Evaluation of the Design of a Regional Ground-Water Quality Monitoring Network, Broward County, Florida

Water-Resources Investigations Report 97-4175

U.S. Geological Survey

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Prepared in cooperation with the

South Florida Water Management District and the
Broward County Department of Natural Resource Protection

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By ROY S. SONENSHEIN

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By Roy S. Sonenshein

ABSTRACT

The Broward County ground-water quality monitoring network consists of 56 wells at 29 sites and was established in 1983 to determine areal, vertical, and seasonal variations in water quality in the Biscayne aquifer (the most permeable part of the surficial aquifer system) and to identify areas where contamination is or might be evident. Hydrogeologic and statistical approaches were used in a recent study to evaluate the design of the ground-water quality monitoring network and to assess the relation between water quality and land use.

An evaluation of the wells at each site indicates that only 14 sites contain wells capable of monitoring vertical variations in water quality in the Biscayne aquifer. The wells at these sites are completed in the upper zone of the surficial aquifer system and in the production zone of the surficial aquifer system (Biscayne aquifer). Because of the uncertainty in the aquifer production zone boundaries, wells at all of the sites, except one, can be considered completed in the production zone. However, seven sites are considered to be without a well completed in the upper zone.

Simulated areas of contribution characterized by a short relative length are ideal to meet network goals because these areas are probably representative of the actual areas of contribution. The area of contribution for 18 wells at 16 sites was in the short-length category, and areas for 3 wells at 3 other sites were at the low end of the medium-length category. Stresses on the ground-water flow system, including drainage canals and well fields, significantly affect the length of the area of contribution at 10 other sites. Adding a well completed in the upper zone or replacing a well completed in the lower zone of the surficial aquifer system with one completed in the upper zone could better meet network goals at eight of these sites. Additional analyses are required at two sites to more accurately determine the area of contribution. Overall, adding, replacing, or moving wells at 10 of 29 sites could better meet the goals of the network.

The Urban Commercial/Industrial/Transportation land-use category and the Barren/Urban Open category were overrepresented in the well classifications in relation to the distribution of land uses in the study area. The Rangeland/Forested Upland/Wetland category and the Agriculture category were underrepresented. The distributions of the sewered and nonsewered categories by site closely matched the distributions for the study area.

Lower median dissolved-solids concentrations seem to relate to land use at wells classified as Urban Commercial/Industrial/Transportation. Elevated total organic carbon concentrations could be explained by the prevalence of organic soils in some parts of the study area. Concentrations of nitrite and nitrite plus nitrate above the detection limit were measured in water samples from only three wells. Higher median concentrations of orthophosphate were related to land use where wells are classified as Agriculture, Barren/Urban Open, and Urban Commercial/Industrial/Transportation. Elevated chromium concentrations are possibly related to the type of well casing;

however, no relation between chromium concentration and land use is apparent. Elevated lead and zinc concentrations were associated with wells classified as Urban Commercial/Industrial/Transportation. Water samples from wells classified as Barren Urban/Open also contained relatively high concentrations of lead and zinc. Canals were considered possible sources of lead and zinc related to the Barren Urban/Open land-use category.

INTRODUCTION

Land use can significantly affect ground-water quality. Consequently, specific information that relates land-use effects to ground-water quality is necessary to properly manage land-use and ground-water resources (Kudrna, 1978; Yangen and Born, 1990). Regional monitoring networks can be established to delineate background concentrations of water-quality constituents in an aquifer and to monitor the effects of land use on the quality of ground water. However, costs of drilling, sampling, and water-quality analyses can limit the design of these networks.

Evaluating the design of the monitoring network for determining the effects of land use on ground-water quality is difficult in Broward County. Land use varies spatially and temporally, and the surface areas contributing flow to the network wells are not easily defined and could vary with changing hydrologic conditions. The nature of any potential contaminant sources must also be considered. There are two broad categories of contaminant source, point and nonpoint. Point sources of contamination, such as leaking underground storage tanks, are limited in space and time. Monitoring systems used to detect known point-source contamination can be developed in space and time based on the location of the point source. Nonpoint sources of contamination, which might be characteristic of a specific land use, can significantly affect the regional (ambient) ground-water quality of an aquifer. Networks designed to monitor nonpoint contamination can be complex and require a relatively large number of well sites, if land uses are varied and mixed.

Two types of general approaches for planning and designing ground-water quality monitoring networks are described by Loaiciga and others (1992, p. 19-30). These same approaches, described below, might also be used to evaluate the design of existing monitoring networks:

- Hydrogeologic approach—This approach is best suited for site-specific studies, such as detection or compliance network design where there are sufficient hydrogeologic data to develop a ground-water flow model.
- Geostatistical approach—This approach is best suited for regional studies, such as the development of an ambient ground-water quality monitoring network.

A ground-water quality monitoring network was developed by the U.S. Geological Survey (USGS) for the Broward County Department of Natural Resource Protection (DNRP) in 1983 to determine the areal, vertical, and seasonal variations in water quality in the unconfined Biscayne aquifer and to identify areas where contamination is evident or where there is potential for contamination (Waller and Cannon, 1986, p. 1-2). The DNRP network is part of a statewide ambient ground-water quality monitoring network. This statewide network was enacted by the State of Florida in 1983, authorized by the Water Quality Assurance Act, to detect ground-water contamination (Herr and Shaw, 1989, p. 1-3). Sites for the DNRP network were selected to provide areal coverage of eastern Broward County; however, no consideration was given to the land uses that might affect the quality of water sampled from each network well. Because different land uses can correspond to different water-quality effects, an ideal network would include wells designed to monitor specific land-use categories. An evaluation of the existing DNRP ground-water quality monitoring network is needed to determine if network goals are being met and to determine if land use significantly affects network results.

The USGS, in cooperation with the South Florida Water Management District (SFWMD) and the Broward County DNRP, began a study in 1991 to: (1) develop criteria for monitoring saltwater intrusion, water-table elevations, well-field protection zones, and regional water quality; (2) develop methods for designing monitoring networks based on mathematical models and statistical techniques; (3) examine existing regional monitoring networks with the ultimate objective of eliminating wells that are redundant; (4) determine locations where additional wells are needed; and (5) optimize temporal measurements. The results of the study are presented in two phases. Phase 1 describes a spatial and temporal statistical analysis of the existing Broward County ground-water level monitoring network, and the results are presented in a report by Swain and Sonenshein (1994). Phase 2 evaluates the design of the DNRP ground-water quality monitoring network in Broward County, and the results are presented in this report.

Purpose and Scope

The purposes of this report are to: (1) evaluate the design of the DNRP ground-water quality monitoring network in Broward County, and (2) assess the relation between water quality and land use. Hydrogeologic and statistical approaches were used to evaluate the design of the network and to assess the relation between water quality and land use.

The hydrogeologic approach required the use of an existing three-dimensional, ground-water flow model of the surficial aquifer system in Broward County, a particle-tracking program, and a Geographic Information System (GIS). The existing ground-water flow model, developed by Restrepo and others (1992) using MODFLOW (McDonald and Harbaugh, 1988), was used to simulate the ground-water flow system for representative dry and wet seasons, assuming steady-state conditions. The particle-tracking program, MODPATH (Pollock, 1989), used the flow model input stress data sets and the ground-water head and cell-by-cell flux data output by the flow model to determine flow paths leading to the vicinity of each well. Land uses that overlie the flow paths leading to the wells were identified using existing land-use data (Sonenshein, 1992; 1995). Comparisons were made using the GIS between the distribution of land uses that overlie the flow paths and the total distribution of land uses within all of eastern Broward County.

The statistical approach required the use of box plots to assess the relation between water quality and land use. The constituents selected for water-quality analysis included dissolved solids, total organic carbon, nitrite, nitrite plus nitrate, orthophosphate, chromium, lead, and zinc.

In this report, the hydrogeologic and statistical approaches are described in detail. The ability of the DNRP ground-water quality monitoring network to meet its goals are subsequently discussed and summarized herein.

General Hydrogeology, Ground-Water Flow, and Water Quality

Broward County is located in southeastern Florida (fig. 1) and encompasses an area of about 1,220 mi^2 (square miles). The study area covers about 424 mi^2 and is limited to the section of Broward County east of Water Conservation Areas 2A, 2B, and 3 (fig. 1). The water-conservation areas are maintained as a wetlands to supply water for urban, agricultural, and industrial needs in coastal Dade and Broward Counties and to supply water to Everglades National Park (south of Water Conservation Area 3).

The surficial aquifer system in eastern Broward County (fig. 2) consists primarily of cavity-riddled limestone and sandstone, sand, shell, and clayey sand and extends from land surface to the top of the intermediate confining unit (Fish, 1988, p. 15). Lateral hydraulic conductivity of the surficial aquifer system varies widely. Local aquifers are separated vertically by semiconfining units. The Biscayne aquifer, the most permeable part of the surficial aquifer system, is the sole source of public-water supply for Broward County (Federal Register Notice, 1979). Geologic and hydraulic characteristics were used by Fish (1988, p. 20) to define the extent of the Biscayne aquifer. The aquifer consists of highly permeable limestone and calcareous sandstone of Pleistocene and Pliocene age. Lateral hydraulic conductivities often exceed 10,000 ft/d (feet per day) in solution-riddled formations. The Biscayne aquifer pinches out at land surface in western Broward County. Near the coast, the maximum depth to the base of the aquifer is greater than 320 ft (feet) below sea level (Fish, 1988, p. 61).

The surficial aquifer system is divided into three zones (fig. 2) for this report: an upper zone, a middle zone (or production zone), and a lower zone. The upper zone extends from the water table to the production zone and consists of surficial peat and muck layers and less permeable units of the upper part of the Biscayne aquifer (Pamlico Sand and Miami Limestone). The production zone consists of highly permeable units of the Biscayne aquifer (Fort Thompson Formation, Anastasia Formation, and Key Largo Limestone). The lower zone consists of the Tamiami Formation, which extends from the base of the production zone to the intermediate confining unit.

Recharge to the surficial aquifer system is derived from two sources, rainfall and primary canals. Rainfall infiltrates directly into the aquifer. Average annual rainfall is more than 60 in. (inches) and ranges

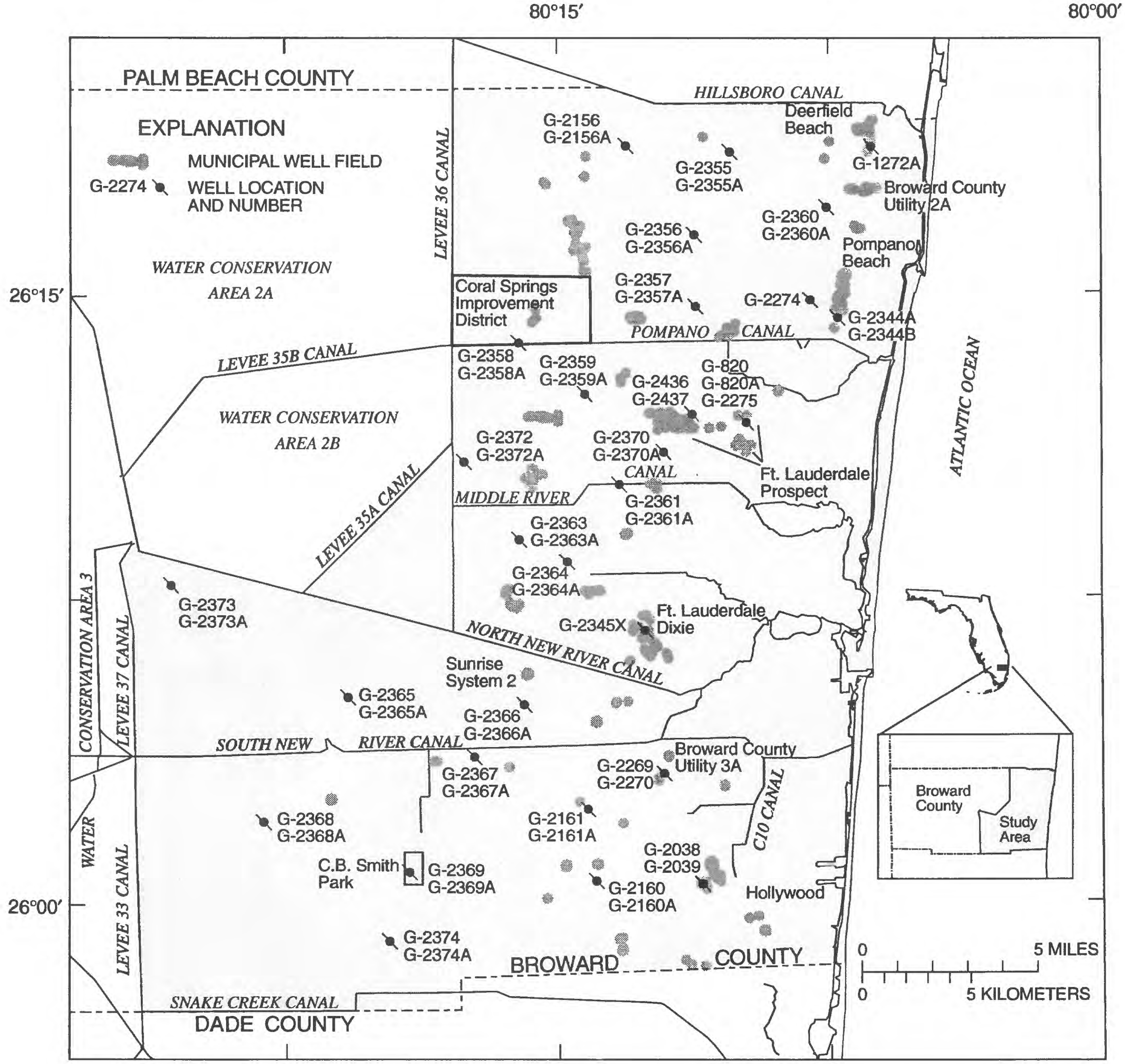

Figure 1. Eastern Broward County showing location of study area, wells, and municipal well fields.

