes on the Ridge and historical changes in the lake levels, and the occurrence of nutrients and pesticides associated with agricultural land use.

The regional ground-water flow system on Lake Wales Ridge has been described in several reports including Geraghty and Miller, Inc. (1980), Barcelo and others (1990), Barr (1992), and Yobbi (1996). Large declines in lake levels during the 1970's and 1980's, changes in ground-water withdrawals in response to land-use changes, and susceptibility of underlying aquifers to contamination from land-use practices have increased public awareness about ground-water flow in the Ridge area. In 1989, the Southwest Florida Water Management District (SWFWMD) declared a 750-square-mile (mi^2) area, roughly corresponding to the Ridge, as a "water-use caution area" on the basis of declining lake and ground-water levels and increasing ground-water use (Barcelo and others, 1990). In this area, Yobbi (1996) developed a model to simulate ground-water flow that included the surficial and underlying aquifer systems.

Water movement and quality in the lakes on Lake Wales Ridge have been addressed in several studies. Sacks and others (1998) studied the flow between lakes and ground water in 10 lake basins in the vicinity of the Ridge. The flow patterns varied between different lakes and varied with seasonal climatic inputs. Typically, flow gradients surrounding the lakes did not correspond with topography. Local topographic gradients, seasonal climatic conditions, and vertical ground-water gradients between the surficial and underlying aquifers were important determinants of lake/ground-water flow patterns. Ground water underlying citrus groves was enriched in most major ions and nitrate due to fertilizer use which, subsequently, enriched major ion concentrations in the lakes (Sacks and others, 1998). Several hydrologic assessments have focused on lakes, including Lake Istokpoga and Lake Placid (Kohout and Meyer, 1959); Crooked Lake (Bradbury and others, 1978); Lake Buffum and vicinity (Jones, 1978); Lake Jackson (Hammett, 1981); Hamilton Lakes area (Anderson and Simonds, 1983); Lake Placid (Adams and Stoker, 1985); Lake June-In-Winter (Belles and Martin, 1985); and Lake Starr (Swancar and others, 2000).

Historical monitoring of ground-water quality on Lake Wales Ridge has focused less on the surficial aquifer system than on the Upper Floridan aquifer, which is the primary source for public-water supply. Barr (1992) evaluated the potential for ground-water contamination in Polk County and noted general differences between water chemistry in the surficial, intermediate, and Upper Floridan aquifer systems. Areas of intense citrus agriculture were the only areas where land use had a discernible influence on the water quality in the Upper Floridan aquifer. Ouellette and others (1998) and Moore and others (1986) summarized information from two Statewide water-quality networks, the FDEP "Very Intense Study Areas" (VISA) networks and the FDEP Background Network, which included 30 wells (17 and 13 wells, respectively) on Lake Wales Ridge in Polk County. Pesticides were analyzed only in the VISA wells during 1990, 1993, and 1996. All VISA wells tested positive for at least one of the pesticides evaluated in the study. The pesticides detected in more than 50 percent of the 17 wells in the surficial aquifer included: bromacil (94 percent of wells), simazine (76 percent), diuron (53 percent), and norflurazon (53 percent). In addition, pesticides were detected in samples from six of the seven wells tapping the Upper Floridan aquifer. Nitrate concentrations in the FDEP wells were found to be substantially higher in the citrus areas than in the noncitrus areas, and median concentrations were consistently above the drinking-water standard of 10 milligrams per liter (mg/L). Background- and VISA-Network well data were compared to examine differences between water quality in citrus and noncitrus areas. Agricultural chemicals identified in the surficial aquifer system as exceeding the Florida Ground Water Guidance Concentration Limits or the USEPA maximum contaminant limits and requiring corrective actions included nitrate, bromacil, diuron, endosulfan sulfate, and simazine (C. Cosper and others, written commun., FDEP, 2000).

Several other studies have focused on agricultural chemicals in the surficial aquifer on Lake Wales Ridge and in the vicinity of central Florida. The Ridge Nitrate Project, a study in Highlands County conducted by the University of Florida Institute of Food and Agricultural Services (IFAS) in coordination with DACS, is currently evaluating nitrate concentrations at specific 2-foot (ft) depth intervals in the surficial aquifer in relation to specific land-use practices (Graham and Alva, 1996). Monitoring results from the Ridge Nitrate Project indicate statistically decreasing trends in nitrate concentrations in ground water underlying areas where the agricultural best management practices for fertilizer application have been implemented (Graham and Alva, 1996).

Nitrate in shallow ground water in the vicinity of Lake Wales Ridge was evaluated by Tihansky and Sacks (1997), where the highest observed nitrate concentrations (4.9 to 57 mg/L) occurred in citrus land-use areas. Nitrogen-isotope ratios indicated that fertilizer was the probable source of nitrate in ground water underlying these areas. Near DeSoto City in central Highlands County, DACS initiated ground-water monitoring in response to information on local elevated pesticide concentrations. Samples collected by DACS in and near private supply wells tapping the surficial aquifer near DeSoto City contained nitrate concentrations as high as 24 mg/L at depths of 70 to 80 ft, and detections of the pesticides bromacil, simazine, norflurazon, desmethyl, and diuron (George Wiegand, DACS, written commun., April 1997). Results indicated that concentrations of pesticides and nitrate were higher in water-supply wells than in monitoring wells and were higher at deeper intervals (50 to 80 ft) than at shallower depths (10 to 40 ft).

Pesticide and nitrate concentrations in the surficial aquifer underlying citrus areas in north Lake Wales Ridge were evaluated in a land-use comparison study (German, 1996). In these areas, nitrate concentrations commonly exceeded the USEPA maximum contaminant level of 10 mg/L, and bromacil concentrations exceeded 20 micrograms per liter (µg/L) in several wells. The USEPA health advisory level for bromacil is 90 µg/L. Bromacil concentrations as high as 57 µg/L in ground water recharging streams draining the western flank of the Ridge were the highest observed in the 1993-97 nationwide sampling conducted by the U.S. Geological Survey (USGS) National Water-Quality Assessment Program (Berndt and others, 1998). The use of bromacil on vulnerable soils on the Ridge is now prohibited. Agricultural pesticides aldicarb and EDB detected in private domestic-supply wells on the Ridge were documented by the FDEP and evaluated by Choquette and Katz (1989), Miller and others (1989), and Katz (1993).

Several current studies address issues related to ground-water quality on Lake Wales Ridge. Nutrients in Lake Persimmon and Little Lake Jackson are being monitored and studied by the SWFWMD and others (Keith Kolasa, SWFWMD, written commun., June 1998). A detailed hydrologic assessment of Lake Starr in central Polk County was conducted by the USGS (Swancar and others, 2000). Two recently completed USGS studies include an evaluation of nitrate concentrations in shallow ground water in citrus areas underlain by flatwoods soils in east-central Florida in the vicinity of Indian River, Martin, and St. Lucie Counties (Crandall, 2000); and a study of pesticides and nutrients in shallow ground water underlying citrus groves in a flatwoods citrus region south of Lake Wales Ridge and in parts of Glades, Hendry, and Collier Counties (Anne Bradner, USGS, written commun., 1999). Citrus groves in these flatwoods regions are underlain by soils that are more poorly drained and contain more organic matter than the soils on the Ridge. Citrus-management practices also differ between the Ridge and flatwoods regions.

Acknowledgments

This study was performed in cooperation with the Florida Department of Agriculture and Consumer Services (DACS). Lorenzo Freeman, U.S. Geological Survey, assisted in compiling data for existing wells on Lake Wales Ridge. Several individuals from agencies monitoring ground water on Lake Wales Ridge were instrumental in providing well information used in this report: Paul Hansard, Florida Department of Environmental Protection; Eric Dehaven, Jill Hood, Terrie Williamson, Keith Kolasa, and Jim Waylen, Southwest Florida Water Management District; and Carole Milliman, South Florida Water Management District. Assistance and counsel with Dennis Howard, Keith Parmer, George Wiegand, and Daniel Moore of Florida Department of Agriculture and Consumer Services to maintain linkages between the vision of the network and the design concepts is gratefully acknowledged.

Realization of a regional ground-water monitoring network focusing on agricultural chemicals involves a substantial commitment of resources, and for this reason, often requires cooperation and active participation by multiple individuals and agencies. Completion of the Ridge network through Phase II has been achieved through cooperative efforts by DACS, USGS, SWFWMD, and FDEP. SWFWMD drilled and maintained historic water-quality records for most of the Phase I wells, and currently performs sampling of the Phase I and II wells of the Ridge network. FDEP drilled and developed all Phase II wells. The vision and continued commitment of these agencies is required for continuation of the network.

DESCRIPTION OF LAKE WALES RIDGE

The study area (fig. 1) is defined by the Lake Wales Ridge physiographic feature (Brooks, 1981a) within Polk and Highlands Counties and covers an area of 684 mi^2. The Ridge forms the topographic crest and most prominent feature of the Florida Peninsula with altitudes ranging from about 150 to 300 ft above sea level. The southern part of Lake Wales Ridge is composed of two secondary ridges separated by the Intraridge Valley (fig. 1), where altitudes range from about 50 to 100 ft. Lake Wales Ridge forms the surface-water drainage divide between the Peace River Basin to the west, the Kissimmee River Basin to the east (fig. 2), and tributaries to the south that flow into Lake Okeechobee.

Lake Wales Ridge is characterized by numerous surface depressions and lakes, typically formed by dissolution of the underlying limestone and subsequent subsidence of the overlying sediments. Numerous lakes account for about 10 percent of the total Ridge area (Barcelo and others, 1990). Surface stream drainage is poorly developed or absent in most areas, although some surface-water flow occurs between interconnected lakes and along the Ridge’s flanks. Alterations to surface drainage have been made on many of the lakes to facilitate floodwater routing between lakes. Discharge from lakes during recent years, particularly in the upland areas, has diminished as a result of regionally low lake levels (Barcelo and others, 1990; Yobbi, 1996).

Mean annual rainfall in the vicinity of Lake Wales Ridge ranges from about 45 to 51 inches (in.) (National Oceanic and Atmospheric Administration, 1997). Monthly rainfall during June through September exceeds rainfall during other months by about 3 to 4 in. (fig. 3). Localized convective thunderstorms predominate during summer months, in contrast to frontal storm activity during other times of the year. During summer months, variations in local precipitation over short distances can be substantial. Tropical storms or hurricanes, which typically occur between June and December, affect year-to-year variability in rainfall amounts and intensities.

Citrus farming is the dominant land use in the study area (fig. 4), with Lake Wales Ridge being one of the most productive citrus areas of the State. About 24 percent (169 mi^2) of the total land area on the Ridge is planted in citrus (Southwest Florida Water Management District, 1998), with about 55 percent located in Polk County and 45 percent in Highlands County. Citrus acreage on the Ridge in Polk and Highlands Counties represents about 14 percent (787,632 acres) of the total citrus acreage statewide (Florida Agricultural Statistics Service, 1998). In 1995, orange and grapefruit trees made up 93 and 7 percent, respectively, of the citrus for the Polk and Highlands County area, (Shahane, 1999).

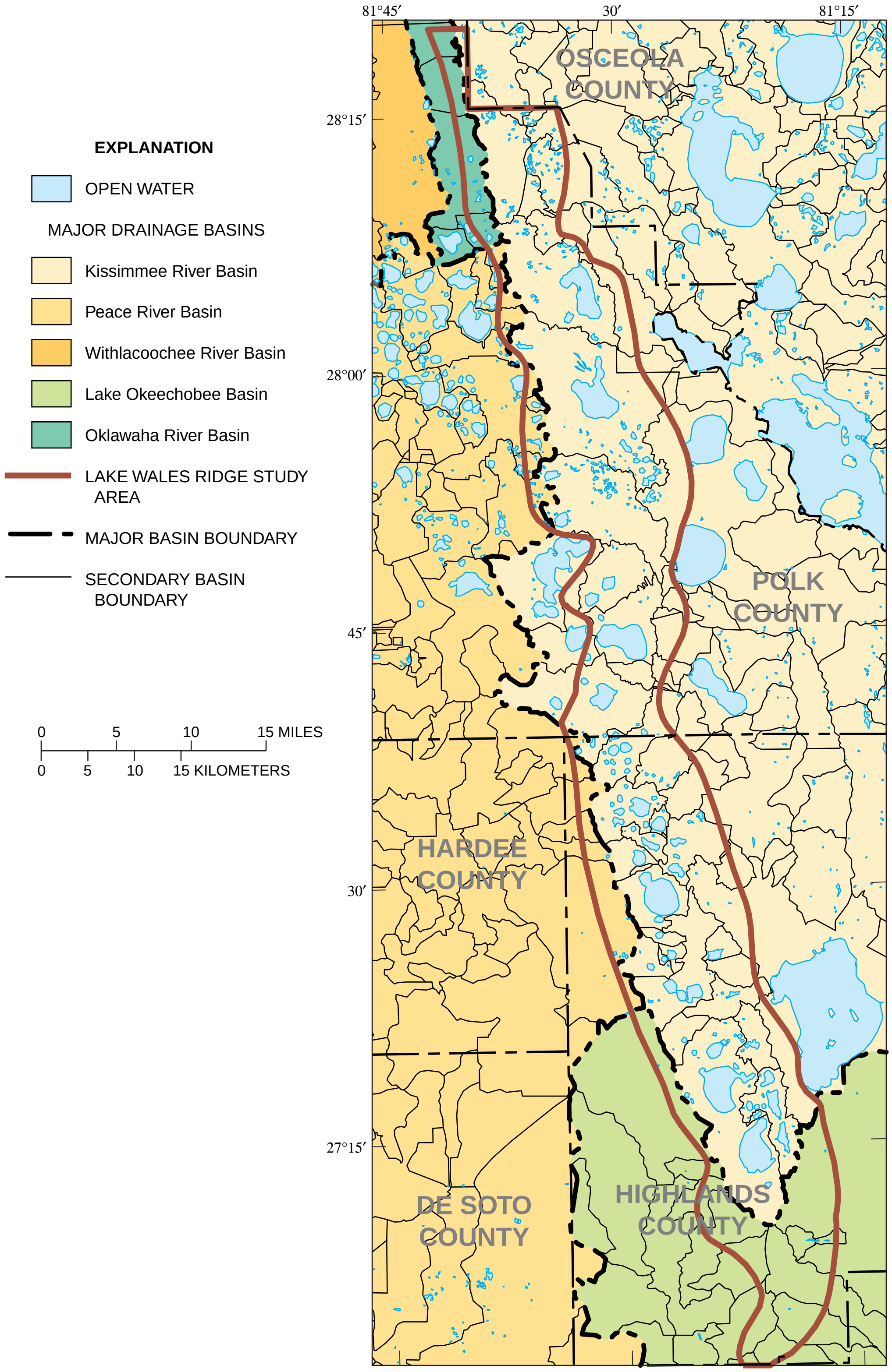

Figure 2. Major surface-water drainage divides on Lake Wales Ridge.

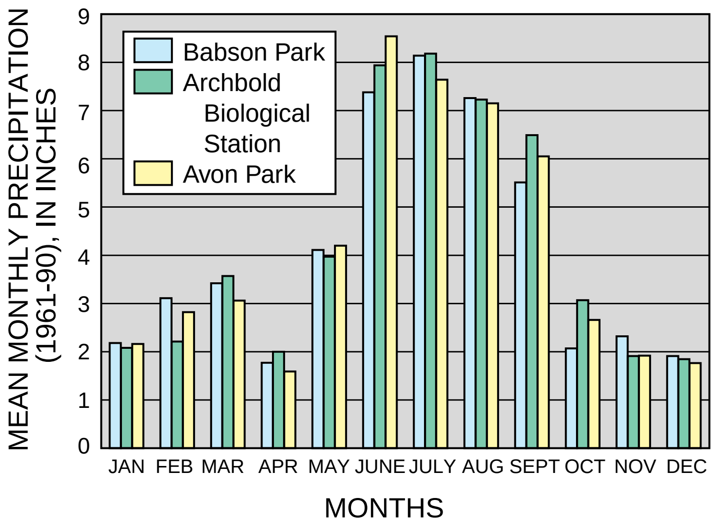

Figure 3. Mean monthly rainfall for selected sites on Lake Wales Ridge. (See fig. 1 for site locations. From National Oceanic and Atmospheric Administration, 1997)

In the late 1960's, citrus land use in Polk County was nearly four times greater than in Highlands County (fig. 5). By 1998, citrus acreage in Polk County was only 25 percent greater than in Highlands County (fig. 5). Between 1966 and 1998, citrus acreage decreased by 68 percent in Polk County and increased by 103 percent in Highlands County (Florida Agricultural Statistics Service, 1998). Winter freezes during 1983, 1985, and 1989, and an increase in urban land use are probable causes for the decrease of citrus in Polk County. Most of the citrus groves in Polk and Highlands Counties are irrigated (93 and 98 percent, respectively) (Florida Agricultural Census Web Page, 1997 data, **http://govinfo.library.orst.edu**).

The hydrogeology of Lake Wales Ridge has been described in several reports (Duerr and others, 1988; Barr, 1992; Yobbi, 1996; Sacks and others 1998). The subsurface of the Ridge consists of a mantled karst terrain where unconsolidated sands and clays overlie an irregular limestone surface. The surficial deposits consist primarily of Pliocene-Pleistocene relict beach and dune sands (fine to coarse grained) interbedded with some clay lenses (Brooks, 1981b).

Lake Wales Ridge is an upland recharge area that is underlain by a surficial aquifer system, intermediate confining unit/aquifer system, and the Upper Floridan aquifer (table 1). Water generally flows from the surficial aquifer to the intermediate and Upper Floridan aquifer systems (Yobbi, 1996). Within the study area, the surficial aquifer ranges from about 50 to 300 ft thick and predominantly consists of sands and clays that thicken from north to south (fig. 6). The surficial aquifer is unconfined, and estimated regional water-table elevations range from about 50 ft to more than 150 ft (Yobbi, 1996).

The water table in the surficial aquifer in the vicinity of Lake Wales Ridge seems to be less affected by topographic gradients than by hydraulic characteristics of the underlying aquifer units (DACS unpublished data, 1998; Sacks and others, 1998). Breaches in the confining unit, seasonal variations in lake levels, local water-table gradients near lakes, and hydraulic head differences between the surficial and underlying aquifer system are factors affecting horizontal and vertical ground-water movement in the surficial aquifer system.

The intermediate aquifer system consists of heterogeneous clay-rich beds that vary widely in lithology, thickness, and hydraulic properties. The intermediate aquifer system, absent in the northern part of Lake Wales Ridge, thickens to more than 500 ft in the southern part of the Ridge (fig. 6). Although the intermediate aquifer system hydraulically separates the surficial aquifer from the Upper Floridan aquifer, the confining unit is commonly breached by sinkholes and subsidence features, particularly beneath lakes (Lee and others, 1991; Sacks and others, 1992, 1998; Evans and others, 1994; and Tihansky and others, 1996).

The Upper Floridan aquifer is a 1,200 to 1,400 ft-thick sequence of limestone and dolomite, and is the most permeable hydrogeologic unit in the study area. The top of the Upper Floridan aquifer is about 100 ft below land surface in the northern part of Lake Wales Ridge and 600 ft below land surface in the southern part (Duerr and others, 1988; Tibbals, 1990). Hydraulic characteristics of the Upper Floridan aquifer vary widely as a result of heterogeneity of the sediments and fracturing and dissolution of the carbonate rocks. Estimated regional recharge rates to the Upper Floridan aquifer on the Ridge range from more than 10 inches per year in northern Polk County to less than 1 inch per year in southern Highlands County (Aucott, 1988). However, significant variations in local recharge rates are likely to occur due to breaching of the overlying confining units.

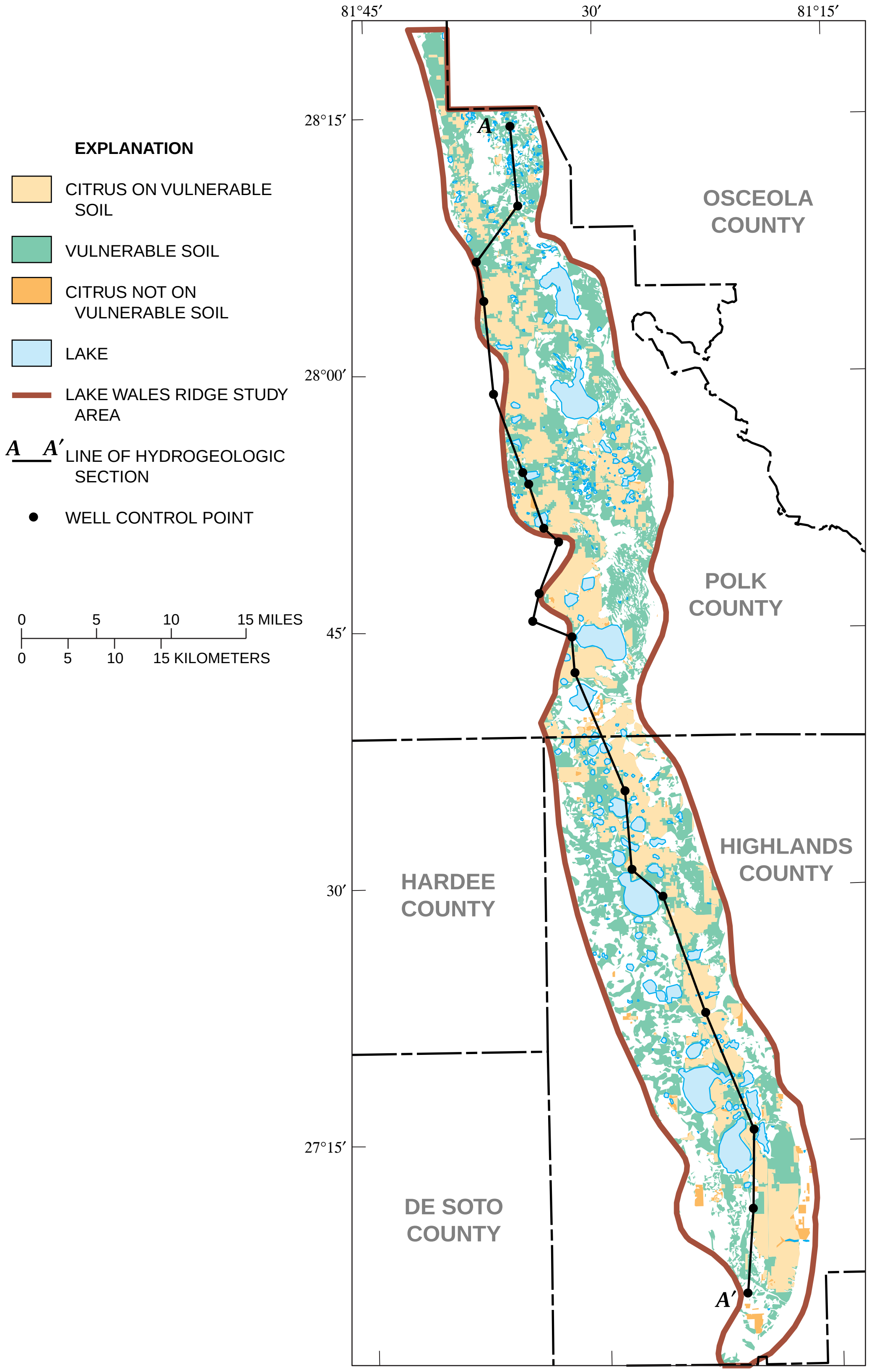

Figure 4. Locations of active citrus groves and soils most vulnerable to leaching on Lake Wales Ridge. Hydrogeologic section appears in figure 6. (From Hooweg and Hornsby, 1998; Southwest Florida Water Management District, 1998.)

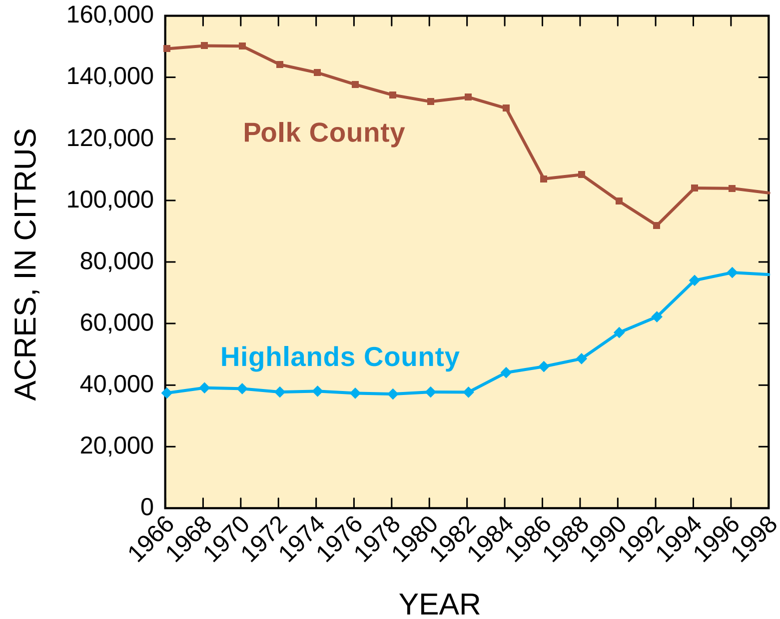

Figure 5. Citrus acreage in Polk and Highlands Counties, 1966-98. (Florida Agricultural Statistics Service, 1966-1998.)