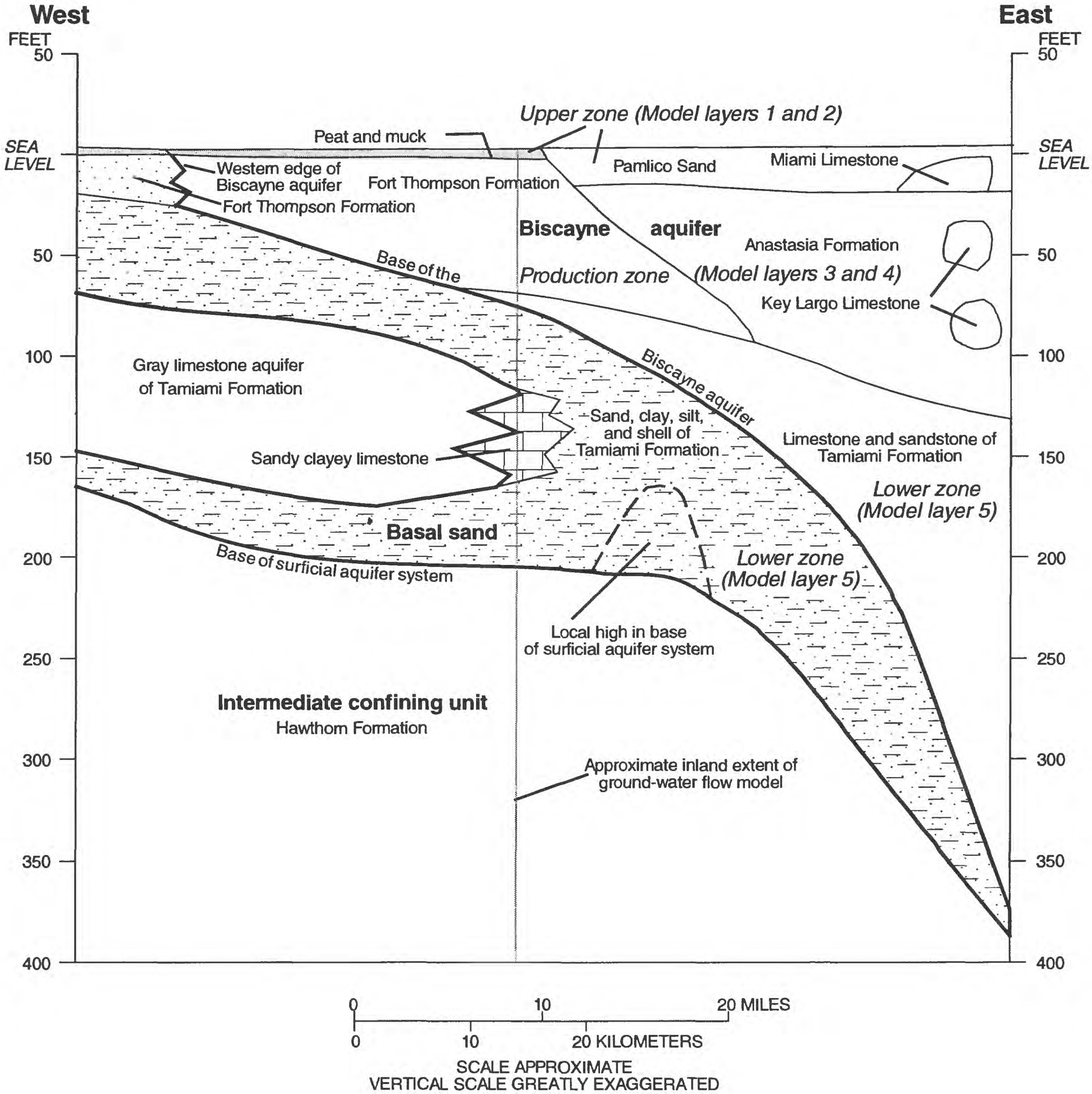

Figure 2. Schematic relations of model layers and geologic formations, aquifers, and confining units of the surficial aquifer system across Broward County (modified from Fish, 1988, p. 17).

from 30 to 100 in. (Jordan, 1984, p. 19-20). Rainfall follows a seasonal pattern, with approximately 70 percent of the annual rainfall usually occurring June to October (Jordan, 1984, p. 22). During dry periods, water stored in water-conservation areas (fig. 1) to the west and north is moved by gravity and by pumps to primary canals and therein toward the coast where it leaks into the surficial aquifer system.

Regional ground-water flow directions in the surficial aquifer system are determined by pumping from the large municipal well fields (fig. 1) and by surface-water management (fig. 3). Prior to development, ground-water flow was from the Everglades (present-day water-conservation areas and western part of the study area) toward the Atlantic Ocean, generally in an easterly or southeasterly direction. However, well fields, levees, and canals have altered natural flow patterns, as shown by a regional water-table contour map (fig. 4). Pumping at the large well fields in northern Broward County has created several cones of depression intercepting regional flow that previously discharged to the Atlantic Ocean. Levees impound surface water, creating high ground-water gradients. The canals were divided into three classes, designated by Fish (1988, p. 69) as gaining, losing, and crossflow. Gaining canals drain water from the aquifer, and losing canals recharge the aquifer. At crossflow canals, ground water flows across or under the canal. A canal can be in different classes during different times of the year, or different reaches of a canal can be in different classes during the same time period. Canal water levels are regulated by the operation of a network of control structures and pumps (fig. 3), thus, controlling water levels in the surficial aquifer system. Certain coastal areas in Broward County are generally unaffected by the operation of these control structures and pumps.

Ground-water flow directions for short periods might be different than the regional flow directions. Brief, local, intense thunderstorms, which are common during the wet season, might result in local ground-water flow directions that are far different than regional flow directions. The opening and closing of surface-water gated structures and the pumping in canals could alter the stage in a canal, causing a particular reach to change from a gaining to a losing condition or the reverse. The area of influence of a canal is affected by many factors, such as the amount of time that particular operating conditions are in effect. The operation of surface-water gated structures and pump stations is usually determined either by stages in the canal or by gradients across the gated structure or pump station. If the conditions requiring a change in the operation of the gated structure or pump station are relatively brief, the corresponding influence on ground-water flow directions would also be brief and the area influenced by such changes would be relatively small.

Pumping of ground water from small municipal well fields and for domestic supply, irrigation, or other uses is intermittent but might also change ground-water flow directions in the immediate vicinity of the well for a short period. Additionally, the volume of water withdrawn from each well for these purposes is relatively small, compared to the total flow through the surficial aquifer system around the well. Effects of these withdrawals on the surficial aquifer system are usually not considered in regional analyses of the study area.

Ground-water quality in the Biscayne aquifer in Broward County has been characterized by Howie (1987) and Radell and Katz (1991). The water is predominantly a calcium bicarbonate type and is generally potable, except in saltwater-intruded areas near the coast. Generally, major-ion chemistry is areally uniform. Calcium, sodium, bicarbonate, and dissolved-solids concentrations greatly increase with well depth, whereas potassium and nitrate concentrations greatly decrease with well depth. No significant seasonal variation is apparent in the major-ion concentrations. The areal and vertical distribution of selected trace-metal concentrations (barium, chromium, copper, lead, and manganese) is not distinct, although dissolved concentrations of these metals were detected in 50 percent or more of the analyses studied by Radell and Katz (1991, p. 12).

Previous Studies

Many publications are available that present water-quality data and describe the effects of land use on water quality. A regional analysis of ground-water quality in Broward County was conducted by Howie (1987). The major-ion and selected trace-metal chemistry of the Biscayne aquifer in southeastern Florida was characterized by Radell and Katz (1991). The potential for ground-water contamination in Polk County, Fla., was estimated and related to land use and hydrogeologic factors by Barr (1992). Rutledge (1987) analyzed the effects of four regional land-use types on ground-water quality in central Florida. A study of the effects of land use in the mostly undeveloped East Everglades area of Dade County was conducted by

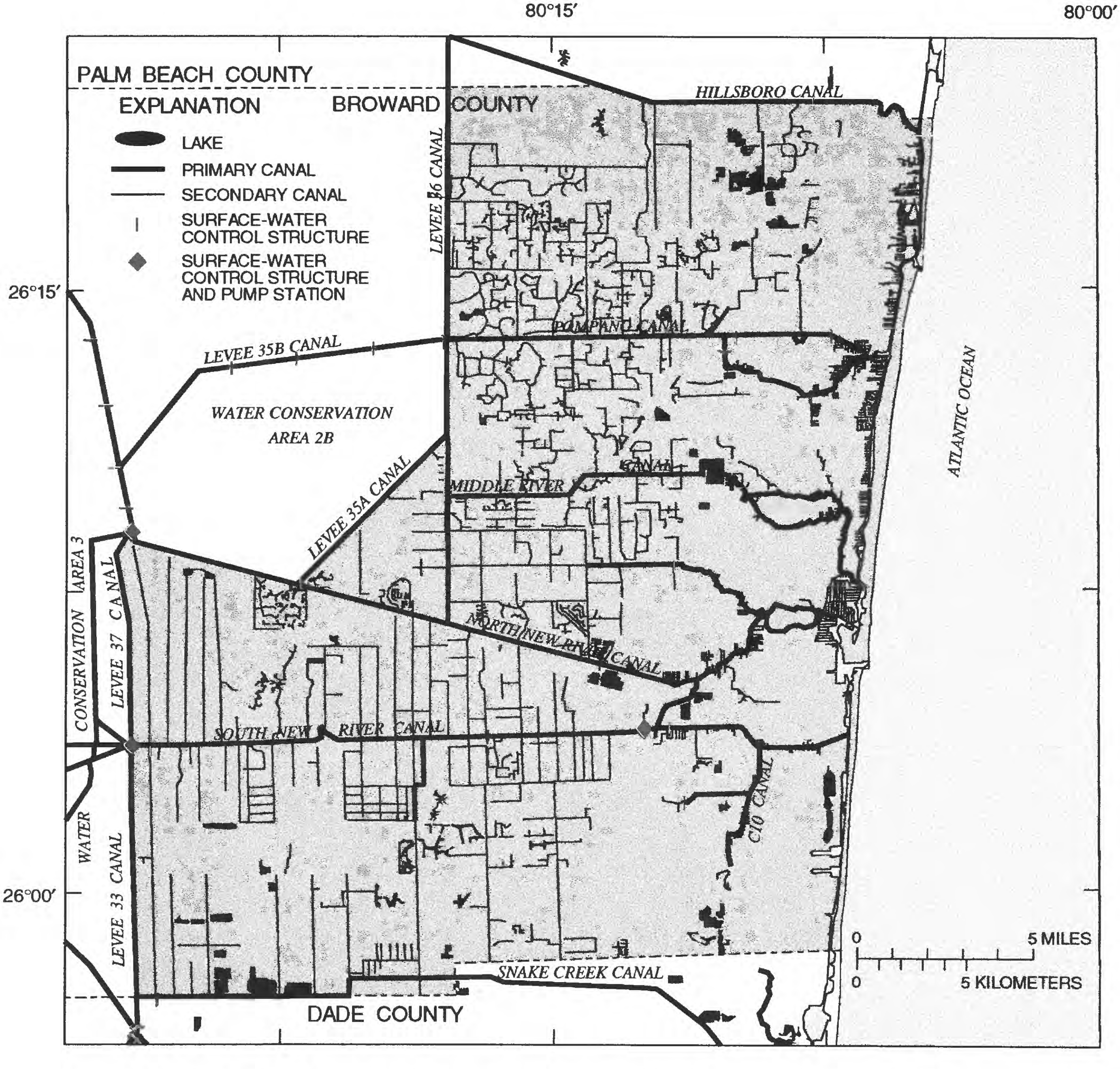

Figure 3. Eastern Broward County showing selected lakes, primary and secondary canals, control structures, and pump stations.

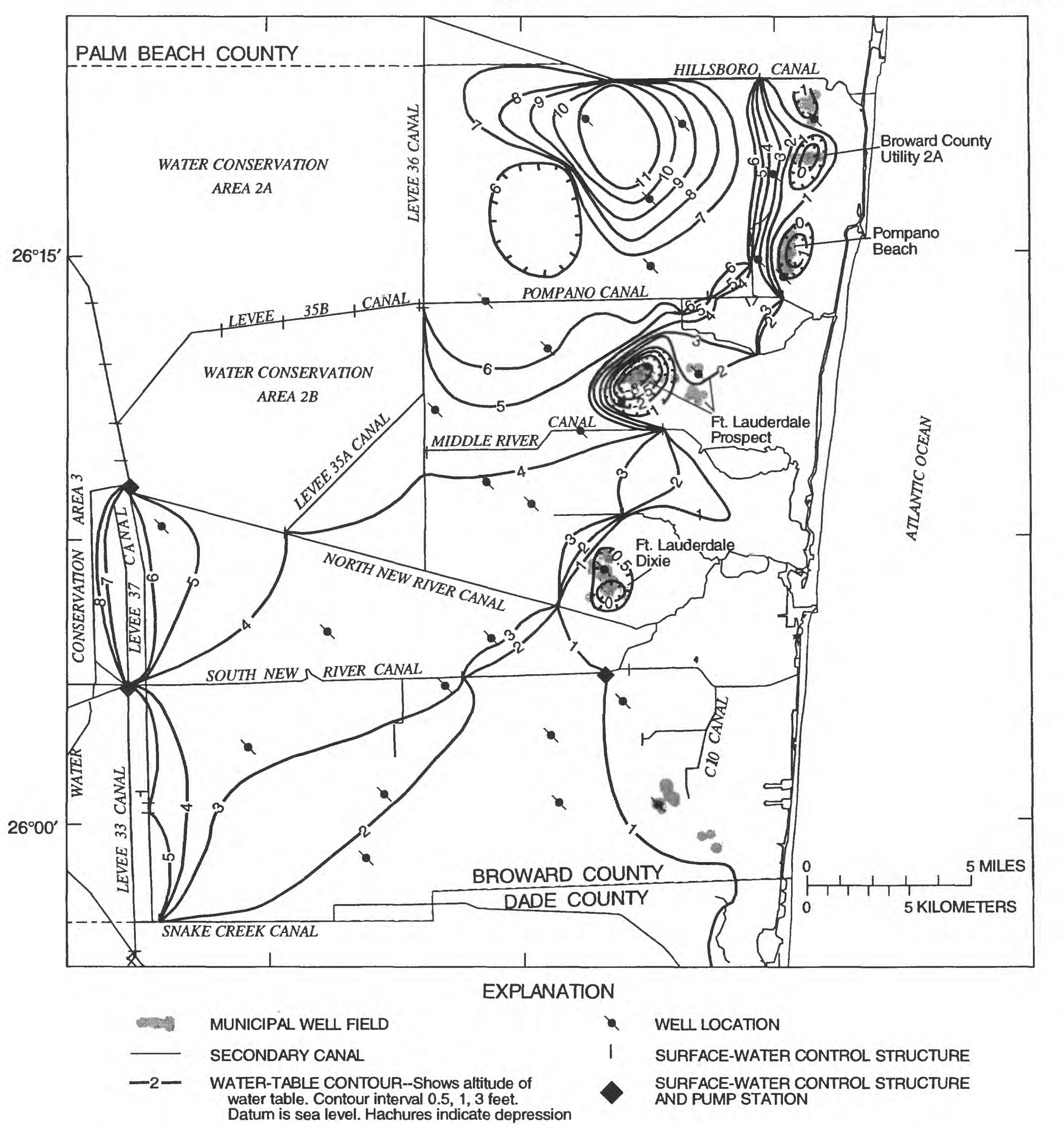

Figure 4. Eastern Broward County showing altitude of the water table in the Biscayne aquifer, April 26-29, 1988 (modified from Lietz, 1991).

Waller (1983). Barton and others (1987) evaluated the relation between water quality and land use using the Kruskal-Wallis test and frequency-of-detection methods in a coastal aquifer system in New Jersey. Similar studies were accomplished in Colorado (Cain and Edelmann, 1986), Connecticut (Grady and Fisher-Weaver, 1988), Long Island, N.Y. (Eckhardt and others, 1989), and Nebraska (Chen and Druliner, 1987). In Florida, the chemical effects of highway runoff on ground-water quality were studied by Howie and Waller (1986). Similar studies of ground-water quality evaluated the effects of spray irrigation using treated municipal sewage (Yurewicz and Rosenau, 1986), effluent migration from septic-tank systems (Waller and others, 1987), and the surface application of dried wastewater-treatment sludge (Howie, 1992).

Rating systems based on hydrogeologic characteristics, such as the LeGrand system (LeGrand, 1983) and DRASTIC (Aller and others, 1985), have been developed to quantify the potential for ground-water contamination from surface sources. Ground-water contamination susceptibility maps can be developed based on these types of rating systems. A GIS was used to facilitate the development of a ground-water contamination susceptibility map for Wisconsin (Wisconsin Department of Natural Resources and Wisconsin Geological and Natural History Survey, 1987). A statewide ground-water monitoring network was developed based on ground-water contamination susceptibility maps for Illinois (O'Hearn and Schock, 1985). A DRASTIC analysis was completed for Broward County by Herr (1990, p. 23). A method for locating wells using ground-water flow simulation and optimization techniques was described by Meyer and Brill (1988).

METHODS OF EVALUATION

The present study was conducted along three lines of research: (1) a hydrogeologic approach to determine the area of contribution using an existing flow model, (2) classification of network wells based on the hydrogeologic approach, and (3) a statistical approach to assess the relation between water quality and land use. This section presents a description of the methods that were used to conduct this research on the DNRP ground-water quality monitoring network in Broward County.

Evaluation of the DNRP ground-water quality monitoring network requires delineation of the surface area which may be affecting the quality of water sampled from network wells. The term "area of contribution" refers to the surface area from which water enters the ground-water system at the water table, eventually flowing to and discharging from a well, such as a municipal supply well (Reilly and Pollock, 1993, p. 2). Wells within the DNRP ground-water quality monitoring network are not discharging wells (except for the brief period when the well is purged prior to obtaining the water sample); therefore, they do not have an area of contribution according to the above definition. In this report, the area of contribution to a passive well is defined as the surface area overlying the ground-water flow paths traced back to land surface from the vicinity of the well. The method used to determine the area of contribution is described in the next section of this report.

Hydrogeologic Approach to Determine Area of Contribution Using an Existing Model

A hydrogeologic approach was used to determine the area of contribution to each well in the DNRP ground-water quality monitoring network. This approach, which required the use of an existing ground-water flow model, a particle-tracking program, and a GIS, was developed in a previous study (Sonenshein, 1995) to identify land uses that overlie flow paths leading to wells. A complete description of the existing ground-water flow model and its limitations are presented in subsequent sections of this report.

Previous investigators often relied on estimates of ground-water flow direction to determine placement of wells (Waller, 1983; Howie and Waller, 1986; Yurewicz and Rosenau, 1986; Waller and others, 1987; and Howie, 1992). Rutledge (1987) and Barr (1992) related the quality of water obtained from selected wells to the land use surrounding the wells. Vowinkel and Battaglin (1989) used circular buffers of varying lengths around individual wells to identify the land uses most probably affecting the quality of water sampled from each well. More recently, investigators have applied a hydrogeologic approach, using the results from a ground-water flow model and particle-tracking postprocessing software to determine the area of contribution to discharging wells (Hutchinson, 1990; Bailey, 1993; and Zarriello, 1993). However, because wells within the DNRP ground-water quality monitoring network are not discharging wells, the areas of contribution to these wells are not easily defined and could vary with changing hydrologic conditions.

The three-dimensional, ground-water flow model, developed by Restrepo and others (1992) using MODFLOW (McDonald and Harbaugh, 1988), was used to simulate ground-water flow representative of dry- and wet-season conditions (May and August 1989) in the surficial aquifer system assuming steady-state conditions. By comparing the results of two differently stressed (seasonal) steady-state simulations, the variations in the area of contribution resulting from different hydrologic and water-use conditions can be estimated. A transient simulation, which permits a more realistic representation of seasonal variations in ground-water flow, would have been preferred for this analysis. However, the version of the MODPATH particle-tracking program used for this report requires output from a steady-state solution. Generally, recharge is greater, ground-water withdrawals are lower, and drain and river stages are higher for the wet-season simulation than for the dry-season simulation.

Flow paths leading to the wells were determined using the MODPATH particle-tracking software. The MODPATH program uses the MODFLOW input data sets and the ground-water head and cell-by-cell flux data output by the MODFLOW code to compute the flow paths of ground water. The options, specified as part of the execution of the MODPATH program, are: (1) output data are stored as flow-line coordinates, (2) particle locations are not simulated at intermediate times, (3) particles are tracked backward toward recharge locations, (4) particles are allowed to pass through cells with weak sinks–these cells contain sinks that discharge only part of the water entering the cell (Pollock, 1989, p. 19), (5) no model zones are specified in which particles stop when they enter these zones, and (6) recharge and evapotranspiration are assigned to the top face of cells.

The MODPATH program requires a porosity value for each model grid cell to calculate the traveltime for each particle. These porosity values are not part of the input data for the MODFLOW steady-state solution and have no effect on the flow path. The traveltime is directly proportional to the porosity, with time of travel increasing with increasing porosity. Because only relative traveltimes are required for the procedure presented in this report, a detailed porosity analysis was not attempted. A porosity of 0.3 (30 percent) was assigned to every model grid cell based on values reported by Fish (1988, p. 37) for selected rock samples.

The flow direction variability is significant in the surficial aquifer system. Water levels and flow directions might change rapidly in water-table aquifers because of changes in recharge rate, well-field pumping rate, and surface-water controls. Additionally, flow paths generally do not converge at the wells. Backtracking from the well location would not define a representative area of contribution (only a narrow zone of flow along the particle paths directly related to the well). Thus, backtracking particles were placed at the edges of the grid cell containing the well to determine the variability in flow conditions and directions that occur in the aquifer in the vicinity of the well that is not accounted for in the steady-state simulations.

Sixteen particles were initially selected to backtrack from each grid cell containing a well (fig. 5). Four particles are located on each vertical face of the grid cell in which the open interval of the well is located, two at the top and two at the bottom of the open interval of the well. Each particle is located on the cell face at a distance from the edge of the cell face equal to one-third of the total width of that face.

The particle pathlines selected to determine the area of contribution for a well depends upon the location of the well within the model grid cell. Using the example shown in figure 5, particles, 1, 2, 9, and 10 would be selected to represent flow to a well located at site A; particles 3, 4, 11, 12, 13, and 14 would be selected for a well located at site B; and particles 5, 6, 7, 8, 11, 12, 13, 14, 15, and 16 would be selected for a well located at site C. Different particle pathlines might be indicated for different time periods because of the variability in flow paths under different hydrologic conditions.

Pathlines simulated by MODPATH might be different from the actual pathlines because of four factors: (1) the pathlines depict an average path of travel for particles of water that are sampled from a well under steady-state conditions for a given time period; (2) the ground-water flow model assigns data values to the center of grid cells, which represent an average of the conditions within the cell over a given time period; (3) the flow paths of individual particles tend to deviate from the average flow path of all the water particles due to small-scale dispersion; and (4) the simulated system is an approximation of the true ground-water system. Therefore, a region around each pathline is selected to represent the area through which the actual pathline

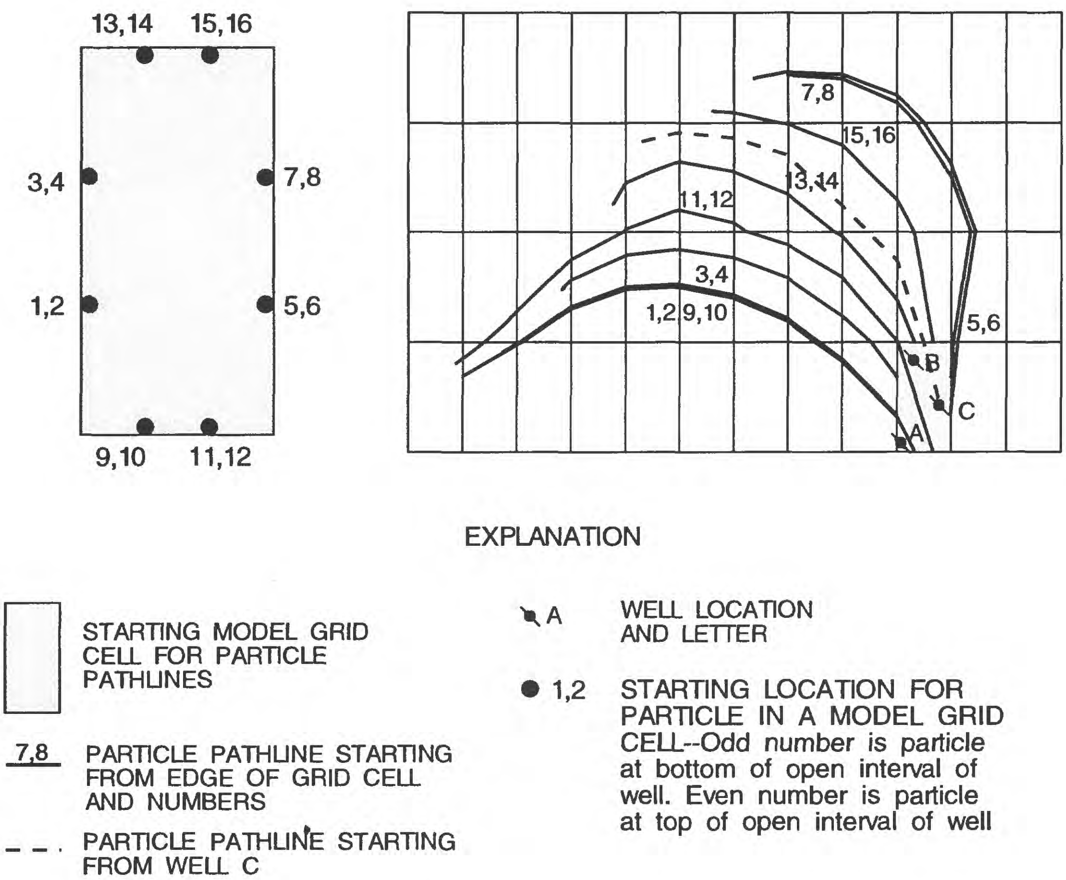

Figure 5. Example of a model grid showing particle paths simulated by MODPATH.

can pass. These regions represent areas of potential contribution to the water sampled from each well.

Two areas of contribution were defined for each well using the wet- and dry-season pathlines. An arbitrary distance of 500 ft around each pathline (one-half of the minimum model grid cell dimension) was used to define this area of contribution. The wet- and dry-season areas of contribution were combined to produce a single region representing the total area of contribution to each well. If the wet- and dry-season areas of contribution varied significantly, this approach was not valid. A GIS was used to identify the land use and sewered or nonsewered areas that lie within the simulated area of contribution and at each well location.

The land uses that occur in these areas of contribution overlie, but do not necessarily contain the recharge points for, simulated flows paths leading to each well. The model represents recharge as the average rate for each grid cell that occurs continuously during a given simulation. However, recharge actually occurs during relatively brief periods of time. During actual recharge, relatively high vertical gradients often are created in the ground-water flow system, and water infiltrating at the surface moves progressively down through the aquifer system. This component of flow, substantially vertical, is not characteristic of steady-state conditions and is not simulated by MODFLOW. Additionally, diffusion and dispersion, which can cause vertical and horizontal motion of particles, are not simulated by MODFLOW. Thus, all land uses in the area of contribution defined for each well could potentially affect the quality of water sampled from the well, even though the output from MODPATH might not indicate this situation (Reilly and Pollock, 1993, p. 20).