Table 1. Relation between geologic and hydrogeologic units in the vicinity of Lake Wales Ridge

[From Yobbi, 1996]

System	Series	Stratigraphic unit	Major lithologic unit	Hydrogeologic unit	
Quaternary	Holocene and Pleistocene	Surficial sand, terrace sand, phosphorite	Sand	Surficial aquifer system	
Tertiary	Pliocene	Undifferentiated deposits	Sand, clay, and limestone	Intermediate aquifer system	Upper confining unit
Tertiary	Miocene	Hawthorn Group: Peace River Formation	Sand, clay, and limestone	Intermediate aquifer system	“water-bearing units”
Tertiary	Miocene	Hawthorn Group: Arcadia Formation	Sand, clay, and limestone; Limestone	Intermediate aquifer system	“water-bearing units”
Tertiary	Miocene	Hawthorn Group: Tampa Member	Limestone	Intermediate aquifer system	“water-bearing units”; Lower confining unit
Tertiary	Oligocene	Suwannee Limestone	Limestone	Floridan aquifer system	Lower confining unit; Upper Floridan aquifer
Tertiary	Eocene	Ocala Limestone	Limestone	Floridan aquifer system	Upper Floridan aquifer
Tertiary	Eocene	Avon Park Formation	Limestone and dolomite	Floridan aquifer system	Upper Floridan aquifer; Middle confining unit
Tertiary	Eocene; Paleocene	Oldsmar and Cedar Keys Formation	Dolomite and limestone	Floridan aquifer system	Middle confining unit; Lower Floridan aquifer

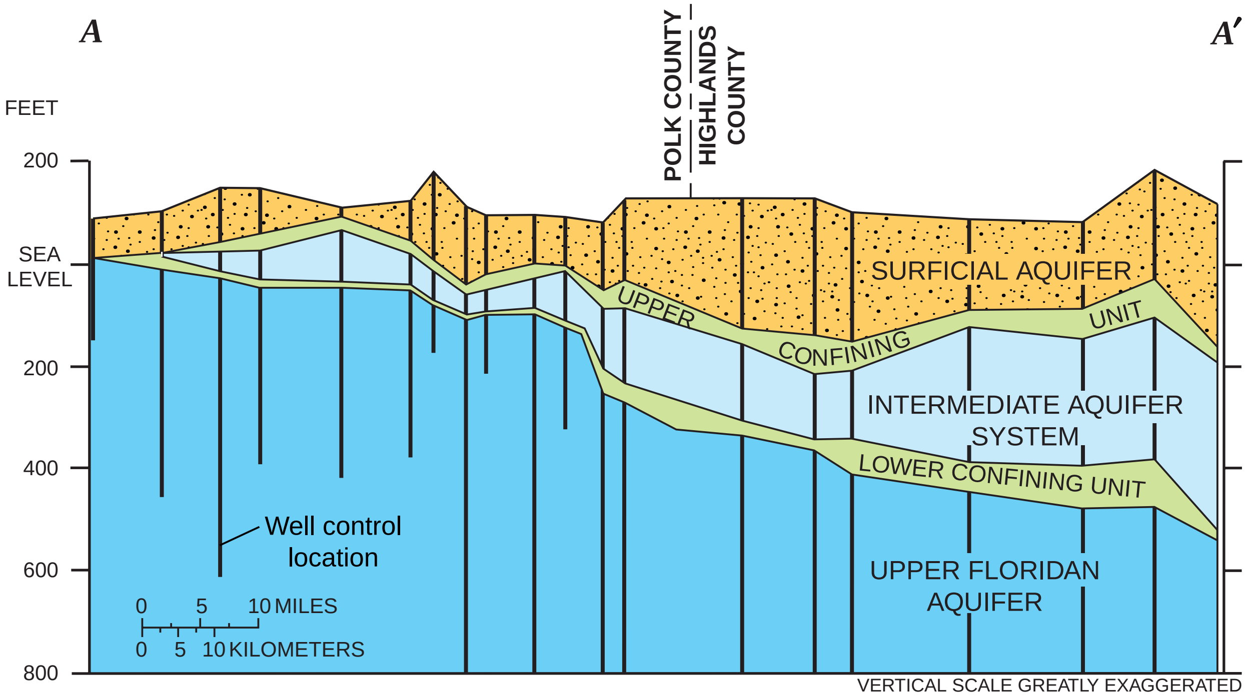

Figure 6. Hydrogeologic cross section trending northwest to southeast along Lake Wales Ridge. Location of section is shown in figure 4. (Modified from Barcelo and others, 1990.)

The Upper Floridan aquifer is the primary source of public-water supply in the study area (Marella, 1997). Although no comprehensive analysis of aquifers supplying domestic water supply on the Ridge is available, analysis of depth data for 800 domestic-supply wells in Polk and Highlands Counties sampled by FDEP indicated that 91 percent of the wells in Highlands County were finished in the surficial aquifer system, and 94 percent of the wells in Polk County were finished in the intermediate and Upper Floridan aquifers.

Agricultural water use is the dominant water use in the vicinity of Lake Wales Ridge. Based on information for permitted water-supply wells on the Ridge, ground-water withdrawals for 1990 totaled 401 million gallons per day (Yobbi, 1996). This total reflects water use for agriculture (68 percent of total), mining (15 percent), public supply (12 percent), recreation (3 percent), and industry (2 percent); private domestic-supply wells were not included, as the data were not available. By aquifer, withdrawals from the Upper Floridan, surficial, and intermediate aquifers were 93, 4, and 3 percent, respectively. Agricultural water use represents 97 percent of the permitted withdrawals from the surficial aquifer on the Ridge, excluding domestic supply (Yobbi, 1996).

Withdrawals for irrigation are highly seasonal and vary annually because of changing climatic conditions. There are about 150 surface-water withdrawal points on Lake Wales Ridge (Barcelo and others, 1990) and about 2,000 permitted ground-water withdrawal wells (James Waylen, SWFWMD, written commun., October 1998). Depth information is available for 91 percent of these permitted wells; however, the aquifer tapped is not specified in the permitting data base.

Well depths and casing depths for the permitted supply wells on Lake Wales Ridge are generally shallower in Highlands County than in Polk County, because depths to the top of the Floridan aquifer are much greater in the southern part of the Ridge than in the northern part (fig. 6). A higher proportion of wells in the southern part of the Ridge tap the shallower surficial and intermediate aquifer systems. About 60 percent of the 716 permitted wells in Highlands County and about 15 percent of the 1,104 permitted wells in Polk County were less than 350 ft deep (fig. 7). This suggests that domestic wells, not included in this data base, are also shallower in Highlands than in Polk County. Based on differences in well depth and differences in confinement of the aquifers tapped, the ground-water supply sources in the southern part of the Ridge may be more susceptible to contamination from land surface than those in the northern part.

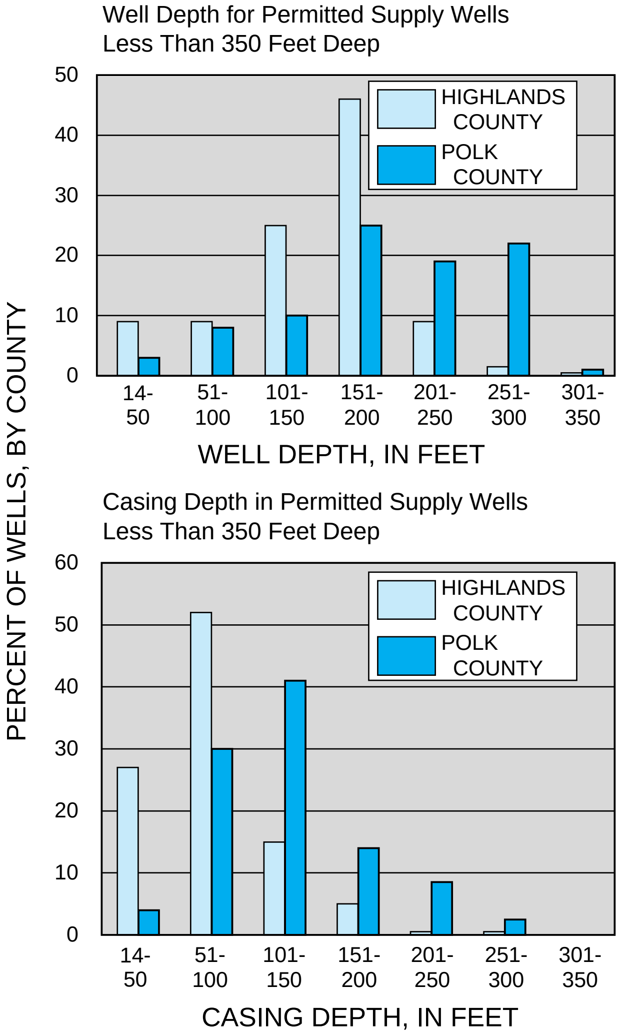

Figure 7. Distributions of well depths and casing depths of permitted water-supply wells less than 350 feet deep on Lake Wales Ridge, by county.

CRITERIA FOR DESIGNING THE NETWORK

The design of the Lake Wales Ridge Monitoring Network was based on consideration of several factors including: the objectives of monitoring, constraints on locations of wells (discussed later in this report), stratification of natural and land-use characteristics affecting probability of ground-water contamination, and probability (statistical) sampling theory. Whenever a subset of sampling points (wells) is to be used to represent a population of interest, in this case ground-water affected by citrus land use on the Ridge, general principles of probability sampling are of critical importance. These principles include clear statements of network objectives, precise definitions of target and candidate populations, and randomized well selection (Alley, 1993).

Candidate wells for the Lake Wales Ridge Network included monitoring wells used for water-quality sampling and observation wells used for measuring water levels. Factors used to eliminate candidate wells from consideration for the Lake Wales Ridge Network included failure to meet well construction requirements; lack of data on well depth, casing depth, or casing material; land use or soil type surrounding the well; and landowner restrictions to access the well for water-quality sampling.

Agencies that have established monitoring wells on Lake Wales Ridge include:

- Florida Department of Agriculture and Consumer Services (DACS),
- Florida Department of Environmental Protection (FDEP),
- Florida Department of Health (DOH),
- Southwest Florida Water Management District (SWFWMD),
- South Florida Water Management District (SFWMD),
- U.S. Geological Survey (USGS), and
- University of Florida Institute of Food and Agricultural Sciences (IFAS).

Information from these and other agencies was compiled to identify existing wells that met pesticide and nitrate sampling requirements and potentially could be included in the network.

Specific data sources and well networks evaluated to identify existing candidate wells on Lake Wales Ridge are shown in table 2. Information describing candidate wells on the Ridge will be useful for future network design refinements. Uses for these supplementary data may include expansion of the network, determination of historical and current water-table elevations and ground-water gradients in the vicinity of network wells, and a basis for comparing records of water-quality at Ridge wells with nearby sites on the Ridge.

Table 2. Existing well networks evaluated to identify candidate wells for the Lake Wales Ridge Network

[DACS, Florida Department of Agriculture and Consumer Services; FDEP, Florida Department of Environmental Protection; SWFWMD, Southwest Florida Water Management District; VISA, Very Intense Study Areas; SFWMD, South Florida Water Management District; FDOH, Florida Department of Health; USGS, U.S. Geological Survey]

Agency and network	Primary function of wells	
	Water quality	Water levels
DACS		
Internal Monitoring (DeSoto City Project)	X	
Contract Projects (Nitrate Monitoring)	X	
Site Investigations for Pesticide Management	X	
FDEP Generalized Water Information System (GWIS) Data Base		
FDEP/SWFWMD VISA & Background Networks	X	
FDEP/SFWMD VISA & Background Networks	X	
FDOH Domestic Well Survey	X	
SWFWMD		
Water-level Observation Network		X
Special Project: Nutrients in Little Lake Jackson and Persimmon Lake	X	X
USGS—National Water Information System (NWIS) Data Base		
Orlando Subdistrict	X	X
Tampa Subdistrict	X	X

Monitoring Objectives

The primary initial focus of the Lake Wales Ridge Network is to provide baseline information on ground-water concentrations of pesticides and nitrates associated with citrus land use throughout the Ridge in Polk and Highlands Counties. These data will be used for the early detection of pesticides transported to ground water and to monitor trends in concentrations of pesticides and nitrate over time. Future design considerations of the Ridge sampling program may include additional objectives, such as delineating contaminated areas, identifying causes of contamination (such as specific land-use management practices), and investigating transport processes of specific contaminants of concern. However, these additional objectives are not part of the baseline network design.

The role of the Lake Wales Ridge Network for nitrate monitoring is to characterize regional concentrations, which are expected to show overall regional declines as a result of implementation of agricultural best management practices. Concurrent research by other scientists and supported by DACS, is focusing on site-specific monitoring of nitrate in ground water related to current and past land-use practices in selected areas on the Ridge, as well as the processes affecting nitrate occurrence and transport (Graham and Alva, 1996; Adair Wheaton, IFAS, written commun., 1999).

The duration of monitoring is expected to be long term (5 years or more), and implementation of the network will occur in a phased approach. Initial sampling of the Lake Wales Ridge Network will focus primarily on providing statistical descriptions of current conditions, seasonal variability and time trends, and guidelines for subsequent sampling needs and network refinement (fig. 8). Subsequent sampling phases and companion studies will provide additional spatial resolution for specific contaminants, and possibly, explanations for observed contamination (fig. 8). For example, other DACS projects in local areas on the Ridge currently include ground-water monitoring near DeSoto City that focuses on the spatial description of pesticides in ground water (George Wiegand, DACS, written commun., 1999), and detailed studies of the distribution of nitrate in shallow ground water related to citrus land-use practices and other factors (Graham and Alva, 1996; Adair Wheaton, IFAS, written commun., 1999).

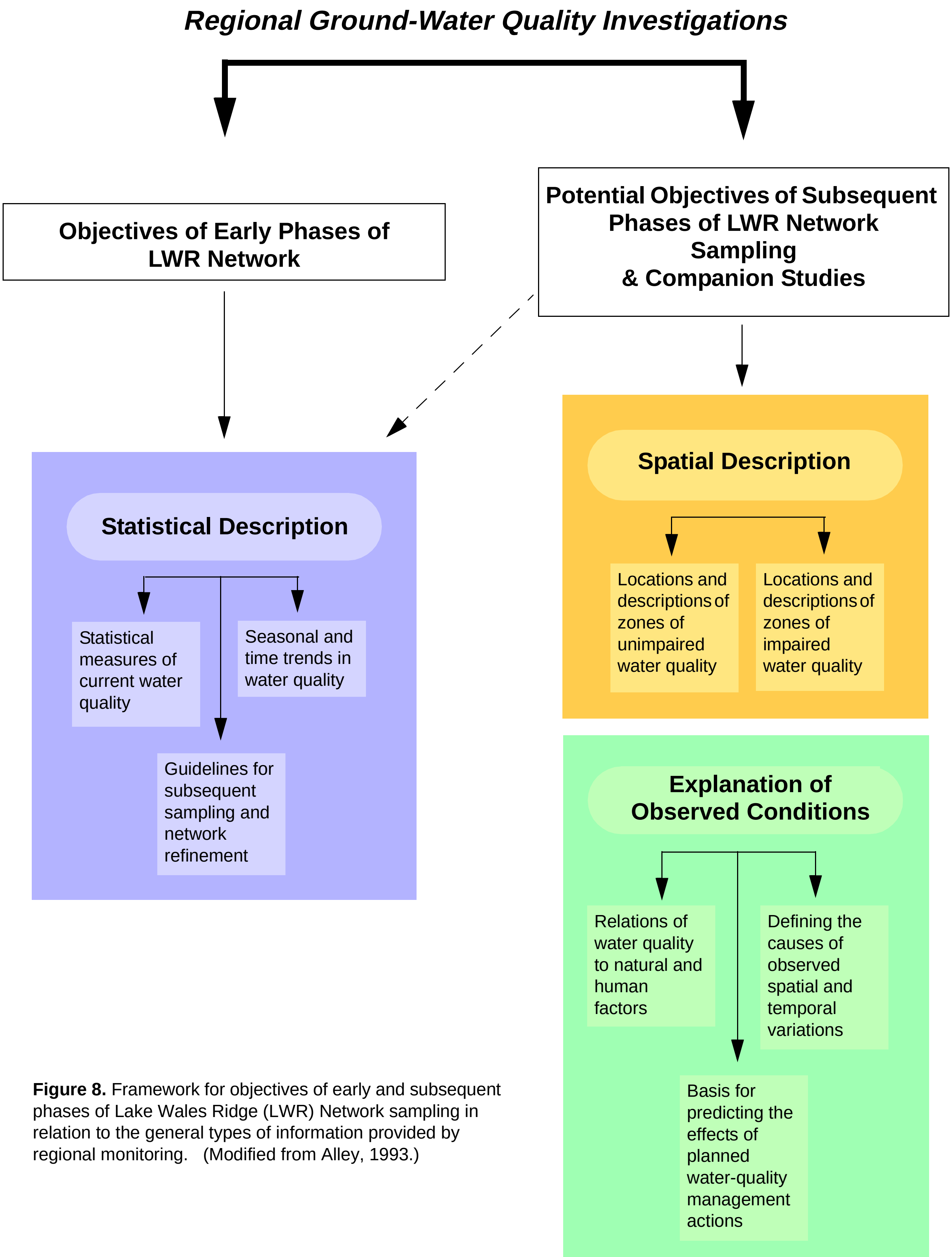

Figure 8. Framework for objectives of early and subsequent phases of Lake Wales Ridge (LWR) Network sampling in relation to the general types of information provided by regional monitoring. (Modified from Alley, 1993.)

Factors Affecting the Transport of Agricultural Chemicals to the Subsurface

Both land-management and natural factors can affect the transport of agricultural chemicals to the subsurface, resulting in both temporal and spatial variations in ground-water quality. Knowledge of these factors is important for both the network design and interpretation of results from water-quality networks.

Climate, soil type, hydrogeology, physiography, properties of agricultural chemicals, and land-use practices can enhance or retard chemical transport (Rao and others, 1985; Hippe and Hall, 1996). Land-use practices include application of agricultural chemicals (chemical properties, amounts, application methods, timing, and frequency) and irrigation (amounts, methods, timing, and frequency), which can vary according to the variety of citrus and the age of groves (Tucker and others, 1995; Shahane, 1999). Theoretical and observed influences of most of these factors are reviewed by Barbash and Resek (1996).

Variations in recharge to the water table, in the form of rainfall or irrigation, can affect the transport of agricultural chemicals to the subsurface, with higher recharge rates promoting chemical transport (Wyman and others, 1985; Schiavon, 1988; Barbash and Resek, 1996). In addition to rainfall, several studies have indicated that variations in temperature may also influence the likelihood of pesticide transport to the subsurface (Barbash and Resek, 1996). Pesticides are more persistent during colder times of the year, because rates of chemical reactions decrease with lower temperatures.

Soil permeability and organic content are of primary importance in controlling the degree to which agricultural chemicals pass from the land surface to ground water (Rao and others, 1985; Barbash and Resek, 1996). Specific soil series on Lake Wales Ridge have been identified (fig. 4) as most vulnerable to leaching of agricultural chemicals on the basis of drainage and organic content (Hoogeweg and Hornsby, 1998).

Variations in ground-water flow rates and flow paths due to differences in topography and lithology, particularly karst features, can affect contaminant transport in the subsurface. Proximity to subsurface karst features in the Upper Floridan aquifer has been shown to affect vertical and horizontal ground-water gradients in the surficial aquifer system (Lee, 1996; Tihansky and others, 1996; and Sacks and others, 1998).

Ground-water flow paths can be important in determining source areas and distance the water has traveled. Depth of the water table below land surface and depth of sampling point below the water table would be expected to affect the occurrence of agricultural chemicals in ground water due to increased traveltime, and dispersion and dilution in the saturated zone, assuming other factors are equal. However, Barbash and Resek (1996) found in the studies they reviewed, that although concentrations generally decreased with depth, few studies found statistically significant relations between concentrations and depth. It is likely that both the range of depths compared and the relatively stronger influence of other factors confound the relation between concentration and depth. Changes in the types of chemicals applied over time, as well as the periodic (versus constant) application of chemicals may result in pulses of chemical concentrations in source waters, which mask depth gradients within the aquifer. Comparison of a large range of depths would be more likely to show differences between different depths. DACS has found an increase in pesticide and nitrate concentrations with depth in 3 years of monitoring 21 nested wells in the vicinity of DeSoto City on Lake Wales Ridge in Highlands County (Wyndham Riotte, DACS, written commun., April 1997).

Increased pumpage rates at monitored wells have been associated with increased detections of pesticides (Baier and Robbins, 1982; Hallberg and others, 1992). Increased pumpage rates also were suspected to be a cause of higher pesticide concentrations in ground water sampled from domestic-supply wells in northeastern Florida (Roaza and others, 1989) and in southern Lake Wales Ridge (Wyndham Riotte, DACS, written commun., April 1997). The frequent or high rates of well pumpage may facilitate the development of preferential ground-water flow paths and accelerate ground-water traveltimes.

Differences in methods of irrigation and in the application of agricultural chemicals can affect the transport of the chemicals to the subsurface (Triano and others, 1990). The likelihood of chemicals migrating beneath a treated area is also dependent on the timing of irrigation and chemical applications relative to the rate of transformation of the compound of interest. Irrigation in citrus groves has many objectives including crop cooling, cold protection, crop fertigation and chemigation, salt leaching, water-table management, crop establishment, field preparation, and soil/dust erosion control (Clark and others, 1993).

Fertigation and chemigation refer to the mixing of fertilizer or pesticides with irrigation waters. Seventy percent of citrus growers in Florida use micro-irrigation systems, which are low water-flow emitting devices that place water on or in the soil beneath each tree. Over half of all growers have irrigation systems designed for delivering pesticides or fertilizer (Ferguson and Taylor, 1993; Smajstrla and others, 1993). In general, irrigation in the study area is highest from March through May—the period when rainfall tends to be lower (fig. 3) and when vegetative growth and fruit production are high. Irrigation can also be high during dry periods in summer months and during cold periods in winter months to combat freezing.

Fertilizer applications are made according to citrus-nutrient needs, which are higher prior to and during periods of increased growth and production between late winter and early summer, and during intermittent warm periods in fall and winter (Tucker and others, 1995). Recommended fertilizer application rates and frequency of application vary according to the age of a grove and the type of fertilizer. Application rates increase as tree size and fruit production increase. Recommended frequency of fertilizer application to young, non-bearing trees is a minimum of 4 to 6 applications for dry fertilizer, and 10 to 30 applications for liquid fertilizer (Tucker and others, 1995). Frequency of application for mature fruit-bearing trees (greater than 4 years old) varies from a minimum recommended rate of 3 times per year for dry fertilizer to more than 10 times per year for liquid fertilizer.

The use of probabilistic sampling methods is critically important for accurately portraying the temporal and spatial variability in water quality for regional studies, and for relating this variability to controlling factors. Incorporating factors that affect water-quality into a probabilistic ground-water sampling design can minimize the number of wells and the frequency of sampling required to meet program objectives and provide a sound scientific framework for subsequent data analyses and interpretations. All of these controlling factors cannot be incorporated directly into the design of the Lake Wales Ridge Network, but are important to consider in evaluating the design for meeting program objectives and for assuring that the design is appropriate for planned data analyses.

Statistical Considerations

A statistical, or probability-based, framework is an important element of any study using selected samples to represent a larger population of interest. In terms of network design, definition of target population is important because each type of target population requires a different set of design choices (Alley, 1993). The objective of early detection of agricultural chemicals for the Lake Wales Ridge Network required defining a “target population” of ground water that was most likely to yield detections of currently used agricultural chemicals. Therefore, factors known or suspected to increase the probability of chemical transport to the subsurface were used to identify the target population of ground water to be sampled.

In defining the target population on Lake Wales Ridge, it was important to minimize the number of sampling points used to obtain estimates of descriptive statistics (such as mean, maximum, and minimum concentrations), time trends, and seasonal variation, and to minimize error in these estimates. Also, it was important to limit sampling to areas where potential sources of agricultural chemicals could be restricted to citrus groves; some agricultural chemicals are used for other types of land-use management in addition to citrus groves.

In a statistical context, probability-based designs, including stratified and systematic sampling, were incorporated into the network design. Probability-based sampling refers to a specific method of random selection. Stratified random sampling involves subdividing a population into nonoverlapping subgroups or “strata,” and randomly sampling within these subgroups for the purpose of obtaining a better estimate of statistical parameters of the population. Systematic sampling is a sample-selection method in which a systematic procedure, with a random starting point, is used to sample at uniform (or “systematic”) temporal or spatial intervals.

When certain conditions are met, stratified and systematic sampling can improve accuracy and precision (uncertainty) associated with statistics describing the distribution of contaminants in the subsurface for a given number of sampling points. These conditions are met when (1) a target population can be subdivided into groups or strata that are internally more homogeneous than the whole, and (2) when the spatial distribution of target analytes is not random (Iman and Conover, 1983; and Gilbert, 1987).

The use of stratified and systematic sampling not only reduces potential biases in accurately representing the targeted population, but also establishes a valid framework for subsequent investigations that compare strata (such as land use) or that expand the target population to include additional strata. For ground-water quality studies, the use of a stratified sampling approach, defined by factors considered to be most important in controlling the occurrence and transport of target analytes, should result in a more efficient monitoring design than that of an unstratified approach.

A systematic sampling approach using a grid pattern is recommended for locating sampling points for ground-water monitoring focused on spatial characterization where contaminants cannot be assumed to occur in a random order (Gilbert, 1987). Systematic sampling with a grid is done by randomly selecting a grid coordinate location and locating sampling sites at grid nodes. Spatial trends in water quality, as opposed to a random distribution, are likely to exist on Lake Wales Ridge. Grove characteristics (such as citrus variety, age, citrus-management practices), as well as environmental factors (such as soil type and hydrogeology) that vary within the study area indicate the potential for spatial trends in ground-water quality.

The timing and frequency of sampling should be determined on the basis of the physical processes known or suspected to affect the occurrence of agricultural chemicals in the subsurface, as well as requirements for statistical analysis. Seasonal application of agricultural chemicals, climatic characteristics, hydrogeological characteristics (such as traveltime), and behavior of the applied chemicals can affect seasonal variation in the transport and fate of chemicals in ground water. Also, comparison of samples representing similar seasons (between years) is important for evaluating long-term trends (Hirsch and others, 1991; Schertz and others, 1991).

Because the first design phase of the Lake Wales Ridge Network is a reconnaissance effort, determining the minimum number of sampling locations for efficiently estimating statistics of interest will not be possible until data are collected and evaluated. Once the data are available from the reconnaissance network, further refinement can be accomplished. Items to consider in refining the network are discussed later in the section “Considerations for Future Investigation.”

Well Construction Requirements

Well construction methods must meet specific requirements for pesticide and nitrate sampling to minimize the possibility of contaminating the ground-water sample, and to ensure that the sample accurately represents the screened zone of the aquifer. Well construction requirements, which were used to evaluate the suitability of existing wells and used to install new wells for the Lake Wales Ridge Network, were followed to minimize potential sample contamination from the ground surface and/or from construction materials. Recommended procedures for well installation and sample collection, which are briefly outlined herein, are documented in detail in Lapham and others (1995), Koterba and others (1995), and Florida Department of Agriculture and Consumer Services (1995). The construction of existing wells should adhere to the recommended guidelines for the installation of new wells as closely as possible.

The preferred drilling method for installing new wells is hollow-stem augering. Prior to drilling, the top 18 in. of soil should be removed to prevent surface materials from entering the borehole. Casing and screen materials should be constructed of polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE), or stainless steel. Casing joints should be flush-threaded eliminating the use of adhesives or glue.

The interior and exterior parts of the drilling equipment should be cleaned prior to installing any wells to remove residues, such as threading lubricants or contaminants that may have collected on the equipment during shipping. Decontaminating drilling equipment reduces the potential for contamination of the bore holes, the pore water at the screened interval, the aquifers, and waters mixed (cross contamination) between wells. All wells should be completed in a manner that ensures that only the aquifer of interest contributes water to the well; the annular space between the well casing and the borehole wall should not become a conduit for water and contaminants.

After completion, a well should be developed to enhance water flow to the well, to remove sediments accumulated during installation, and to provide water that accurately represents the unit of aquifer being sampled. Well development should be documented and provide information regarding the time required to purge the well prior to water-quality sampling. The preferred methods of purging, in order of recommended use, are bailing, mechanical surging, pumping (or overpumping), and backwashing.