Description of Existing Ground-Water Flow Model

As previously stated, the hydrogeologic approach required use of a ground-water flow model (as well as MODPATH and GIS) to determine the area of contribution to each well in the DNRP ground-water quality monitoring network. A three-dimensional, ground-water flow model of the surficial aquifer system in eastern Broward County was developed by SFWMD to be used as a basis for ground-water elements in the Broward County Water Supply Plan (Restrepo and others, 1992, p. 1). The surficial aquifer system can be modeled in a hydraulically similar fashion to granular porous media, as previously documented through the use of aquifer tests (Fish, 1988, p. 21-35) and through successful calibration of porous-media models of the surficial aquifer system (Merritt, 1996; Swain and others, 1996). The USGS modular, three-dimensional, ground-water flow model code, MODFLOW (McDonald and Harbaugh, 1988), is capable of simulating ground-water flow in anisotropic, heterogeneous, and layered aquifer systems and was selected for development of the Broward County model by Restrepo and others (1992, p. 5). A block-centered finite-difference approach is employed in the code to simulate ground-water levels and flow, using data that quantify aquifer characteristics (transmissivity, specific yield and storage, and vertical conductance) and aquifer stresses (recharge, evapotranspiration, well withdrawals, and surface-water interactions). A three-dimensional model was required because of the vertical heterogeneity within the surficial aquifer system. The model was calibrated using steady-state and transient simulations.

The model area encompasses about 630 mi^2 (fig. 6) and includes all of eastern Broward County, parts of Dade and Palm Beach Counties, and parts of the water-conservation areas (fig. 1). Although the primary objective of the model is to simulate ground-water flow in eastern Broward County, parts of Dade and Palm Beach Counties are included to provide realistic hydraulic boundary conditions. The model grid (fig. 6) consists of 13,400 uniform grid cells totaling 2,000,000 ft^2 (square feet) each, of which 8,780 are active and 4,620 are inactive (no flow). The grid consists of 100 rows with a spacing of 1,000 ft and 134 columns with a spacing of 2,000 ft. Vertically, the model contains five layers representing various permeable units of the surficial aquifer system. The ranges of top and bottom elevations, thicknesses, and hydraulic properties for each layer are given in table 1.

The top two model layers define the low-permeability surface units of the upper zone of the surficial aquifer system (fig. 2). Layer 1 accounts for soil conditions and surface features. All river, drain, recharge, and evapotranspiration cells are included in this layer, which has a maximum thickness large enough (25 ft) to

Table 1. Ranges of elevations, thicknesses, and hydraulic properties of the model layers

[Layers 1 and 2 represent the upper zone of the surficial aquifer system, layers 3 and 4 represent the production zone of the surficial aquifer system, and layer 5 represents the lower zone of the surficial aquifer system]

Layer	Top elevation[1] (feet above or below sea level)	Bottom elevation (feet below sea level)	Thickness (feet)	Lateral hydraulic conductivity (feet per day)	Transmissivity (feet squared per day)	Vertical leakance[2] (feet per day per foot)
1	1.0 - 19.8	16.5 - 5.0	14.9 - 25.0	25 - 527	See footnote 3	0.0206 - 18.50
2	16.5 - 5.0	90.0 - 10.6	5.0 - 82.4	33 - 1,119	322 - 13,851	0.0248 - 13.00
3	90.0 - 10.6	126.4 - 28.6	2.9 - 60.0	60 - 14,908	180 - 595,337	0.2330 - 75.70
4	126.4 - 28.6	168.6 - 36.6	2.9 - 60.0	60 - 14,908	180 - 595,337	0.0332 - 4.28
5	168.6 - 36.6	320.2 - 109.0	10.0 - 230.3	33 - 93	536 - 15,178	Not required

[1]Values shown in feet above sea level for layer 1; values shown in feet below sea level for layers 2 to 5.

[2]Vertical leakance is used by MODFLOW to compute vertical flow from a layer to the layer below and is defined by McDonald and Harbaugh (1988, p. 5-11 to 5-12).

[3]Transmissivity for layer 1 varies with the water level.

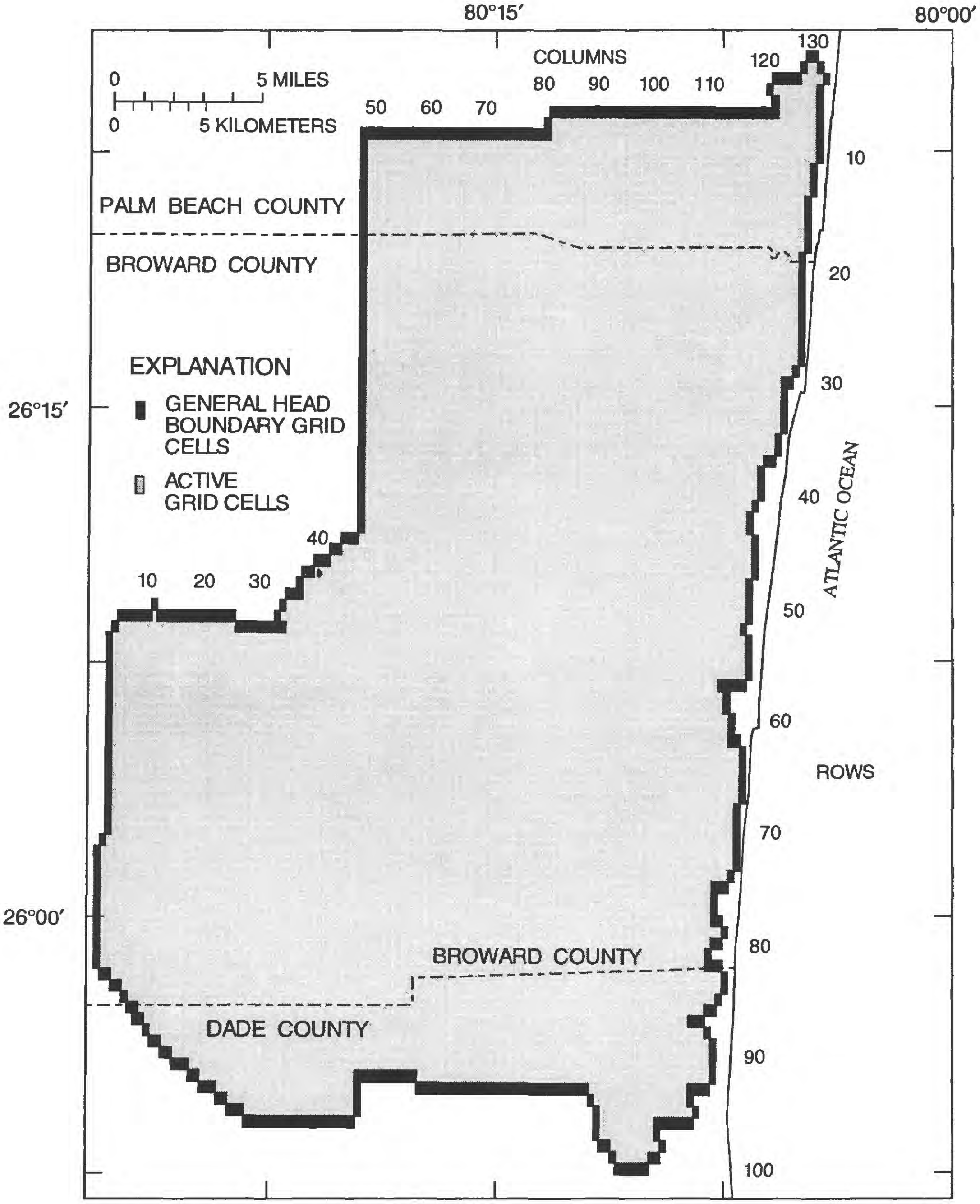

Figure 6. Model area showing general head boundary and active grid cells.

avoid drying of these cells (caused by numerical iterations) during model simulations. The second layer extends to the top of the highly permeable limestones of the Biscayne aquifer. Layers 3 and 4 represent the production zone of the surficial aquifer system (fig. 2). The midpoint of the production zone was used to define the bottom of layer 3 (top of layer 4). The less-permeable sands, silts, and shell-rich units of the surficial aquifer system of the Tamiami Formation are represented by layer 5 (fig. 2).

No-flow, general-head, and general-head acting as specified head boundaries were used in the model to simulate a constant-head boundary around the edge of the active model cells. The Atlantic Ocean and the water-conservation areas (fig. 1) were selected as the eastern and western boundaries, respectively. Major canals in Palm Beach and Dade Counties were selected as the northern and southern boundaries, respectively. The boundaries selected are far enough from the study area (Broward County) to prevent stresses in the study area from affecting the boundaries and to avoid boundary flow effects within the study area (Restrepo and others, 1992, p. 11).

The ground-water flow model was calibrated using both steady-state and transient conditions (Restrepo and others, 1992, p. 25-31). The initial steady-state calibration was used to detect errors in the input data sets, make initial adjustments to the aquifer parameters, and generate starting heads for the transient runs. Steady-state runs were used to calibrate the model for conditions in January 1983 and January 1989, and for average conditions in 1989. Transient runs were used to calibrate the model using monthly stress periods with five time steps for the periods January 1983 to December 1985 and January 1989 to December 1989. Various model parameters were modified during the calibration process, including canal-bed conductances, lateral hydraulic conductivity, vertical anisotropy of the model layers, evapotranspiration surface elevations, and storage coefficients. A trial-and-error process was used to match simulated ground-water levels to observed water levels at the end of each stress period. Observed water levels were obtained from 46 wells monitored with continuous recorders or monthly measurements by the USGS. The average absolute error between simulated and observed water levels was less than 0.75 ft. A sensitivity analysis indicated that the model is most sensitive to changes in lateral hydraulic conductivity and canal-bed conductance (Restrepo and others, 1992, p. 35).

Model Limitations

The three-dimensional, ground-water flow model developed by Restrepo and others (1992) and related particle-tracking analyses are idealized approximations of reality, and several factors should be considered when interpreting simulation results. The uncertainty inherent in most estimates of hydrogeologic parameters and boundary conditions is the most important limitation to consider when evaluating ground-water flow model output (Pollock, 1989, p. 20).

Another limitation is the use of a discrete network of finite-difference cells to represent the ground-water flow system. As the cell size increases, the correspondence of model simulations to local ground-water flow conditions decreases. For example, the width of the canals in Broward County (generally no more than 100 ft) is significantly less than the dimensions of the grid cells in the Broward County model (1,000 by 2,000 ft). Therefore, the simulated response of the ground-water system to canal stage is represented at a coarser scale than the actual effects of the canals.

The critical limitation of the MODPATH particle-tracking program is the inability of the version of MODPATH used for this report to simulate advective transport under transient flow conditions. This limitation results from the desire to design an efficient computer program that produces a manageable amount of numerical output (Pollock, 1989, p. 19). Thus, any variations in flow direction occurring over time periods that exceed the length of the steady-state conditions represented in the model will not be accounted for by the MODPATH simulations used in this report. The resulting flow paths simulated by MODPATH might be very different from the actual long-term flow paths. Also, the vertical movement of ground water in the surficial aquifer system in Broward County in response to short-term transient events, such as local rainfall and changes in the state of a canal control structure, is not represented by the model under steady-state conditions.

Many of the limitations associated with the steady-state capture area (area of contribution) analyses presented in this report are the result of dual steady-state flow simulations used to represent the wet and dry periods. An alternative approach that could be used effectively in future studies is to base capture area analyses on a single steady-state simulation that represents the average annual hydrologic conditions. A steady-state simulation of average annual conditions better represents pathlines that develop over periods of several years. In many cases, the use of an average annual steady-state simulation will produce capture areas that are very close to those predicted by a complete transient flow analysis of the system (D.W. Pollock, U.S. Geological Survey, oral commun., 1994).

Classification of Network Wells

The various classifications assigned to the wells in the DNRP ground-water quality monitoring network were based on the altitude of the well open interval and the characteristics of the areas of contribution to each network well. The altitude of the well open interval is an important factor that determines the extent of the contributing area. Wells were first classified according to the aquifer zone of the open interval of each well (table 2). Aquifer zones were determined by comparing the altitude of the open interval of each well to the corresponding altitude represented by model layer boundaries for the grid cell in which the well was located (table 3). Because the model layer boundary values represent the average value for each grid cell, the assignment of a model layer and aquifer zone may be approximate at several wells. The hydraulic characteristics of the aquifer zone containing a particle can have a significant effect on the simulated particle pathline and the related area of contribution. Errors in the simulated pathlines might occur because of the approximate boundaries assigned to the model layers. For example, an open interval near an aquifer zone boundary (between layers 2 and 3 or layers 4 and 5) increases the uncertainty in the simulated pathlines and area of contribution.

The second well classification is a comparison of the simulated wet- and dry-season areas of contribution. The similarity between the flow directions and distances, when considered in combination with the total traveltime along the pathlines, is an indication of how well the simulated areas correspond to the actual areas of contribution. If the simulated traveltime is much greater than the length of a wet or dry season (6 months) and the direction of flow toward the well from the two areas is markedly different, then the particle flow paths might not accurately represent the actual area of contribution.

The third well classification is the relative length of the area of contribution to each well. This measurement is an indication of the total area of contribution to the well based on the length of the longest particle pathline. The accuracy in predicting the area of contribution increases with a decrease in the length of the area. Generally, the farther the particles are backtracked from a well, the larger the traveltime, resulting in a greater error in accurately predicting the particle path due to the model limitations previously described. The total area, a function of the subjective selection of the number of particles used to represent each well, could be a biased classification, and therefore, was not used to classify the wells. The three categories used for length and the number of wells in each category are listed in table 4. The lengths of contributing areas limiting each category were selected to provide an approximately equal number of wells in each category.