Documentation of wells should include information regarding installation and construction; well permitting information; maps depicting the well location; previous site and sampling information, including the location of existing data; written permission of well owner or land owner to sample the well; a description of land use surrounding the well; and photographs of land use in the vicinity of the well. Information on nearby land use should be updated periodically to identify changes that may affect water quality.

Field and Laboratory Methods

In addition to proper well construction, adherence to quality-assurance standards for field and laboratory methods is critical for future comparison and analysis of data from the Lake Wales Ridge Network. Field and laboratory quality-assurance programs, including internal and external laboratory quality-control components, need to be documented and implemented (Alley, 1993; Koterba and others, 1995). Protocols (mandatory) and recommended procedures must be documented to ensure internal consistency between field personnel and between laboratories. The protocols will specify requirements for water-quality sampling and laboratory analysis, including the collection, processing, and handling of ground-water samples.

Consistency between data measurements is required for spatial comparison of water quality and for analysis of trends over time. Field methods used for ground-water sampling and the measurement of field water-quality characteristics (such as temperature, specific conductance, and dissolved oxygen) must be documented and be consistent between wells and between sampling events. Quality-assurance protocols and procedures (for example, Koterba and others, 1995) must be incorporated into each data-collection activity.

Water-quality laboratories have internal protocols and procedures designed to address all analytical techniques, as well as specifications for reporting results. Since more than one laboratory will be analyzing the Lake Wales Ridge samples, information describing which laboratory performed an analysis will be documented for each sample. Furthermore, each laboratory will have a quality-assurance plan that addresses ongoing documentation of laboratory procedures for each water-quality constituent, and includes records of current and past method-detection limits and reporting levels. Changes in methods, detection limits, or reporting levels over time or between laboratories will be important for data interpretation, particularly for trend analysis and comparing results originating from different laboratories.

LAKE WALES RIDGE NETWORK DESIGN

The Lake Wales Ridge Network design objectives required identifying and targeting ground water most susceptible to contamination. Part of the network design was based on incorporating existing monitoring wells into the network, provided these wells met design specifications. Monitoring sites for the network were selected by evaluating existing wells as network candidates, and by delineating additional drilling sites in locations that lacked qualifying wells. A statistical design framework allows for valid inferences to be made regarding the targeted population. Targeted water-quality constituents were specified by DACS and pesticides were restricted to chemicals currently or recently used for citrus management. Defining standard protocols for sampling the wells and for laboratory analyses is important for comparing water quality between wells and for evaluating trend analyses. Adequate design and planned management of the data base will ensure the utility, updating, and accessibility of the water-quality data.

Delineation of Sampling Areas

To identify ground water targeted for sampling from both existing and new wells, the study area was stratified on the basis of active citrus land use and vulnerable soils. Sampling was restricted to sites completely surrounded by citrus groves on vulnerable soils, which ensured that sampling always occurred downgradient of citrus groves on vulnerable soils regardless of flow-path directions. The targeted sampling zone in the aquifer was the area directly beneath the water table where agricultural chemicals initially enter the aquifer. The highest concentrations of agricultural chemicals are likely to occur near the water table where effects of mixing, dispersion, dilution, and chemical degradation are minimal compared with deeper zones in the aquifer.

Table 3. Areal extent of active citrus groves and vulnerable soils in the Lake Wales Ridge study area, by county

[Locations of active citrus groves and vulnerable soils are shown in fig. 4]

County	Area (square miles)		
	Active citrus on vulnerable soils	Total active citrus	Total study area (citrus/noncitrus)
Highlands	69	76	351
Polk	86	91	333
Total (Highlands and Polk)	155	167	684

The most recent digital GIS coverage of citrus land use, based on 1994-95 aerial photographs (digital orthophoto quadrangles, scale 1:124,000) having a resolution of 1 meter (Southwest Florida Water Management District, 1998), was used to define active citrus areas. These active citrus areas were further refined by selecting only those groves situated on soils that were classified as most vulnerable to leaching (C.G. Hoogeweg and A.G. Hornsby, written commun., May 1998). This classification is based on physical soil characteristics related to soil permeability (drainage) and organic matter content.

Active citrus groves cover 24 percent (167 mi^2) of the Lake Wales Ridge study area (fig. 4). The majority of citrus groves on the Ridge are planted on vulnerable soils; 91 and 95 percent of the citrus groves are on vulnerable soils in Highlands and Polk Counties, respectively (table 3; fig. 4).

Within the aquifer, the length of the well screen below the water table was used to limit the targeted zone for ground-water sampling. For existing wells, the maximum length of the screened interval was 20 ft. The 20 ft limit for the length of the screened interval was necessary because few existing monitoring wells on Lake Wales Ridge have screens less than 20 ft long. For newly installed wells, the top of the screened interval will be at or near the water table and the overall screen length will not exceed 10 ft. The 10-ft-long screens will ensure that water is sampled near the top of the water table, thus reducing the potential of sampling waters of widely varying ages and/or origins (sources). As discussed later, the influence of screen length on water quality from wells having 20-ft-long versus 10-ft-long screens will need to be evaluated prior to combining the data sets for regional analysis.

Selection of Monitoring Sites

Selection of monitoring sites was constrained only by the desire to use existing wells where possible and by accessibility to sites on private land. Wells from existing networks were selected by screening the data bases using information on well location, depth to ground water, and well construction. The study area was stratified (using land use, soils, and proximity to the water table) and a randomized grid sampling approach was then used as a general guideline for site selection. This approach was used to minimize variability in water quality induced by extraneous factors (such as urban and suburban contaminant sources) and to avoid possible sample-selection bias (Gilbert, 1987; Scott, 1990; Alley, 1993).

There are no definitive rules for determining sample size for ground-water-quality monitoring networks, particularly when there are a number of target analytes of interest. Sample sizes of 20 to 50 generally are assumed to be adequate for estimating confidence intervals and population characteristics for many hydrologic applications. However, the skewness and the variance of the population distribution, as well as seasonality and trends, can affect errors associated with sample statistics (Helsel and Hirsch, 1995, p. 65-94). If distributions of target analytes are highly skewed, as is common with water-quality data, additional observations (wells) may be needed to reduce the error associated with estimates of population characteristics. Analysis of current and historical data will provide some guidance for determining sample sizes required for specific objectives (applications) and for specific water-quality constituents.

Existing Wells

Existing wells were mapped and given priority rankings on the basis of location to citrus land use and vulnerable soils. Data were obtained for 69 candidate wells (tables 4 and 5) on Lake Wales Ridge that had some available well-construction data and were potentially accessible for sampling. Wells in table 4 include FDEP VISA and Background Network monitoring wells and water-quality monitoring wells listed in two or more agencies' data bases. Wells in table 5 include wells listed in a single agency's data base and having an unknown history of use for water-quality monitoring. Wells located within a target area (active citrus groves on vulnerable soils) and with adequate well construction data were given the highest ranking of 1 (19 wells). Rankings of 2 and 3 (21 wells) were assigned to wells located near the edge of a target area and wells located in a target area but having incomplete information on well construction. Wells outside a target area were assigned a rank of 0 (29 wells). Only the 19 wells having a ranking of 1 were further considered as potential candidates for the Lake Wales Ridge Network.

The compilation of well data also included 18 well networks, designed for local-scale studies, and from which water-level or water-quality data had been collected (table 6). Some of these local-scale networks were established by public agencies and others were established by private firms as part of DACS Prospective Site Investigations to evaluate specific pesticides regarding Federal or State chemical registration requirements. At the time of this report, none of the wells in the local-scale networks qualified as Lake Wales Ridge Network sites, either due to limitations on site access or to inadequate well construction. However, ground-water flow paths have been delineated in most of these study areas, which may be useful for siting future network wells.

The small number of candidate existing wells meeting design requirements precluded randomized selection of existing wells for the Lake Wales Ridge Network. Fortunately, the wells that met the design requirements showed a reasonably uniform spatial distribution. In areas where these candidate wells were in close proximity, the well with the shallowest depth to water was selected, resulting in a final selection of 13 of the 19 candidate wells for the Phase I sampling network (fig. 9 and table 7).

Historical data for these 13 Phase I wells will provide important information for analysis of trends in nutrients and selected pesticides over time. Twelve of the wells are located in Polk County and one well is in central Highlands County (fig. 9). The FDEP, in cooperation with the SWFWMD, monitored 11 of the wells as part of the VISA Network and one well as part of the Background Network. Eleven of the Phase I wells (table 5) are part of ground-water data bases maintained by the USGS; 10 of these were included in a study of the effects of citrus land use on ground-water quality (German, 1996). Ten of the Phase I wells are included as part of the SWFWMD ground-water observation network.

Sampling of the VISA and Background Network wells was initiated in 1990 and continued until the spring of 1999. Currently, there is uncertainty about whether these wells will continue to be sampled as part of the FDEP Temporal Variation (TV) Network, the long-term network that is replacing the VISA and Background Networks. However, SWFWMD will continue quarterly sampling for selected constituents, including nutrients, at most VISA wells through September 2000 (Eric Dehaven, SWFWMD, oral commun., September 1999).

New Well Sites

Locations for drilling new wells for the Lake Wales Ridge Network were identified in areas that lacked existing monitoring wells (fig. 9). A randomized grid approach was used to identify candidate drilling sites. For site selection, a 3-mi by 3-mi square grid was randomly placed on a map of the study area. When targeted drill sites (grid nodes) fell outside or at the edge of citrus groves located on vulnerable soils, the candidate drill site was shifted to the closest nearby location surrounded by citrus growing on vulnerable soils. A total of 19 candidate drill sites (16 in Highlands County and 3 in Polk County) were identified. Phase II drilling, which was completed during winter 1999 and spring 2000, included 11 of these candidate sites (table 7 and fig. 9). The remaining eight candidate sites are proposed for Phase III drilling, which has not yet been scheduled.

The spatial distribution of proposed drill sites was designed to be consistent with the distribution of existing wells in the Phase I Lake Wales Ridge Network. The total sample size of the network after Phase III drilling is complete will include 31 wells. This sample size should provide reasonably accurate estimates of confidence intervals (margin of error) for population characteristics.

Table 4. Candidate surficial aquifer wells on Lake Wales Ridge used previously for water-quality monitoring by two or more public agencies

[Candidate ranking: 0, does not meet network specifications; 1, most desirable to 3, least desirable.
L, Lake; Rd, Road; nr, near; Pk, Park; Pt, Point; Mtn, Mountain.

Networks: DEP-B, Florida Department of Environmental Protection (FDEP) Background Network; DEP-V, FDEP VISA Network; SFWMD, South Florida Water Management District (SFWMD) Network; SWFWMD, Southwest Florida Water Management District (SWFWMD) Network; SWFOBS, SWFWMD water-level observation network; SWFOBS, SWFWMD water-level observation network; USGS-TP, U.S. Geological Survey (USGS) Tampa Subdistrict; USGS-O, USGS Orlando Subdistrict; GERMAN, USGS water-quality study (German, 1996)]

DACS ID	Well name	Alternate well name	Latitude	Longitude	Candidate ranking	Alternate well ID	Network(s)
2	Lake Groves Rd		271559	812425	0	967	DEP-B, USGS-TP, SWFOBS, SFWMD
4	HI-0004		271750	812505	0	271746081250501	DEP-B, SFWMD, USGS-TP
7	Sebring 412 - Shallow		272746	812327	0	208	DEP-B, USGS-TP, SWFOBS
8	MR-0156		273528	812609	0	273528081260901	DEP-B, SFWMD
9	ROMP 43X - Surficial	Shallow well nr Avon Park	273609	812853	0	205	USGS-TP, SWFOBS
12	ROMP CL-2 - Deep urficial		274522	813039	0	17	DEP-V, USGS-TP, SWFOBS
21	ROMP 57X - Surficial	ROMP 57A, nr Lake Wales	275348	813357	0	16	USGS-TP, SWFOBS
22	ROMP 58 - Surficial	ROMP 58 NRSD nr L Wales	275507	813537	0	163	USGS-TP, SWFOBS
32	USGS P-47 - Shallow		281051	813625	0	679	USGS-TP, SWFOBS
35	Loughman - Shallow		281532	813450	0	281532081345002	DEP-B, USGS-OR, USGS-TP
6	SEBRING 412-A NRSD		272745	812326	1	208	DEP-B, USGS-TP, SWFOBS
11	USGS P-48 - Shallow		274226	813152	1	791	DEP-B, USGS-OR, SWFOBS
14	Wardlaw Rd - Surficial	Ridge wrap VC-5	274625	813009	1	185	DEP-V, USGS-OR, SWFOBS, GERMAN
15	Breezy Pt Rd nr Babson Pk	Ridge wrap VC-4	274732	813250	1	974	USGS-OR, SWFOBS, GERMAN
16	N Lake Patrick Rd	Ridge Wrap VC-6	274806	813114	1	274800081311001	DEP-V, USGS-OR, SWFOBS, GERMAN
17	Murray Rd - Surficial	Ridge wrap VC-10B	274850	813024	1	179	DEP-V, USGS-OR, SWFOBS, GERMAN
18	Muncie Rd - Surficial		275050	813354	1	275040081335801	DEP-V, USGS-OR, GERMAN
19	Golfview Rd nr Babson Pk	Ridge wrap VC-1	275127	813152	1	174	USGS-OR, SWFOBS, GERMAN
23	Mtn Lake Corp South	SE Mtn Lake nr L Wales	275513	813316	1	274800081331501	DEP-V, USGS-OR, GERMAN
24	Mtn Lake N SF nr L Wales	Ridge wrap VC11-B	275558	813316	1	162	DEP-V, USGS-OR, SWFOBS, GERMAN
25	St Helena Rd	Ridge wrap VC-12	275742	813344	1	160	DEP-V, USGS-OR, SWFOBS, GERMAN
26	Lake Mable Loop Rd South (near Waverly, Fla.)		275857	813444	1	275903081342801	DEP-V, USGS-OR, GERMAN
27	Tindel Camp Rd	Ridge wrap P-8	275857	813522	1	158	DEP-V, SWFOBS
28	Swann Rd - Surficial		280120	813514	1	280115081352001	DEP-V, USGS-OR, GERMAN
29	Water Tank Rd - Surficial	Ridge wrap VC-9	280252	813543	1	124	DEP-V, USGS-OR, SWFOBS, GERMAN
30	Water Tank Rd - West	Ridge wrap P-7	280253	813650	1	125	DEP-V, SWFOBS
1	Bairs Den		271226	811943	2	982	DEP-B, USGS-TP, SWFOBS, SFWMD
3	ROMP 28X - Surficial		271600	812022	2	216	DEP-B, USGS-TP, SWFOBS
5	HC-0002		272341	812449	2	272341081244901	DEP-B, SFWMD
13	ROMP CL-2 - Surficial		274522	813039	2	17	DEP-V, USGS-TP, SWFOBS
20	ROMP 14 - Surficial		275155	813139	2	275154081314001	DEP-B, SWFWMD
31	Herrans NURS WT MONI		280412	813543	2	271305081213001	DEP-B, SWFWMD
33	PO0002		281202	813847	2	281202081384702	DEP-B, USGS-TP
34	USGS SH OBS on US 27		281511	813931	2	281511081393102	DEP-B, USGS-TP
10	ROMP 43XX - Surficial		273616	812848	3	203	DEP-B, SWFOBS

Table 5. Candidate surficial aquifer wells on Lake Wales Ridge used previously for water-quality monitoring by one public agency, or for water-level monitoring by one or more public agencies

[Candidate ranking: 0, does not meet network specifications, 1, most desirable to 3, least desirable; Rd, Road; nr, near]

[Networks: SWF-LLJX, Southwest Florida Water Mangement District (SWFWMD) Little Lake Jackson nutrient study; SWFOBS2, SWFWMD water-level observation network; USGS-ORL, U.S. Geological Survey (USGS) Orlando; USGS-TPA, USGS Tampa]

DACS ID	Local network well ID	Site name	Latitude	Longitude	Network	Candidate ranking
LLJ-1	1A-SH	1A-SH - Little Lake Jackson	272812	812808	SWF-LLJ X	0
LLJ-2	1B-DP	1B-DP - Little Lake Jackson	272812	812808	SWF-LLJ X	0
LLJ-3	2A-SH	2A-SH - Little Lake Jackson	272751	812801	SWF-LLJ X	0
LLJ-4	2B-DP	2B-DP - Little Lake Jackson	272751	812801	SWF-LLJ X	0
LLJ-5	3A-SH	3A-SH - Little Lake Jackson	272736	812828	SWF-LLJ X	0
LLJ-6	3B-DP	3B-DP - Little Lake Jackson	272736	812828	SWF-LLJ X	0
LLJ-7	4A-SH	4A-SH - Little Lake Jackson	272756	812840	SWF-LLJ X	0
LLJ-8	4B-DP	4B-DP - Little Lake Jackson	272756	812840	SWF-LLJ X	0
ORL-1	275431081353101	754135144 (Florida Citrus Canners)	275431	813531	USGS-ORL	0
ORL-3	275659081343201	756134122 (J Snively)	275659	813432	USGS-ORL	0
SWF-1	360	Ridge wrap H-4	272635	812858	SWFOBS2	0
SWF-10	214	Ridge wrap H-7	272029	812755	SWFOBS2	0
SWF-12	1042	ROMP 28 - Surficial	272209	812604	SWFOBS2	0
SWF-12A	1042A	ROMP 28 - Surficial-OB1	272209	812604	SWFOBS2	0
SWF-12B	1042B	ROMP 28 - Surficial-OB2	272209	812604	SWFOBS2	0
SWF-12C	1042C	ROMP 28 - Surficial-OB3	272209	812604	SWFOBS2	0
SWF-9	207	Ridge wrap H-5	273120	812441	SWFOBS2	0
TPA-1	271611081245701	71612401 (H440)	271611	812457	USGS-TPA	0
TPA-2	271630081240001	Shallow well, 207 Tangerine Rd., near Lake Placid, Fla.	271630	812400	USGS-TPA	0
SWF-3	933	Ridge wrap VC-2	274821	813244	SWFOBS2	1
SWF-5	107	Ridge wrap P-6	280530	813623	SWFOBS2	1
SWF-6	181	Ridge wrap CLP-7	274828	813218	SWFOBS2	1
SWF-11	215	Ridge wrap H-8	271748	811904	SWFOBS2	2
SWF-2	499	Ridge wrap P-5	280835	813744	SWFOBS2	2
SWF-4	59	Ridge wrap P-4	281434	813910	SWFOBS2	2
SWF-7	202	Ridge wrapRidge wrap H-1	273817	813123	SWFOBS2	2
SWF-8	204	Ridge wrap H-2	273611	813142	SWFOBS2	2
TPA-3	271733081231901	CTLC grove #2 East of Lake June in Winter	271733	812319	USGS-TPA	2
TPA-4	271734081232101	CTLC grove #1 East of Lake June in Winter	271734	812321	USGS-TPA	2
TPA-5	271746081251601	CTLC UNDV #1 West of Lake June in Winter	271746	812516	USGS-TPA	2
TPA-6	271746081253001	CTLC UNDV #3 West of Lake June in Winter	271746	812530	USGS-TPA	2
ORL-2	275559081335901	755133111 (Waverly Bros.)	275559	813359	USGS-ORL	3
ORL-4	280551081364001	(R K Harman)	280551	813640	USGS-ORL	3
TPA-7	273124081260701	Withers-Horshman deep well near Sebring, Fla.	273124	812607	USGS-TPA	3

Final decisions on the installation of new wells will depend on several factors. Availability of funds will determine the number of new wells and the timing of their installation. Ultimately, locations of drilling sites will be determined based on constraints regarding site access, which could restrict drill sites to road right-of-ways within citrus areas. To avoid introducing sampling (selection) bias into the network, an attempt will be made to locate drilling sites as close as possible to targeted grid locations.

Table 6. Local-scale ground-water monitoring networks in the surficial aquifer on Lake Wales Ridge

[None of these networks yielded monitoring wells that qualified as candidates for the LWR network, due to inadequate well construction or to restrictions on access to sample the wells]

[Candidate ranking: 0, does not meet network specifications; 1, most desirable to 3, least desirable]

[BMP, Best Management Practices; DACS, Florida Department of Agriculture and Consumer Services; IFAS, University of Florida Institute of Food and Agricultural Services; PVT, private; SWFWMD, Southwest Florida Water Management District; USGS, U.S. Geological Survey]

DACS ID	Site name	Agency	County	No. of wells	No. of piezometers	Candidate ranking	Study/agency
A	Archibold (Site F) - DACS	DACS	Highlands	5	-	0	Citrus Ridge NO3 study (DACS/IFAS)
F	Lake Annie - USGS Tampa	USGS	Highlands	-	8	0	USGS Tampa, lake study
H	Lake Olivia - USGS Tampa	USGS	Highlands		10	0	USGS Tampa, lake study
L	Saddle Blanket Lake - USGS Tampa	USGS	Polk	-	9	0	USGS Tampa, lake study
K	Reynolds (site B) - DACS	DACS	Highlands	4	-	1	Citrus Ridge NO_3 study (DACS/IFAS)
P	Templeton North - DACS	DACS	Highlands	5	-	1	Citrus Ridge NO_3 study (DACS/IFAS)
Q	Templeton South - DACS	DACS	Highlands	5	-	1	Citrus Ridge NO_3 study (DACS/IFAS)
C	Bromacil study - DACS	PVT	Polk	15	6	1	DuPont study
E	Fenamiphos study - DACS	PVT	Highlands	21	4	1	Levine-Fricke-Recon
O	Temik (aldicarb) BMP - DACS	PVT	Highlands	8	44	1	Rhone-Poulenc Ag Co./Hydoscience
I	Lake Starr - USGS Tampa	USGS	Polk	1	41	1	USGS Tampa, lake study
N	Swim Lake - USGS Tampa	USGS	Polk	-	8	1	USGS Tampa, lake study
D	DeSoto City study - DACS	DACS	Highlands	21	-	2	DACS pesticide group
M	Sandy Ridge (site C) - DACS	DACS	Highlands	6	-	2	Citrus Ridge NO_3 study (DACS/IFAS)
B	Azafenidin study - DACS	PVT	Highlands	7	4	2	DuPont study
J	Persimmon Lake - SWFWMD	SWF	Highlands	27	4	2	K. Kolasa/SWFWMD
R	Thiazopyr study - DACS	PVT	Polk	8	3	3	Rohm & Haas
G	Lake Isis - USGS Tampa	USGS	Highlands	-	10	3	USGS Tampa, lake study

New wells should be drilled and screened near the water table, preferably using screened intervals of 10 ft. Longer screened intervals could be used if there is evidence of substantial water-table fluctuation in the area, which might preclude sampling during drought conditions.

Water-Quality Analyses

Water-quality analyses for the network will include field measurements and selected major ions, nutrients, trace elements, pesticides, and pesticide degradates. Primary target analytes are nutrients and pesticides. Other analytes will aid in evaluating basic water chemistry and the potential for chemical interactions, and ensuring the quality assurance of laboratory analysis. SWFWMD personnel will collect field samples. Chemical analysis of samples collected from the wells will be performed by the DACS, FDEP, SWFWMD, and SWFWMD-contract laboratories; DACS pesticide laboratory will perform all pesticide analyses.

Targeted Analytes

The analytes targeted for the Lake Wales Ridge Network (table 8) will focus on chemicals currently applied in citrus groves. The target analytes will also include pesticide degradates, as well as selected pesticides recently banned or discontinued. Analytes may be added to or deleted from the list when agricultural chemicals are introduced or discontinued (or banned) in the vicinity; analytes also may be added or deleted to investigate chemicals of concern for health or other reasons.

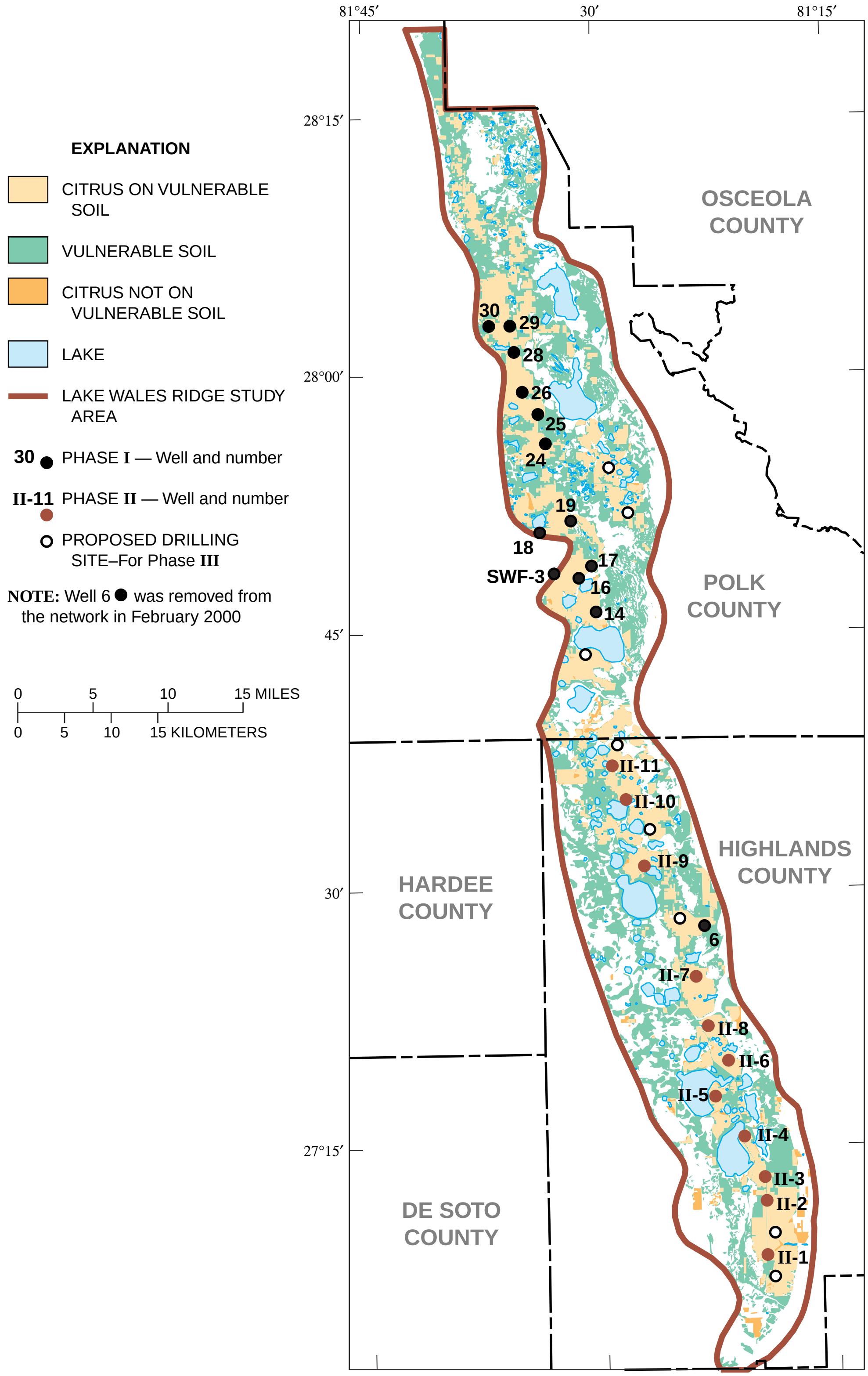

Figure 9. Locations of existing Phase I and Phase II wells, and proposed Phase III drilling sites for the Lake Wales Ridge Network.