Land use and sewered or nonsewered areas represent the final well classifications. Land-use data for the study area in 1986 were obtained from a digital, spatial data base developed for Broward County (Sonenshein, 1992, p. 24). Land use was classified using a

Table 2. Distribution of aquifer zone by well

Aquifer zone for completion interval	MODFLOW model layers	Number of wells
Upper zone of the surficial aquifer system	1,2	21
Production zone of the surficial aquifer system	3,4	24
Lower zone of the surficial aquifer system	5	11

Table 3. Elevations for model layers in rows and columns containing wells

[Elevations, in feet above sea level for layer 1; elevations, in feet below sea level for all other layers]

Well number	Top of layer 1	Top of layer 2	Top of layer 3	Top of layer 4	Top of layer 5	Bottom of layer 5
G-820	8.90	15.00	39.30	69.30	99.30	294.91
G-820A	8.60	15.00	39.70	72.90	106.10	292.72
G-1272A	14.40	10.60	90.00	124.90	159.80	278.31
G-2038	10.00	15.00	27.20	76.10	125.10	246.54
G-2039	10.00	15.00	27.20	76.10	125.10	246.54
G-2156	14.00	11.00	90.00	114.70	139.40	240.38
G-2156A	14.00	11.00	90.00	114.70	139.40	240.38
G-2160	8.00	15.00	38.90	78.00	117.10	213.17
G-2160A	8.00	15.00	38.90	78.00	117.10	213.17
G-2161	5.00	15.00	38.40	77.20	116.00	196.20
G-2161A	5.00	15.00	38.40	77.20	116.00	196.20
G-2269	7.00	15.00	31.70	74.70	117.70	259.96
G-2270	7.00	15.00	31.70	74.70	117.70	259.96
G-2274	9.20	15.00	43.60	75.20	106.70	303.54
G-2275	8.60	15.00	39.70	72.90	106.10	292.72
G-2344A	10.60	14.40	40.00	72.20	104.50	317.14
G-2344B	10.60	14.40	40.00	72.20	104.50	317.14
G-2345X	5.70	15.00	52.70	96.20	139.80	278.16
G-2355	13.10	11.90	84.10	122.00	159.90	177.58
G-2355A	13.10	11.90	84.10	122.00	159.90	177.58
G-2356	12.40	12.60	57.80	103.20	148.50	201.09
G-2356A	12.40	12.60	57.80	103.20	148.50	201.09
G-2357	11.60	13.40	74.50	108.80	143.10	250.67
G-2357A	11.60	13.40	74.50	108.80	143.10	250.67
G-2358	10.40	14.60	38.60	63.10	87.50	162.96
G-2358A	10.40	14.60	38.60	63.10	87.50	162.96
G-2359	10.00	15.00	52.40	87.20	122.00	195.48
G-2359A	10.00	15.00	52.40	87.20	122.00	195.48
G-2360	17.70	7.30	60.20	93.70	127.20	265.21
G-2360A	17.70	7.30	60.20	93.70	127.20	265.21
G-2361	7.50	15.00	53.10	83.70	114.20	199.14
G-2361A	7.50	15.00	53.10	83.70	114.20	199.14
G-2363	7.90	15.00	46.80	77.20	107.70	162.08
G-2363A	7.90	15.00	46.80	77.20	107.70	162.08
G-2364	5.00	15.00	55.20	93.30	131.50	185.84
G-2364A	5.00	15.00	55.20	93.30	131.50	185.84
G-2365	9.60	15.00	40.00	68.40	96.70	109.54
G-2365A	9.60	15.00	40.00	68.40	96.70	109.54
G-2366	5.90	15.00	42.50	80.10	117.60	191.42
G-2366A	5.90	15.00	42.50	80.10	117.60	191.42
G-2367	5.00	15.00	39.40	75.70	112.00	151.06
G-2367A	5.00	15.00	39.40	75.70	112.00	151.06
G-2368	5.00	15.00	27.00	53.90	80.80	144.39
G-2368A	5.00	15.00	27.00	53.90	80.80	144.39
G-2369	4.00	15.00	34.90	70.10	105.30	126.91
G-2369A	4.00	15.00	34.90	70.10	105.30	126.91
G-2370	9.30	15.00	48.40	78.20	108.10	226.83
G-2370A	9.30	15.00	48.40	78.20	108.10	226.83
G-2372	10.60	14.40	38.30	63.60	88.90	110.03
G-2372A	10.60	14.40	38.30	63.60	88.90	110.03
G-2373	7.00	15.00	27.10	37.20	47.40	177.49
G-2373A	7.00	15.00	27.10	37.20	47.40	177.49
G-2374	7.00	15.00	29.90	67.50	105.10	127.39
G-2374A	7.00	15.00	29.90	67.50	105.10	127.39
G-2336	9.40	15.00	45.50	74.90	104.20	266.35
G-2437	9.40	15.00	45.50	74.90	104.20	266.35

Table 4. Distribution of relative length of area of contribution

[<, less than the value; >, greater than the value]

Relative length of area of contribution	Range of length of longest particle pathline (feet)	Number of wells in range
Short	<600	18
Medium	600 - 5,000	17
Long	>5,000	21

system created for the Florida Department of Transportation (Kuyper, Becker, and Shopmeyer, 1981). The classification system consists of seven primary (level 1) land-use categories (table 5), all of which are present in Broward County. These categories have been divided into secondary (level 2) and tertiary (level 3) land-use categories. The Broward County land-use, digital, spatial data layer contains 22 level 2 categories (table 5). For statistical analyses, land uses present in eastern Broward County were combined into six categories (table 6). Land-use categories were combined based on the assumption of similar potential effects on ground-water quality.

The following procedure was used in classifying land use for the present study. First, the land use was identified at the well location. Next, a land use was selected for each well based on the predominant land use in the simulated area of contribution. In designating a predominant land use, emphasis was placed on the most immediate upgradient land use from the well when areas of contribution contained varied land uses. For wells with significantly different wet- and dry-season areas of contribution, land use in the regions surrounding and adjacent to these areas was also considered when assigning a land-use category.

The same procedure used in classifying land use was also used to classify each well as either in a sewered or nonsewered area, both at the well and in the area of contribution. Septic tank systems are used in nonsewered areas for the disposal of sewage and may affect the quality of water in the Biscayne aquifer (Waller and others, 1987, p. 2). Isolated undeveloped land uses, such as Forested Upland (F), Water (H), and Wetland (W), are considered sewered if the land use falls within the sewered boundaries, even though there are probably no sewer lines in the undeveloped area. A digital, spatial data layer was created showing the sewered or nonsewered areas in the study area. The data layer was prepared from a map showing sewered areas in eastern Broward County in 1993 (Broward County Department of Natural Resource Protection, 1993).

Statistical Approach to Assess Relation Between Water Quality and Land Use

Constituent concentration data obtained from water-quality analyses can be used to determine relations, or the lack of such relations, between land use and ground-water quality. Although problems, such as spatial autocorrelation and uncertainty in land-use categorical data (Barringer and others, 1990), can occur when attempting to relate land-use and ground-water quality data, a relation between regional ground-water quality and human activities has been shown to exist in many areas throughout the United States (Cain and others, 1989).

An assessment of the relation between water quality and land use was made by applying statistics to the water-quality data collected from the wells in the DNRP ground-water quality monitoring network. Eight water-quality constituents, which are common indicators of contamination, were selected for evaluation. These constituents included dissolved solids, total organic carbon, nitrite, nitrite plus nitrate, orthophosphate, chromium, lead, and zinc. A mean value for each constituent was determined for each well using the total available data base. Data reported as below a specified detection limit were assigned a value equal to the detection limit. Concentrations of several constituents including nitrite, nitrite plus nitrate, and chromium were commonly below the detection limit. Concentrations reported as less than a detection limit were considered equal to the detection limit for the statistical analyses in this report.

Table 5. Level 1 and 2 land-use codes and categories in the Broward County land-use digital spatial data layer

[From Restrepo and others, 1992, p. 88-91]

Level 1		Level 2	
Land-use code	**Land-use category**	**Land-use code**	**Land-use category**
A	Agriculture	AC	Cropland
		AF	Confined Feeding Operations
		AM	Groves/Ornamentals/Nurseries/Tropical Fruits
		AP	Pasture
B	Barren Land	BB	Beaches
		BL	Levees
		BP	Extractive (strip mines, quarries, gravel pits)
		BS	Spoil Areas
F	Forest Upland	FE	Coniferous Forests
		FM	Mixed Forests
		FO	Nonconiferous Forests
R	Rangeland	RG	Grassland
		RS	Scrub/Brushland
H	Water		
W	Wetland	WF	Forested Fresh Wetlands
		WN	Nonforested Fresh Wetlands
		WS	Forested Salt Wetlands
U	Urban Land	UC	Urban Commercial
		UI	Urban Industrial
		UO	Urban Open
		UR	Urban Residential
		US	Urban Institutional
		UT	Urban Transportation

Table 6. Distribution of combined land-use categories in eastern Broward County

Land-use code	Land-use category	Level 1 or 2 land-use categories (from table 5)
A	Agriculture	All A
G	Rangeland/Forested Upland/Wetland	All F, R, and W
H	Water	H
I	Urban Commercial/Industrial/Transportation	UC, UI, UT
O	Barren/Urban Open	All B and UO
R	Urban Residential/Institutional	UR, US

The median, 10th percentile, and 90th percentile concentrations were determined for each constituent. Box plots were prepared for all constituents (except nitrite and nitrite plus nitrate) to visually compare the median and ranges of concentrations among land-use categories. Because most of the data for the two nitrogen constituents were reported as below the detection limit, no box plots were prepared for these constituents.

EVALUATION OF THE DESIGN OF A REGIONAL GROUND-WATER QUALITY MONITORING NETWORK

The DNRP ground-water quality monitoring network in Broward County was developed in 1983 to determine the areal, vertical, and seasonal variations in water quality in the Biscayne aquifer and to identify areas where contamination is (or might be) evident. The determination of the areal, vertical, and seasonal variations in water quality and the description of water quality in the aquifers were addressed by Radall and Katz (1991). In 1991, the DNRP ground-water quality monitoring network consisted of 56 wells at 29 sites (fig. 1, table 7). Two wells are located at each site, except for one site (Fort Lauderdale Prospect Well Field, Executive Airport) which has three wells and three sites (Pompano Beach Well Field west, Fort Lauderdale Dixie Well Field, and Deerfield Beach) which have one well. Additional wells at the three sites with only one well either have been destroyed or were not considered part of the network for the purposes of this report. Two sites with two wells at each site, originally included in the network, have been destroyed and also were not considered part of the network for the purposes of this report. Generally, at each site, one well was completed near the top of the upper zone of the surficial aquifer system, and the other well was completed in the highly permeable production zone of the surficial aquifer system (Biscayne aquifer). At four sites, wells that existed before development of the network and were completed below the production zone were used as the deep wells (wells G-2039, G-2161, G-2270, and G-2274).

The design of the DNRP ground-water quality monitoring network in relation to monitoring vertical variations and land-use effects on water quality and the relation between water-quality constituents and land use are addressed in this report to determine whether the goals of the network are being met. To accomplish the goal of monitoring the vertical variations in water quality in the Biscayne aquifer, one well should be completed in the upper zone of the surficial aquifer system and one well in the production zone of the surficial aquifer system at each site. Based on the aquifer zone (table 8), the upper zone (model layers 1 and 2) and the production zone (layers 3 and 4) are approximately equally represented among the wells (table 2). Approximately twice as many wells are completed in each of these zones than are completed in the lower zone of the surficial aquifer system (layer 5).

An initial evaluation of the wells at each site indicates that 14 of the 29 sites meet the goal to monitor the top two zones of the surficial aquifer system (table 9). At two of the remaining sites, wells are completed only in the lower zone. At seven sites, at least one well

Table 7. Site names, site identification numbers, open interval or depth, and casing material for wells used in this study

Well number	U.S. Geological Survey site identification number	Site name	Open interval or well depth (feet below land surface)	Casing material
G-820	261158080095101	Fort Lauderdale Prospect Well Field (Executive Airport)	215-224	Iron
G-820A	261144080094601		99-100	Iron
G-2275	261150080094602		155-157	Iron
G-1272A	261834080061903	Deerfield Beach	52-55	Polyvinyl chloride
G-2038	260027080110102	Hollywood Well field (Hollywood Circle)	134-143	Iron
G-2039	260027080110103		184-187	Iron
G-2156	261837080130501	Parkland	98-99	Polyvinyl chloride
G-2156A	261837080130502		41-44	Polyvinyl chloride
G-2160	260032080135702	Perry Airport	115	Polyvinyl chloride
G-2160A	260032080135703		49-52	Polyvinyl chloride
G-2161	260219080141102	Davie Road Extension	145	Polyvinyl chloride
G-2161A	260219080141103		52-55	Polyvinyl chloride
G-2269	260311080120401	Broward County Utility 3A Well Field (Oak Ridge)	48-50	Iron
G-2270	260311080120402		180-183	Iron
G-2274	261450080080001	Pompano Beach Well Field west (I-95 and 15th Street)	123-130	Polyvinyl chloride
G-2344A	261423080071503	Pompano Beach Well Field east	92-95	Polyvinyl chloride
G-2344B	261423080071504		35-38	Polyvinyl chloride
G-2345X	260641080123520	Fort Lauderdale Dixie Well Field	100-103	Polyvinyl chloride
G-2355	261828080101301	Butler Road	93-96	Polyvinyl chloride
G-2355A	261828080101302		50-53	Polyvinyl chloride
G-2356	261627080111201	Sample and Lyons Roads	93-96	Polyvinyl chloride
G-2356A	261627080111202		53-56	Polyvinyl chloride
G-2357	261441080111001	Coconut Creek	80-83	Polyvinyl chloride
G-2357A	261441080111002		53-56	Polyvinyl chloride
G-2358	261348080160401	Coral Springs Improvement District	96-99	Polyvinyl chloride
G-2358A	261348080160402		46-49	Polyvinyl chloride
G-2359	261232080140401	North Lauderdale	97-100	Polyvinyl chloride
G-2359A	261232080141402		52-55	Polyvinyl chloride
G-2360	261707080073301	I-95 and 44th Street	97-100	Polyvinyl chloride
G-2360A	261707080073302		45-48	Polyvinyl chloride
G-2361	261020080131701	Inverrary	79-82	Polyvinyl chloride
G-2361A	261020080131702		26-29	Polyvinyl chloride

Table 7. Site names, site identification numbers, open interval or depth, and casing material for wells used in this study (Continued)