Table 7. Description of Phase I and II wells in the Lake Wales Ridge Network

[Well locations are shown in fig. 9.]

[DGPS, digital ground positioning system; Casing material: V, glued polyvinyl chloride (PVC); X, nonglued PVC; P, PVC - no information available regarding use of glue; Rd, Road; nr, near; CR, county road; SR, State road]

DACS ID	Well ID	SWFWMD Universal ID	Well name	Alternate well name	DGPS latitude	DGPS longitude	Well depth (feet)	Casing depth (feet)	Screened interval length (feet)	Casing mate-rial	Casing diam-eter (inches)
Phase I Wells											
6	272745081232601	208-10922-0	Sebring 412-A NRSD		272748.256	812326.478	60	40	20	P	6
14	274625081300901	185-10897-0	Wardlaw Rd - Surficial	Ridge wrap VC-5	274609.804	813007.695	39	19	20	X	4
16	274806081311401	182-10894-0	North Lake Patrick Rd	Ridge wrap VC-6	274808.840	813112.789	55	35	20	X	4
17	274848081302202	179-10892-0	Murray Rd - Surficial	Ridge wrap VC-10B	274850.556	813022.624	21	10	11	X	4
18	275040081335801	811-545-0	Muncie Rd - Surficial		275048.636	813343.370	90	70	20	X	4
19	275128081314201	174-10886-0	Golfview Rd nr Babson Park	Ridge wrap VC-1	275129.080	813141.250	65	45	20	P	4
24	275600081331501	162-10871-0	Mt. Lake Corp. N SF	Ridge wrap VC11-B	275559.730	813315.158	60	40	20	X	4
25	275745081333501	160-10869-0	St. Helena Rd	Ridge wrap VC-12	275742.808	813343.288	70	50	20	X	4
26	275903081342801	945-679-0	Lake Mable Loop Rd South		275900.970	813443.125	79	59	20	X	4
28	280115081352001	138-262-0	Swann Rd - Surficial		280120.876	813513.444	97	77	20	X	4
29	280255081354201	124-10830-0	Watertank Rd - Surficial	Ridge wrap VC-9	280253.4130	813527.363	89	69	20.0	X	4
SWF-3	274820081324501	933-667-0	West Cody Villa Rd	Ridge wrap VC-2	274824.988	813248.956	150	130	20.0	P	4
30	280252081365001	125-10831-0	Water Tank Rd West	Ridge wrap P-7	280252.602	813650.280	145	125	20	V	4
Phase II Wells											
II-1	270835081194201	2350-17872-0	Hickory Branch Rd - Surficial		270835.4447	811942.4395	90	80	10	X	2
II-2	271148081194201	2351-17873-0	Rozier Rd - Surficial		271148.2898	811942.1454	50	40	10	X	2
II-3	271313081194401	2352-17874-0	SR 70 - Surficial		271312.7864	811943.922	35	25	10	X	2
II-4	271529081210701	2353-17875-0	Old SR 8 - Surficial		271529.3074	812107.2187	60	50	10	X	2
II-5	271752081224401	2354-17876-0	Jackson Rd - Surficial		271752.0788	812244.244	15	5	10	X	2
II-6	271946081220301	2355-17877-0	Cemetary Rd - Surficial		271945.6438	812202.8888	40	30	10	X	2
II-7	272459081240401	2356-17878-0	17th St South - Surficial		272459.0836	812404.4248	80	70	10	X	2
II-8	272158081232101	2357-17879-0	Dinner Lake Rd - Surficial		272158.301	812321.4908	30	20	10	X	2
II-9	273122081271201	2358-17880-0	Arbuckle Creek Rd - Surficial	Baltimore Rd - Surficial	273121.9352	812712.6104	50	40	10	X	2
II-10	273517081282801	2359-17881-0	Sears Rd - Surficial		273516.524	812827.9164	35	25	10	X	2
II-11	273705081290901	2360-17882-0	CR 627 - Surficial		273704.9259	812909.3647	60	50	10	X	2

Table 8. Agricultural chemicals and degradates targeted in Phases I and II sampling of the Lake Wales Ridge Network

Common name	Selected trade name(s)	Chemical use	Chemical class	Analyte category
Aldicarb	TEMIK	insecticide, acaricide, nematicide	carbamate	pesticide
Aldicarb sulfone			aldicarb degradate	pesticide degradate
Aldicarb sulfoxide oxime (or Aldoxycarb)			aldicarb degradate	pesticide degradate
Arsenic		herbicide	inorganic	pesticide
Atrazine	ATTREX, ATRACHEM	herbicide	triazine	pesticide
Deethylatrazine			atrazine degradate	pesticide degradate
Deisopropylatrazine			atrazine degradate	pesticide degradate
Bentazon	BASAGRAN, PLEDGE	herbicide	miscellaneous	pesticide
Bromacil	HYVAR, BROMAX, UROX	herbicide	uracil	pesticide
Chlorphyrifos	LORSBAN, DURSBAN	insecticide	organophosphorous	pesticide
Copper		nematicide, fungicide, herbicide	inorganic	pesticide, nutrient
Dimethoate	BANVEL, ROXION	insecticide	organophosphorous	pesticide
Diuron	KARMEX, DYNEX, DIREX	herbicide	urea	pesticide
Ethion	ETHANOX, RHODOCIDE	insecticide, acaricide	organophosphorous	pesticide
Fenamiphos	PHENAMIPHOS, NEMACUR	nematicide	organophosphorous	pesticide
Fenamiphos sulfone			fenamiphos degradate	pesticide degradate
Fenamiphos sulfoxide			fenamiphos degradate	pesticide degradate
Imidacloprid	ADMIRE, CONFIDOR, STORM	insecticide	chloronicotinyle	pesticide
Iprodione	ROVRAL, KIDAN, CHIPCO	fungicide	amide	pesticide
Metalaxyl	EISOMIL	fungicide	amino acid derivative	pesticide
Methomyl	LANNATE, LANOX, DUMIL	insecticide	carbamate, thiodicarb degradate	pesticide
Metribuzin	CONTRAST, SENCOR, VETO	herbicide	triazinone	pesticide
Nitrate		nematicide	inorganic	nutrient
Norflurazon	SOLICAM, EVITAL, ZORIAL	herbicide	amine	pesticide
Methyl Norflurazon			norflurazon degradate	pesticide degradate
Oryzalin	SURFLAN, DIRIMAL	herbicide	dinitroaniline	pesticide
Phosphate		nematicide	inorganic	nutrient

Sampling and Laboratory Analyses

Because the Lake Wales Ridge Network is to be a long-term monitoring effort, documentation of sampling and laboratory analyses is needed to provide a basis for comparing data and accounting for changes in water quality over time. Historical water-quality data from existing wells in the network will be important in assessing long-term trends. Historical sampling of pesticides and nitrate at existing FDEP VISA and Background Network wells selected for the Lake Wales Ridge Network has been performed by SWFWMD. Chemical analyses for VISA and Background Network wells have been performed by several laboratories (C. Cosper and others, written commun., FDEP, 2000), including the FDEP-Central, USGS-Ocala, and Savannah laboratories.

Initially, the Lake Wales Ridge Network wells will be sampled quarterly. After seasonal variability has been assessed, the sampling frequency may be reduced. The initial sampling of the Lake Wales Ridge Network, in April 1999, coincided with the final sampling of the FDEP citrus VISA Network. The Lake Wales Ridge Network quarterly sampling is scheduled for April, July, October, and January. Laboratory analysis of pesticides and nutrients will be performed by DACS Pesticide and Food laboratories in Tallahassee, Fla., with supplemental analyses performed by the SWFWMD and FDEP-Central laboratories, and other contract laboratories as needed.

Data-Base Management

Well-construction and water-quality data for the Lake Wales Ridge Monitoring Network is anticipated to reside in the Florida Ground-Water Information System (GWIS) data base, maintained by FDEP, and publicly accessible on the Internet web site at **http://www.dep.state.fl.us/water/division/monitoring/**. This website lists well attributes, coding conventions, and historical water-quality data for existing Ridge Network wells that were part of the FDEP VISA and Background Networks. Based on methods described by Katz and Collins (1998), these data are subjected to various quality-assurance and quality-control tests, such as ionic charge balances and identification of outliers, prior to releasing the data (Paul Hansard, FDEP, oral commun., March 1999).

Implementation Plan and Schedule

The plan to implement the Lake Wales Ridge Monitoring Network will depend on several factors. Timing of the plan is anticipated to occur in phases. The availability of funding will drive the timing and number of new wells installed. Logistical constraints, including availability of drill rigs, field personnel, permission for site access, and permitting of wells, will affect the timing of drilling. Analysis of historical water-quality data for the Ridge and evaluation of preliminary data from the Phase I sampling efforts may affect plans to fully implement the network, for example by altering the sampling frequency or the number of targeted drill sites.

Implementation of the Lake Wales Ridge Network is expected to occur in three phases, with Phases I and II completed at the time of this report (2000) (fig. 10). Phase I included sampling 13 existing wells (table 7 and fig. 9). These wells were sampled quarterly beginning in April 1999. Sampling of one Phase I well (Well #6, Sebring 412-A) was discontinued in February 2000 due to poor yield and high turbidity of the water samples. In Phase II an additional 11 wells were drilled in Highlands County, and a total of 23 Phase I and II wells (table 7 and fig. 9) were sampled beginning in April 2000. Phase III will include drilling of an additional 8 wells, including 5 sites in Highlands County and 3 sites in Polk County (fig. 9), expected to occur prior to spring 2001. Full implementation of the plan would consist of 15 wells in Polk County and 16 wells in Highlands County, for a total of 31 wells in the network. According to this plan, sampling of the full network could commence in spring 2001.

Phase I
Spring 1999 through Winter 1999

Sample 13 existing monitoring wells
(12 in Polk County and 1 in Highlands County)

Quarterly sampling commenced
in April 1999

Phase II
Spring 2000 through Winter 2000

Drill 11 additional wells in Highlands County
prior to Spring 2000

Sample 24 wells

Phase III
Spring 2001 through Winter 2001

Drill 8 additional wells prior to Spring 2001

Sample 31 wells
(15 in Polk County and 16 in Highlands County)

Figure 10. Design plan and schedule for drilling and sampling wells in the Lake Wales Ridge Network.

(Locations of existing and planned wells are shown in figure 9. Dates are approximate and the plan is subject to modification. The Phase I well in Highlands County (Sebring 412A) was dropped from the network in February 2000.)

CONSIDERATIONS FOR FUTURE DEVELOPMENT OF THE NETWORK

“A characteristic of virtually all water-quality sampling programs is that knowledge is attained about a more efficient design after sampling is completed and the results are analyzed. For long-term studies, the anticipation that modifications may be made to the network at a future date favors the utilization of fairly simple designs at the outset.” (Alley, 1993, in “Regional Ground-Water Quality Monitoring”)

The most effective sampling design for describing ground-water quality on Lake Wales Ridge and understanding controlling factors, given current resources, will be derived using a phased approach. By implementing the network in phases, water-quality data are accumulated and analyzed, and the design is expanded over time. The FDEP envisions using a stepwise approach in the tiered sampling plan for statewide water-quality monitoring under the Integrated Water Resources Monitoring (IWRM) Program for Florida (Copeland, 1997; Paulic, 1998). As water-quality results become available, the Lake Wales Ridge Network design must be evaluated in terms of meeting program objectives and priority issues. Historical data and local-scale investigations need to be incorporated into the analysis of data collected from the network to gain valuable perspective on long-term changes, and on local factors and processes affecting contaminant transport. Understanding local-scale processes is commonly required to interpret regional-scale data—an issue known as the “scales-clash” problem in regional network design. One approach to the scales-clash problem is to incorporate local-scale, process-oriented monitoring networks within regional monitoring networks. The USGS National Water-Quality Assessment (NAWQA) Program has used this combined regional- and local-scale approach in study units across the United States (Gilliom and others, 1995).

The task of assessing water quality on Lake Wales Ridge is both enhanced and complicated by the existence of other monitoring efforts being conducted by various agencies, including local-scale studies funded or directed by DACS, FDEP, the Water Management Districts, and the USGS. This work includes studies of nitrate in ground water (IFAS and SWFWMD); prospective site-investigation studies for regulatory purposes; the FDEP Background, VISA, Drinking Water, and IWRM networks; and various studies performed by the USGS and Water Management Districts. Ideally, these data-collection and research efforts need to be included as components of the DACS Lake Wales Ridge Network, with some vehicle for real-time information exchange among scientists and managers, such as an annual meeting or a document summarizing pertinent information.

Topics for future investigations that relate to the development of the Lake Wales Ridge Network and to the interpretation of network data are discussed below. Considerations for future investigation are separated into three major sections: “Regional Water-Quality Analysis,” “Network Analysis,” and “Topics for Additional Study” (table 9). “Regional Water-Quality Analysis” and “Network Analysis” primarily cover the analysis of data from the Lake Wales Ridge Network. “Topics for Additional Study” covers ideas for local-scale or subject-driven studies to improve our understanding of the sources, transport, and fate of agricultural contaminants in ground water on the Ridge. These studies might be directed by DACS or by other agencies interested in ground-water quality on the Ridge.