Well number	U.S. Geological Survey site identification number	Site name	Open interval or well depth (feet below land surface)	Casing material
G-2363	260859080160401	Panama Canal	77-80	Polyvinyl chloride
G-2363A	260859080160402		17-20	Polyvinyl chloride
G-2364	260825080144401	Mirror Lake Park	77-80	Polyvinyl chloride
G-2364A	260825080144402		16-19	Polyvinyl chloride
G-2365	260505080204701	West Davie	71-74	Polyvinyl chloride
G-2365A	260505080204702		22-25	Polyvinyl chloride
G-2366	260453080155601	Sunrise System 2 Well Field (Pine	54-57	Polyvinyl chloride
G-2366A	260453080155602	Island)	22-25	Polyvinyl chloride
G-2367	260337080171901	Cooper City	58-61	Polyvinyl chloride
G-2367A	260337080171902		22-25	Polyvinyl chloride
G-2368	260202080230701	West Rolling Oaks	56-59	Polyvinyl chloride
G-2368A	260202080230702		19-22	Polyvinyl chloride
G-2369	260046080190701	C.B. Smith Park	68-71	Polyvinyl chloride
G-2369A	260046080190702		19-22	Polyvinyl chloride
G-2370	261107080120301	Fort Lauderdale Prospect Well	101	Iron
G-2370A	261107080120302	Field	45-48	Polyvinyl chloride
G-2372	261055080173501	West Sunrise	101-106	Polyvinyl chloride
G-2372A	261055080173502		28-33	Polyvinyl chloride
G-2373	260752080253701	Weston	55-60	Polyvinyl chloride
G-2373A	260752080253702		17-22	Polyvinyl chloride
G-2374	255905080194001	Flamingo	95-100	Polyvinyl chloride
G-2374A	255905080194002		30-35	Polyvinyl chloride
G-2436	261202080111601	Fort Lauderdale Prospect Well	43-63	Polyvinyl chloride
G-2437	261202080111602	Field (Executive Airport west)	112-121	Iron

Table 8. Water-quality well classifications

[Open interval aquifer zone: L, lower zone of the surficial aquifer system; P, production zone of the surficial aquifer system; U, upper zone of the surficial aquifer system. Land-use codes: A, Agriculture; G, Rangeland/Forested Upland/Wetland; I, Urban Commercial/Industrial/Transportation; O, Barren/Urban Open; R, Urban Residential/Institutional]

Well number	Open interval aquifer zone	Comparison between wet- and dry-season areas of contribution	Relative length of area of contribution	Predominant land use in area of contribution	Land use at well	Sewered or nonsewered category	
						Area of contribution	Well
G-820	L	Similar	Long	I	I	Sewered	Sewered
G-820A	P	Similar	Long	I	I	Sewered	Sewered
G-1272A	U	Similar	Short	R	R	Sewered	Sewered
G-2038	L	Similar	Long	R	R	Sewered	Sewered
G-2039	L	Similar	Long	R	R	Sewered	Sewered
G-2156	U	Similar	Short	G	G	Nonsewered	Nonsewered
G-2156A	U	Similar	Short	G	G	Nonsewered	Nonsewered
G-2160	P	Similar	Long	R	R	Sewered	Sewered
G-2160A	P	Similar	Medium	R	R	Sewered	Sewered
G-2161	L	Different	Log	R	I	Nonsewered	Nonsewered
G-2161A	P	Different	Short	I	I	Nonsewered	Nonsewered
G-2269	P	Similar	Medium	R	R	Nonsewered	Sewered
G-2270	L	Similar	Long	R	R	Sewered	Sewered
G-2274	L	Similar	Long	R	R	Sewered	Sewered
G-2275	L	Similar	Long	I	I	Sewered	Sewered
G-2344A	P	Similar	Long	R	I	Sewered	Sewered
G-2344B	U	Similar	Short	R	I	Sewered	Sewered
G-2345X	P	Different	Long	O	O	Nonsewered	Nonsewered
G-2355	U	Similar	Medium	I	I	Sewered	Sewered
G-2355A	U	Similar	Medium	I	I	Sewered	Sewered
G-2356	P	Similar	Medium	A	A	Nonsewered	Nonsewered
G-2356A	U	Similar	Short	A	A	Nonsewered	Nonsewered
G-2357	U	Similar	Short	I	I	Sewered	Sewered
G-2357A	U	Similar	Short	I	I	Sewered	Sewered
G-2358	L	Different	Long	R	R	Sewered	Sewered
G-2358A	U	Similar	Medium	R	R	Sewered	Sewered
G-2359	P	Similar	Medium	R	R	Sewered	Sewered
G-2359A	U	Similar	Short	R	R	Sewered	Sewered
G-2360	P	Similar	Long	R	I	Sewered	Sewered
G-2360A	U	Similar	Medium	R	I	Sewered	Sewered
G-2361	P	Similar	Medium	O	O	Sewered	Sewered
G-2361A	U	Similar	Short	O	O	Sewered	Sewered
G-2363	P	Similar	Medium	R	R	Sewered	Sewered
G-2363A	U	Similar	Short	R	R	Sewered	Sewered
G-2364	P	Similar	Medium	R	R	Sewered	Sewered
G-2364A	U	Similar	Short	R	R	Sewered	Sewered
G-2365	P	Similar	Medium	G	G	Nonsewered	Nonsewered
G-2365A	U	Similar	Short	G	G	Nonsewered	Nonsewered
G-2366	P	Similar	Long	A	O	Sewered	Sewered
G-2366A	U	Similar	Long	A	O	Sewered	Sewered
G-2367	P	Similar	Medium	O	O	Nonsewered	Nonsewered
G-2367A	U	Similar	Short	O	O	Nonsewered	Nonsewered
G-2368	P	Similar	Long	R	R	Nonsewered	Nonsewered
G-2368A	U	Similar	Short	R	R	Nonsewered	Nonsewered
G-2369	P	Different	Long	O	O	Sewered	Sewered
G-2369A	U	Different	Long	O	O	Sewered	Sewered
G-2370	P	Similar	Medium	I	I	Sewered	Sewered
G-2370A	U	Similar	Medium	I	I	Sewered	Sewered
G-2372	L	Similar	Long	O	O	Sewered	Sewered
G-2372A	U	Similar	Short	O	O	Sewered	Sewered
G-2373	L	Similar	Long	G	G	Nonsewered	Nonsewered
G-2373A	U	Similar	Short	G	G	Nonsewered	Nonsewered
G-2374	P	Different	Medium	G	G	Nonsewered	Nonsewered
G-2374A	U	Similar	Short	G	G	Nonsewered	Nonsewered
G-2436	P	Similar	Medium	I	I	Sewered	Sewered
G-2437	L	Similar	Long	I	I	Sewered	Sewered

Table 9. Evaluation of well sites

[Aquifer zones: L, lower zone of surficial aquifer system, P, production zone of surficial aquifer system; U, upper zone of surficial aquifer system]

Site name	Well number	Open interval aquifer zone	Well meets length of area of contribution goal	Remarks and evaluation of site
		Sites Meeting Aquifer Zone Goals		
Pompano Beach Well Field east	G-2344A G-2344B	P U	No Yes	No changes
Sample and Lyons Roads	G-2356 G-2356A	P U	No Yes	No changes
North Lauderdale	G-2359 G-2359A	P U	No Yes	No changes
I-95 and 44th Street	G-2360 G-2360A	P U	No No	No changes; size of area of contribution of well G-2360A is at low end of medium group
Inverrary	G-2361 G-2361A	P U	No Yes	No changes
Panama Canal	G-2363 G-2363A	P U	No Yes	No changes
Mirror Lake Park	G-2364 G-2364A	P U	No Yes	No changes
West Davie	G-2365 G-2365A	P U	No Yes	No changes
Sunrise System 2 Well Field (Pine Island)	G-2366 G-2366A	P U	No No	Additional analysis required
Cooper City	G-2367 G-2367A	P U	No Yes	No changes
West Rolling Oaks	G-2368 G-2368A	P U	No Yes	No changes
C.B. Smith Park	G-2369 G-2369A	P U	No No	Additional analysis required
Fort Lauderdale Prospect Well Field	G-2370 G-2370A	P U	No No	Relative length of area of contribution affected by well-field pumping
Flamingo	G-2374 G-2374A	P U	No Yes	No changes
		Sites Not Meeting Aquifer Zone Goals		
Fort Lauderdale Prospect Well Field (Executive Airport)	G-820 G-820A G-2275	L P L	No No No	Replace wells G-820 and G-2775 with well completed in upper zone of surficial aquifer system
Deerfield Beach	G-1272A	U	Yes	Add well completed in production zone of surficial aquifer system

Table 9. Evaluation of well sites (Continued)

[Aquifer zones: L, lower zone of surficial aquifer system, P, production zone of surficial aquifer system; U, upper zone of surficial aquifer system]

Site name	Well number	Open interval aquifer zone	Well meets length of area of contribution goal	Remarks and evaluation of site
Sites Not Meeting Aquifer Zone Goals--Continued				
Hollywood Well Field (Hollywood Circle)	G-2038 G-2039	L L	No No	Well G-2038 is completed near base of production zone of surficial aquifer system; replace well G-2039 with well completed in upper zone of surficial aquifer system
Parkland	G-2156 G-2156A	U U	Yes Yes	No changes; well G-2156 is completed near top of production zone of surficial aquifer system
Perry Airport	G-2160 G-2160A	P P	No No	No changes; well G-2160A is completed near base of upper zone of surficial aquifer system; has an area of contribution at low end of medium group
Davie Road Extension	G-2161 G-2161A	L P	No Yes	Replace well G-2161 with well completed in upper zone of surficial aquifer system
Broward County Utility 3A Well Field (Oak Ridge)	G-2269 G-2270	P L	No No	Replace well G-2270 with well completed in upper zone of surficial aquifer system
Pompano Beach Well Field west (I-95 and 15th Street)	G-2274	L	No	Well G-2274 is completed near base of production zone of surficial aquifer system; add well completed in upper zone of surficial aquifer system
Fort Lauderdale Dixie Well Field	G-2345X	P	No	Add well completed in upper zone of surficial aquifer system
Butler Road	G-2355 G-2355A	U U	No No	Well G-2355 is completed near top of production zone of surficial aquifer system and size of area of contribution of well G-2355A is at low end of medium group
Coconut Creek	G-2357 G-2357A	U U	Yes Yes	No changes; well G-2357 is completed near top of production zone of surficial aquifer system
Coral Springs Improvement District	G-2358 G-2358A	L U	No No	No changes; well G-2358 is completed near base of production zone of surficial aquifer system
West Sunrise	G-2372 G-2372A	L U	No Yes	No changes; well G-2372 completed near base of production zone of surficial aquifer system
Weston	G-2373 G-2373A	L U	No Yes	No changes; well G-2373 completed near base of production zone of surficial aquifer system
Fort Lauderdale Prospect Well Field (Executive Airport west)	G-2436 G-2437	P L	No No	Replace well G-2437 with well completed in upper zone of surficial aquifer system

is completed in the upper zone but not in the production zone. At six sites, at least one well is completed in the production zone but not in the upper zone. At eight of the nine sites with no wells completed in the production zone, one of the wells is completed either near the top or base of this zone. Thus, based on the uncertainty in the aquifer zone boundaries, these eight sites can be considered inclusive of sites containing wells completed in the production zone. Adding a well completed in the production zone at the Deerfield Beach site would satisfy the goal to monitor the top two zones of the surficial aquifer system. At one of the eight sites without a well completed in the upper zone, a well (G-2160A) completed near the base of the upper zone is considered to be completed in the upper zone. The other seven sites require a well completed in the upper zone to meet the goal of monitoring vertical variations in ground-water quality.

To accomplish the goal of monitoring the effects of land use on ground-water quality, wells should have an area of contribution which can be easily defined, allowing land uses that might affect the quality of water sampled from wells to be determined. Variations between the simulated wet- and dry-season areas of contribution for seven wells at five sites (table 8) indicate that the actual areas of contribution for these wells might be different than the combined wet- and dry-season areas. However, the land use and sewered or nonsewered categories in surrounding areas do not vary from those in the designated area of contribution. Thus, the predominant land use and sewered or nonsewered categories assigned to the area of contribution for these wells are considered representative and suitable for the statistical analyses presented in this report.

Simulated areas of contribution characterized by a short relative length are ideal to meet the second goal of the network because these areas are probably representative of the actual areas of contribution. The short area of contribution category (less than 600 ft) contained 18 wells (table 8) at 16 sites distributed throughout the study area (figs. 7 and 8). The open interval for all of the wells in this category is the upper zone, except for well G-2161A which is open to the production zone. Adjacent well G-2161 is completed in the lower zone and should be replaced with a well completed in the upper zone to meet the goal of the network. Maps of the study area showing combined areas of contribution to wells completed in the upper, production, and lower zones of the surficial aquifer system are shown in figures 7, 8, and 9, respectively.

Thirteen sites where wells are not characterized by a short relative length of area of contribution were evaluated to determine if the land uses affecting the quality of water could be identified and categorized. Generally, the land uses closest to the wells in the area of contribution will have the greatest effect on ground-water quality due to the relatively short flow paths. The relative length of the area of contribution for shallow wells (G-2160A, G-2355A, and G-2360A) at three sites (figs. 7 and 8) is on the low end of the medium category. These three wells can be considered suitable for network purposes. The relative length of the area of contribution is characterized as long for wells at nine sites and is characterized as medium for wells at one site. These 10 sites are located near significant stresses on the ground-water flow system, such as drainage canals and well fields. Ground-water flow at these 10 sites and site conditions relative to network goals are evaluated in the next sections of this report.

Assessment of Well Classifications at Selected Sites

This section presents an assessment of the well classifications at 10 sites in the DNRP ground-water quality monitoring network. This assessment is made to determine whether the goals of the network (as outlined in the previous section) are being met. Each well is classified according to open interval aquifer zone, comparison between wet- and dry-season areas of contribution, relative length of area of contribution, and land use and sewered or nonsewered at the well and in the area of contribution.