Regional Water-Quality Analysis

Regional water-quality analysis (table 9) includes a summary and analysis of historical water-quality data for Lake Wales Ridge and analysis of Phase I samples. Historical data for network wells need to be assembled into a single data base and directly referenced to the network wells. These data include records maintained by various agencies and water-quality analyses performed at several different laboratories.

Interpretive data analyses should include an evaluation of spatial variability of target analytes and temporal trends at these wells. Relations between observed water quality and environmental factors, such as depth to the water table and land-use practices, should be explored. Information should also be compiled on application methods used for agricultural chemicals and irrigation practices during the time period examined for trends, including dates when specific chemicals were used initially and when their use was discontinued or banned. This information would be needed to relate water quality to implementation of best management practices, and to potentially date ground water based on concentrations of specific pesticides and their degradation products. Included in this study would be an initial assessment of seasonal

Table 9. Topics for future investigation related to the Lake Wales Ridge Network design

[LWR = Lake Wales Ridge]

REGIONAL WATER-QUALITY ANALYSIS	NETWORK ANALYSIS	POTENTIAL TOPICS FOR ADDITIONAL STUDY
Compile a detailed summary of previous water-quality studies of nutrients and pesticides on LWR. Build historical database for LWR Network wells.	Determine if LWR Network is providing adequate temporal and spatial resolution, and sufficient accuracy of regional estimates (confidence limits) to meet project objectives.	Conduct local-scale studies to address specific issues, such as: (1) delineate sources or management practices associated with contamination, (2) evaluate transport and fate of specific pesticides in ground water, or (3) delineate extent of contamination.
Describe spatial variations in water quality and compare to environmental factors, such as land-use practices and hydrogeology.	Critically evaluate field sampling methods and lab protocols, including analytical methods and detection limits, interlab variability.	Evaluate relative concentrations of pesticides and nutrients in seepage lakes, including effects of ground water-surface water interactions on the chemical evolution of agricultural chemicals.
Investigate seasonal variability of nutrients and pesticides, and time-of-travel for recharge waters between land surface and the water table.	Evaluate adequacy of analyte list for water-quality interpretation, current pesticide usage, and pesticide degradates.	Detailed evaluation of dates of recharge of sampled waters: consider using isotopes and tracers; installing water-level recorders in selected wells.
Evaluate long-term trends (1990-2000) at LWR Phase I Network wells that have historical records.	Determine cost effectiveness and data efficiency of network design, including number of wells and sampling frequency.	Evaluate the potential for contamination to migrate to underlying aquifers.
Compile information on chemical application and irrigation in citrus areas (past and present).		

variations in chemical concentrations in ground water and evaluation of ranges of traveltimes for water movement between land surface and the water table, particularly in the vicinity of Ridge wells.

Network Analysis

Network analysis (table 9) is a critical evaluation of preliminary data to evaluate the methods, approach, and cost effectiveness of the network for meeting program objectives prior to full implementation of the network. The network analysis would focus on using the Phase I and II data to evaluate the long-term design prior to Phase III drilling and sampling. The analysis would assess the adequacy of the field sampling and laboratory methods as well as examine the variability of agricultural chemicals in ground water to evaluate the effectiveness of the network design for meeting program objectives. Network analysis would address the cost effectiveness of the network by focusing on the minimum number of wells needed to achieve given error limits for regional estimates, and the sampling frequency needed to describe seasonal and long-term variability and statistical trends. For example, a selected subset of wells could be sampled at a high frequency and other wells at a reduced frequency; for long-term evaluation, a subset of network wells could be monitored regularly and a larger, more comprehensive set of wells monitored only during “active phases” of data collection.

The Lake Wales Ridge Network will consist of wells with 10-ft-long screened intervals in Phase II and III wells, and 20-ft-long screened intervals in most Phase I wells (table 7). Of particular concern is the increased potential for mixing waters of substantially different ages in the 20-ft screens. The nonuniform lengths of screened intervals between the network wells could result in differences between water-quality samples collected from nonuniform screen lengths. For example, if concentration gradients or substantial age differences exist in the aquifer zone tapped by the screened intervals. A study of the effect of varying screen lengths on water-quality samples would need to address variations in concentration within a screened interval and variations between 10-ft- and 20-ft-long screened intervals at a site during a sampling event.

The variation in screen length could confound regional analyses using all network wells. For example, water-quality differences between wells having 20-ft- and 10-ft-long screens may result from differences in screened interval length in determining the zone of water sampled rather than land-use or environmental factors.

In addition to providing a thorough evaluation of target analytes with regard to current agricultural use, a network analysis could include potential hydrogeologic interpretations, such as identifying sources of contamination, examining potential for chemical interactions, and age-dating waters.

Topics for Additional Study

Topics for additional study (table 9) address issues related to the occurrence, transport, and fate of pesticides and nutrients on Lake Wales Ridge. Study topics focus on issues directly related to interpretation of chemical data from the regional network. Specific topical study needs and priorities should be apparent subsequent to the analysis of network data, and may differ from the examples presented in table 9. Some of the studies currently being conducted on the Ridge may provide additional information.

Local-scale or topic-oriented studies could delineate sources or management practices associated with observed contamination, evaluate the transport and fate of specific contaminants, or delineate the areal extent of specific contaminants in the aquifer. Ground-water gradients and flow paths have been delineated in detail in several areas of the Lake Wales Ridge (table 6), thus providing supporting information for interpreting data from existing or future monitoring wells in these areas. Selection of local-scale study sites should focus on areas where the hydrogeology and land-use management are well understood and areas typical of land-use management and hydrogeological settings on the Ridge.

A water-quality survey of seepage lakes surrounded by citrus groves on vulnerable soils could provide information on concentrations of agricultural chemicals in surface water and potential effects of interactions between ground water and surface water on the chemical evolution of contaminants. Seepage lakes, with no incoming or outgoing surface flow, make up about 70 percent of Florida lakes (Palmer, 1984). The vast majority of lakes on the Ridge are seepage lakes, having direct and dynamic interactions with ground water in the vicinity of the water table (Sacks and others, 1998). A comparison between concentrations of agricultural chemicals in lakes and adjacent ground water would provide information on the utility of lake sampling as an index to ground-water quality, as well as differences in chemical degradation in lake environments versus subsurface ground-water environments. In most areas of the Nation, concentrations of pesticides in surface waters are generally higher than those in nearby ground waters (Barbash and Resek, 1996). Because seepage lakes are fed by ground water, concentrations in lakes would be expected to be somewhat lower than concentrations in ground water due to dilution from rainfall and chemical degradation.

Additional work needs to be done to establish ages of ground water in the upper part of the surficial aquifer. Without specific knowledge of the traveltime required for water to move from land surface to the water table, or the flow paths in the surficial aquifer, it will be difficult to relate observed water quality to specific current or past land-use practices. Several approaches could be used to determine dates of recharge and flow paths, including the use of herbicides and their degradates as tracers of surface-water and ground-water flow (Adams and Thurman, 1991; Mills, 1991), isotopes—such as tritium (^{3}H), tritium/helium-3 ($^{3}H/^{3}He$), krypton-85 (^{85}Kr)—chlorofluorocarbons, and surfactants in pesticides (Plummer and others, 1993). Water-level recorders in selected wells could be used to evaluate the time of response to recharge events. Dates of introduction of particular pesticides could provide a basis for assigning maximum ages to sampled waters.

Lastly, if there is concern regarding contaminant transport or degradation within lower depths of the surficial and underlying aquifers or in adjacent areas, comparative regional studies or local flow-path studies could be done. For example, on a regional scale, statistical comparisons could be made with similarly defined strata, such as citrus areas in nonvulnerable soils, and noncitrus areas. On a more local scale, changes in water quality with depth and changes along flow paths could be determined using nested wells or wells with multilevel samplers in smaller study areas. Some of the Phase I (VISA) wells are paired with VISA wells finished in the lower surficial, intermediate, and Upper Floridan aquifers; and the DACS/IFAS Ridge Citrus Water Quality Project includes wells equipped with multilevel samplers.

SUMMARY

The Florida Department of Agriculture and Consumer Services (DACS) has proposed establishing long-term, water-quality sampling networks to monitor shallow ground water in agricultural areas of Florida. The objectives of these networks are to provide information for early detection of pesticides in the subsurface and for evaluating current conditions and temporal trends in pesticide and nitrate concentrations.

Lake Wales Ridge was selected as a pilot study area for establishing a regional, shallow ground-water monitoring network for agricultural chemicals. The Ridge not only is one of the most intensively farmed citrus areas of Florida, but also is hydrologically vulnerable due to particular environmental conditions that result in a high potential for transport of agricultural chemicals from land surface to underlying aquifers. The combination of extensive well-drained, clean surficial sands coupled with hydraulic connections with deeper karstic limestone extends the threat of contaminant migration to the deeper aquifers, which are more heavily utilized for water supply purposes.

The Lake Wales Ridge Network will bridge the knowledge gap that currently exists between short-term pesticide permitting studies of limited spatial extent and monitoring the deeper Upper Floridan aquifer system, which provides most of the municipal and industrial water supply. Water-quality sampling will focus on chemicals currently applied in citrus groves on Lake Wales Ridge, but will also include selected pesticides that have been recently banned or discontinued, and selected pesticide degradates. The network design was developed on the basis of the objectives of monitoring, factors affecting aquifer vulnerability, probability (statistical) sampling theory, and specifications regarding well construction, sampling, and laboratory analysis. The network will serve as a prototype for DACS to use for planned monitoring of agricultural chemicals elsewhere in Florida.

Design of the Lake Wales Ridge Network required identifying areas of the Ridge most susceptible to contamination from agricultural chemicals and applying probability-based sampling within these areas. The targeted sampling area was restricted to ground water occurring near the water-table surface in the surficial aquifer and underlying active citrus groves established on vulnerable soils. These restrictions not only ensured that ground-water recharge areas overlain by active citrus groves were sampled, but also that areas most susceptible to leaching, and therefore most likely to have the highest chemical concentrations were sampled. Digital coverages of citrus land use and soils vulnerable to leaching were used to define targeted sampling areas. Active citrus areas on vulnerable soils covered 155 mi^2 of the 684 mi^2 study area.

Probability-based sampling in the target areas ensured a broad spatial distribution of wells to capture regional variability in land-management practices, soil types, and hydrogeological setting, as well as provided a basis for drawing valid statistical inferences describing the targeted area. Network design criteria included specifications for well construction to minimize the potential contamination of samples, and specifications for field sampling and laboratory analytical methods to facilitate temporal and spatial comparisons of water quality and to ensure comparability between water-quality samples.

Monitoring sites for the network include the use of existing wells and the installation of new wells. A comprehensive review of existing wells screened in the surficial aquifer was performed to select candidate monitoring wells, and included wells monitored by the Florida Department of Agriculture and Consumer Services, Florida Department of Environmental Protection, Florida Department of Health, South Florida Water Management District, Southwest Florida Water Management District, University of Florida Institute of Food and Agricultural Sciences, and U.S. Geological Survey.

Of 69 existing monitoring wells and 18 local-scale well networks (consisting of 133 wells) on Lake Wales Ridge, 19 wells met network design specifications, which included well construction, citrus locations on vulnerable soils, and site accessibility. Of these 19 wells, 12 wells in Polk County and 1 well in Highlands County were selected for the network. These 13 network wells had been used previously for water-quality sampling, and 11 of the 13 wells had been sampled for selected pesticides and nitrate between 1989 and 1999.

In areas lacking existing wells, a randomized grid approach was used to identify 22 target drill sites. Of these sites, 17 were in Highlands County and 5 were in Polk County. The final number of sites and drilling locations, as well as the schedule for drilling new well sites, will be determined by availability of funding and the ability to gain site access for drilling and water-quality sampling.

Development of the network will occur in phases, depending on funding and logistical constraints and on initial sampling results. Sampling the 13 existing wells constituted Phase I implementation; quarterly sampling was initiated in April 1999. Phase II implementation included drilling 11 additional wells in Highlands County that were sampled beginning in April 2000. Phase III is expected to include drilling an additional eight wells.

Because implementation of the network will proceed in phases, evaluation of existing data will be critical to maximize cost efficiency of the sampling design, and to ensure that design objectives are met. Future evaluations, as detailed in this report, should include a preliminary regional water-quality analysis and a network analysis using Phase I and Phase II data. Information from existing local-scale and process-oriented studies on the Ridge, which are being conducted by other agencies, should also be included as a component of the network design. The preliminary regional evaluation may indicate other sampling design needs, such as better spatial delineation of chemical concentrations and determining ages of sampled waters, or the need for additional process-oriented studies to delineate land-management practices, sources, and processes affecting the transport of constituents of concern.

This report summarizes the design framework for establishing the Lake Wales Ridge Monitoring Network. Results of initial sampling will help to evaluate the presence of agricultural chemicals in shallow ground water, and will be used to determine the spatial and temporal variability of agricultural chemicals in ground water underlying citrus groves on the Ridge. Knowledge of this variability and its relation to natural factors and land-management practices will guide the development of the Ridge monitoring program. Design components found to be effective for this pilot study will be used to design similar networks focused on agricultural chemicals elsewhere in Florida. Establishing shallow ground-water monitoring networks in agricultural areas on Lake Wales Ridge and elsewhere in Florida is an important tool for ensuring that managment of land resources is compatible with maintaining the quality of the Florida's water resources.

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