Coral Springs Improvement District Site

Wells G-2358 and G-2358A are located in the Coral Springs Improvement District on the northern side of the Pompano Canal (fig. 1). Well G-2358 is completed at the top of the lower zone of the surficial aquifer system, and well G-2358A is completed at the bottom of the upper zone of the surficial aquifer system. Thus, it is possible that one or both wells are actually completed in the production zone of the surficial aquifer system. Two primary factors influence flow to these wells: (1) seepage of water under the levee from Water Conservation Area 2A (fig. 1), and (2) pumpage of water southward through a series of canals into the Pompano Canal to prevent flooding from heavy rains and seepage from Water Conservation Area 2A. The

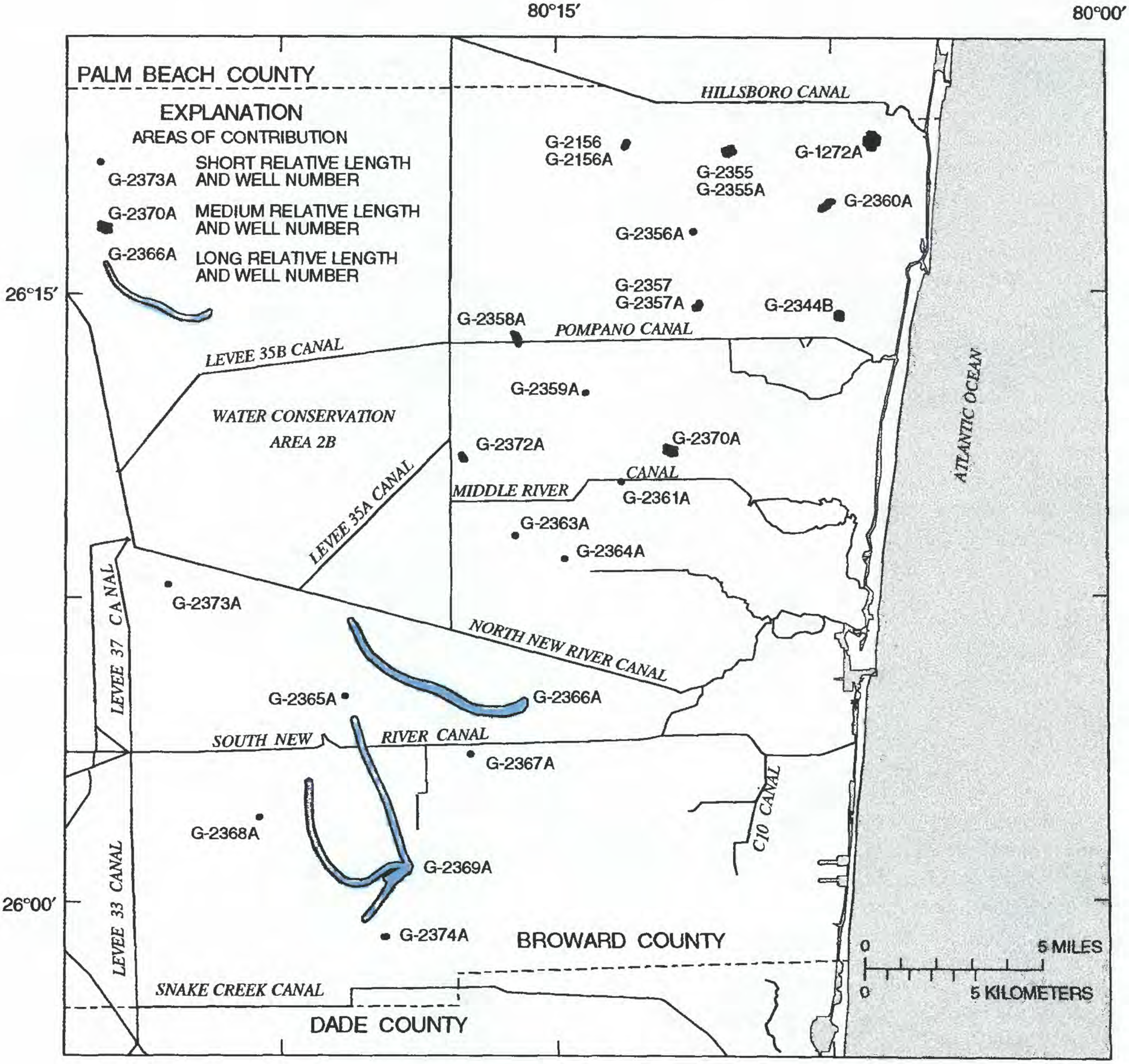

Figure 7. Eastern Broward County showing combined area of contribution to wells completed in the upper zone of the surficial aquifer system.

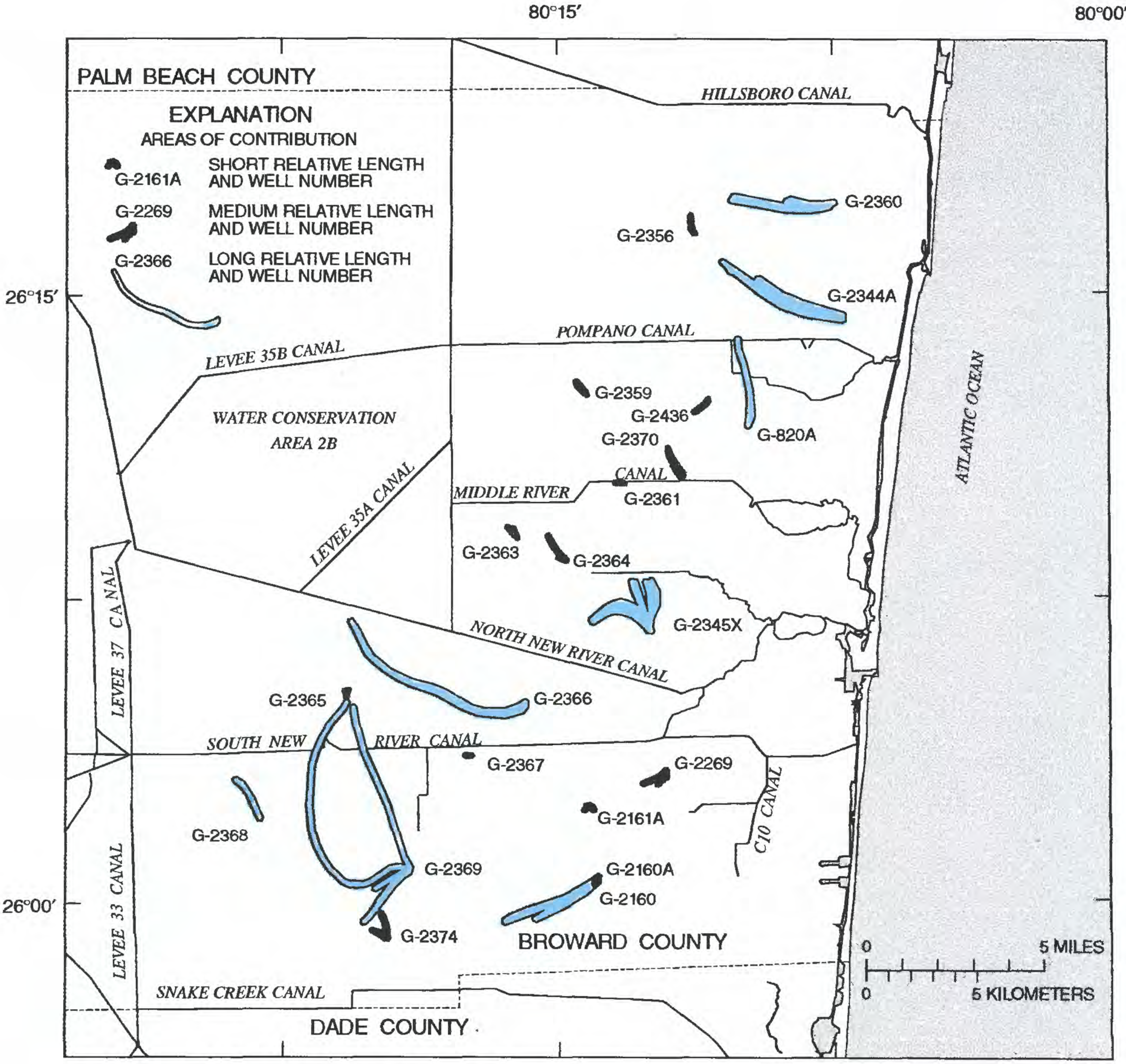

Figure 8. Eastern Broward County showing combined area of contribution to wells completed in the production zone of the surficial aquifer system.

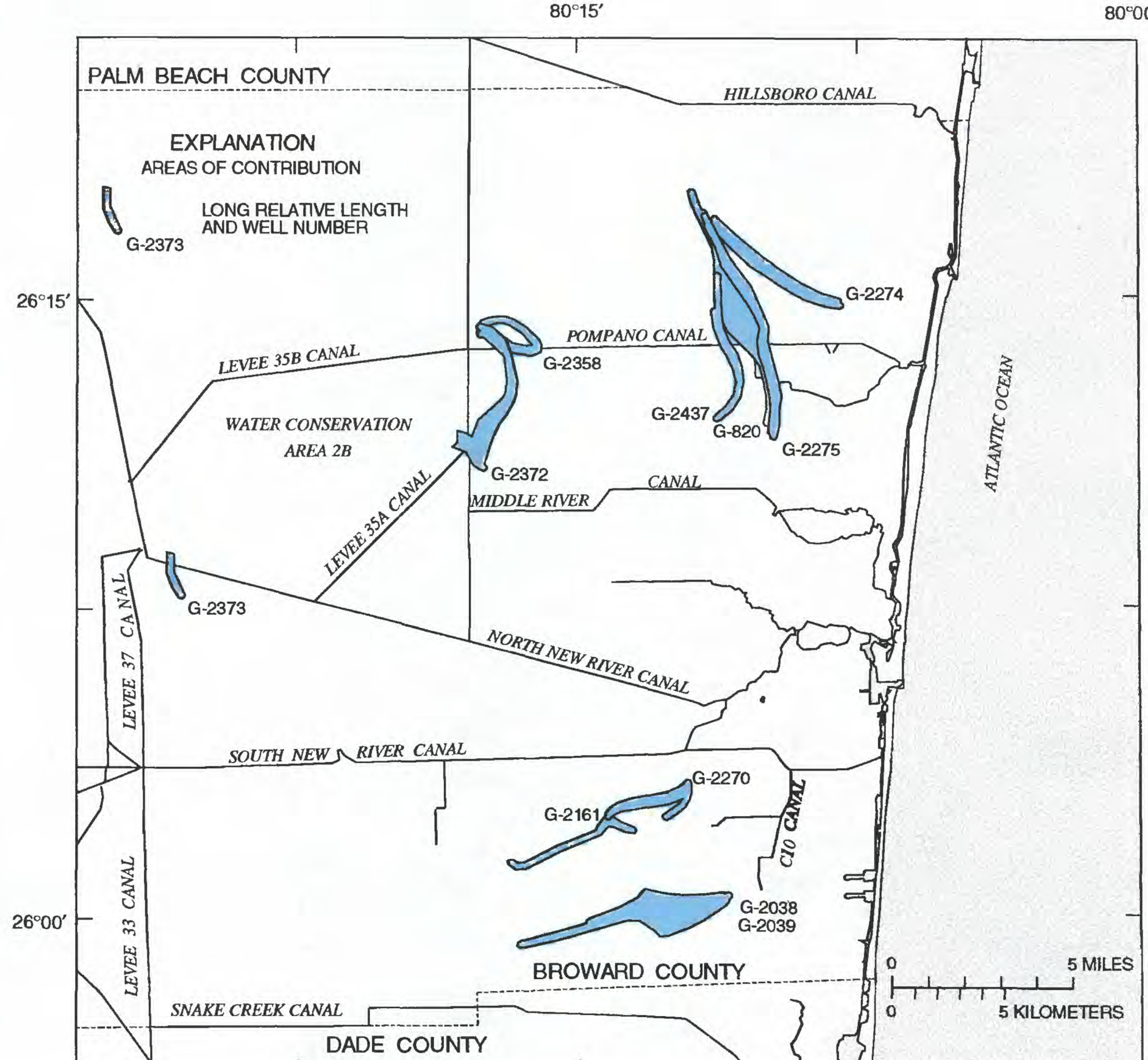

Figure 9. Eastern Broward County showing combined area of contribution to wells completed in the lower zone of the surficial aquifer system.

length of the longest pathline in the area of contribution for the shallow well (G-2358A) is greater than 1,800 ft for dry-season conditions but less than 50 ft for wet-season conditions (fig. 10). The directions of the pathlines differ for the deep well (G-2358) under both conditions. However, the predominant land-use category in the area of contribution is the same for both conditions and for the two wells; that is, Urban Residential/Institutional (R). Because the land use in the areas of contribution for wells G-2358 and G-2358A does not vary, these wells can be considered suitable for network purposes.

C.B. Smith Park Site

Wells G-2369 and G-2369A are located at the C.B. Smith Park site in the southwestern part of the study area (fig. 1). Deep well G-2369 is completed in the production zone of the surficial aquifer system, and shallow well G-2369A is completed in the upper zone of the surficial aquifer system. Ground-water flow to the wells is predominantly influenced by canals to the east. The simulated areas of contribution are similar for both wells (figs. 7 and 8) but differ between wet- and dry-season conditions (as represented by well G-2369 in fig. 11). Simulated pathlines leading to the open intervals of these wells are as long as 40,000 ft. The simulated pathlines are from two directions from the wells (northwest and southwest), a result of the effect of the canals on ground-water flow and backtracking from the edges of the model grid cell instead of the well. However, the closest land uses, Urban Open (UO), Rangeland (R), and Wetland (W), are the same for the contributing areas in the two directions. A profile of a simulated particle pathline to these wells (fig. 12) indicates upward flow toward the wells, an indication that canals are capturing flow from the lower part of the production zone. Thus, actual pathlines leading to the well might be much different than those simulated by the model. The 1,000-ft wide model grid cells are too large to adequately represent local flow patterns. The canal that is represented by the drain cell is much narrower (less than 100 ft) than the model grid cell. The flow pattern indicated by MODPATH may only be representative of flow paths near the canals. A more detailed model is required to more accurately determine the area of contribution to the wells at this site.

Broward County Utility 3A Well Field Site

Wells G-2269 and G-2270 are located in the Broward County Utility 3A Well Field (fig. 1 and table 10). Well G-2269 is completed in the production zone of the surficial aquifer system, and well G-2270 is completed in the lower zone of the surficial aquifer system. Ground-water flow to the wells is predominantly influenced by pumping at the well field. The length of the

Table 10. Sites with wells characterized by medium or long areas of contribution and influenced by municipal well fields

Site name	Production interval (feet below land surface)	Wells at site
Broward County Utility 3A Well Field	80 - 180	G-2269, G-2270
Fort Lauderdale Dixie Well Field	80 - 150	G-2345X
Fort Lauderdale Prospect Well Field (three sites)	60 - 150	G-820, G-820A, G-2275 G-2370, G-2370A G-2436, G-2437
Hollywood Well Field	60 - 140	G-2038, G-2039
Pompano Beach Well Field	72 - 165	G-2274
Sunrise System 2 Well Field	102	G-2366, G-2366A

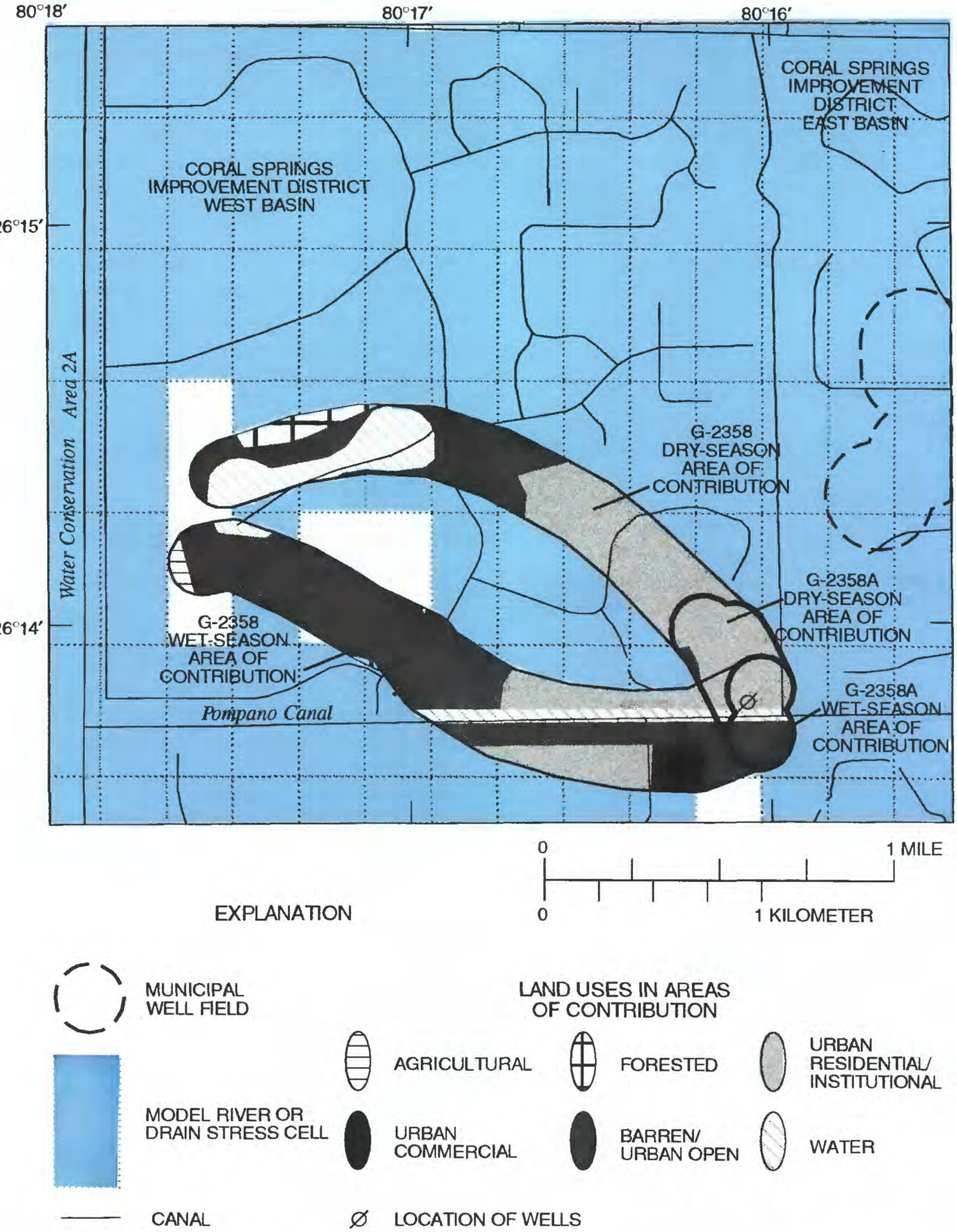

Figure 10. Dry- and wet-season areas of contribution to wells G-2358 and G-2358A.

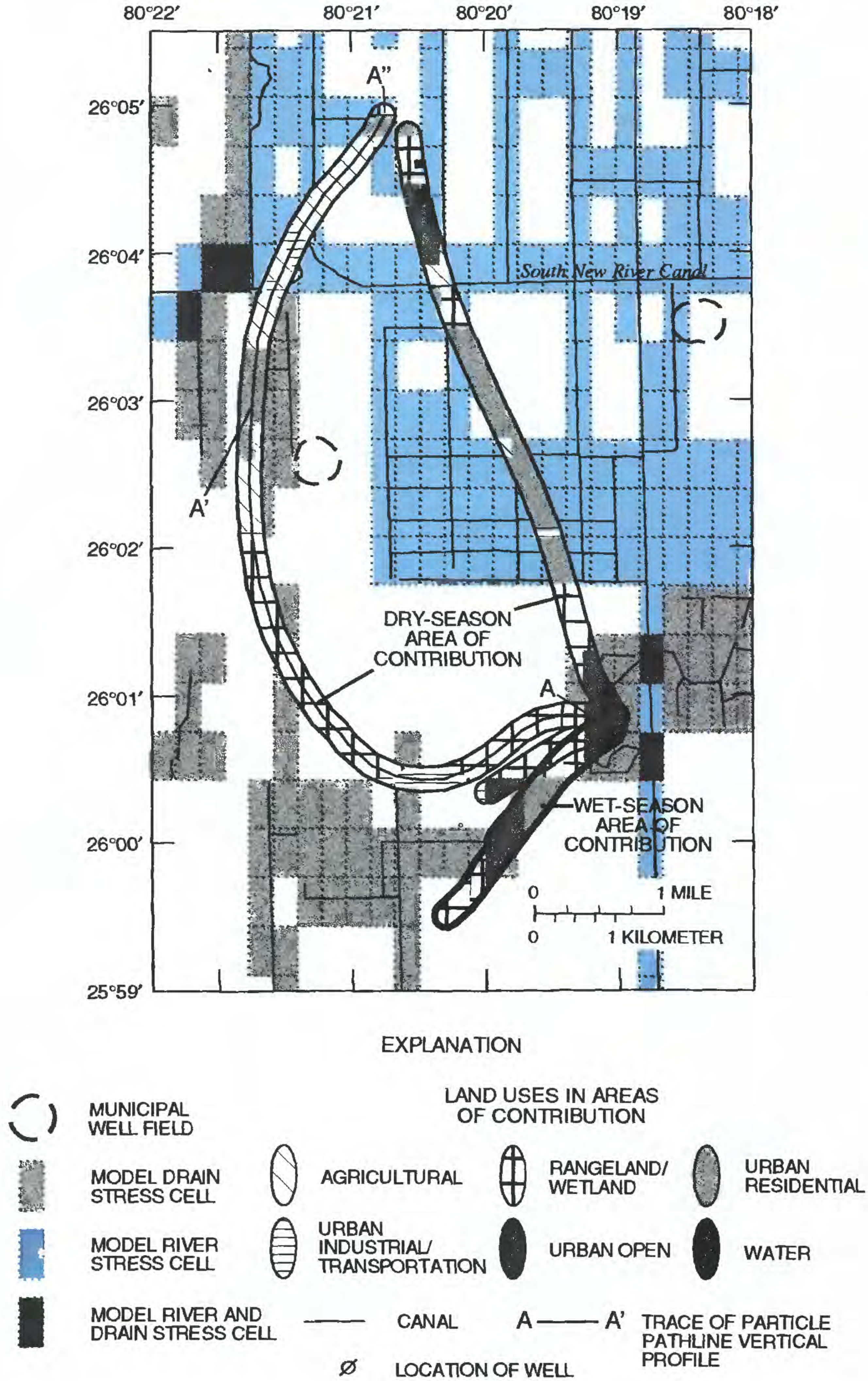

Figure 11. Dry- and wet-season areas of contribution to well G-2369.

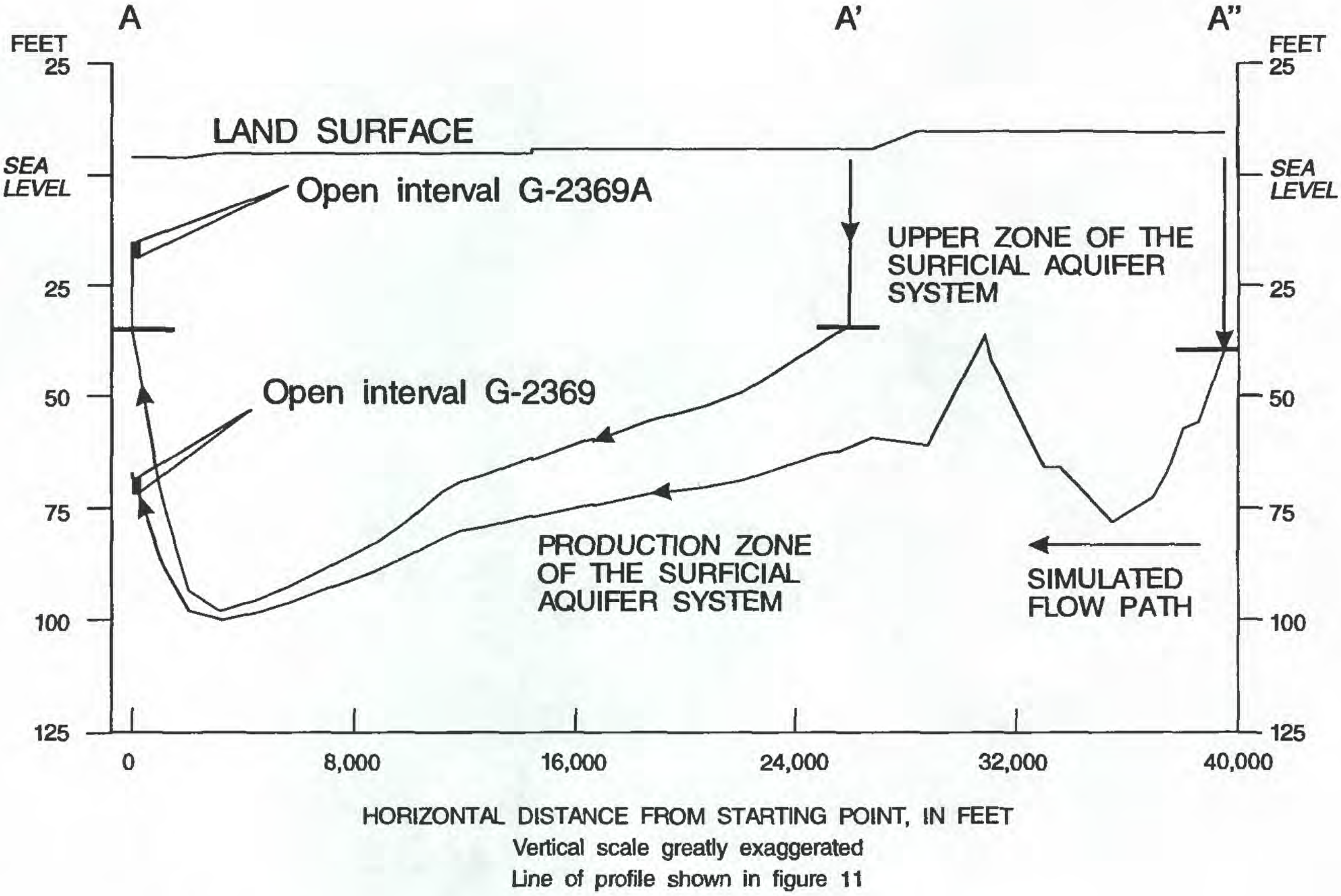

Figure 12. Selected particle pathlines leading to wells G-2369 and G-2369A.

simulated area of contribution for shallow well G-2269 differs between wet- and dry-season conditions (fig. 13). The longest particle pathline representing wet-season conditions is less than 700 ft long (at the low end of the medium range of the relative length of area of contribution). Land use in the area of contribution is entirely Urban Residential/Institutional (R). The longest particle pathline representing dry-season conditions is greater than 4,100 ft long. Land use in the area of contribution is Urban Residential/Institutional (R) in the vicinity of the well, but changes to predominantly Forested (F) conditions within 1,000 ft of the well. Simulated particle pathlines for deep well G-2270 completed in the lower zone are longer than 12,000 ft. In the lower zone, regional flow predominates and particle velocities are relatively low compared to velocities in the more permeable production and upper zones of the surficial aquifer system. Thus, water sampled from well G-2270 is relatively old, and the quality of this water probably does not reflect the influences of modern land uses. Replacing well G-2270 with a well completed in the upper zone would result in the two wells at the site better meeting the goals of the network.

Pompano Beach Well Field Site

Well G-2274 is located 1 mi (mile) west of the Pompano Beach Well Field (fig. 1 and table 10). The primary influence on ground-water flow to the vicinity of the well is the ground-water mound northwest of the site (fig. 4). The well is considered to be completed in the lower zone of the surficial aquifer system, but might actually be completed in the production zone of the surficial aquifer system due to uncertainty in defining the actual layer boundaries. A profile of a simulated particle pathline indicates that pathlines are predominantly in the production zone, moving down into the lower zone close to the well (fig. 14). Simulated flow paths for well G-2344A (located in the Pompano Beach Well Field), also completed in the production zone, are similar. Shallow well G-2344B at this nearby site has a short area of contribution. Because of the similarity in

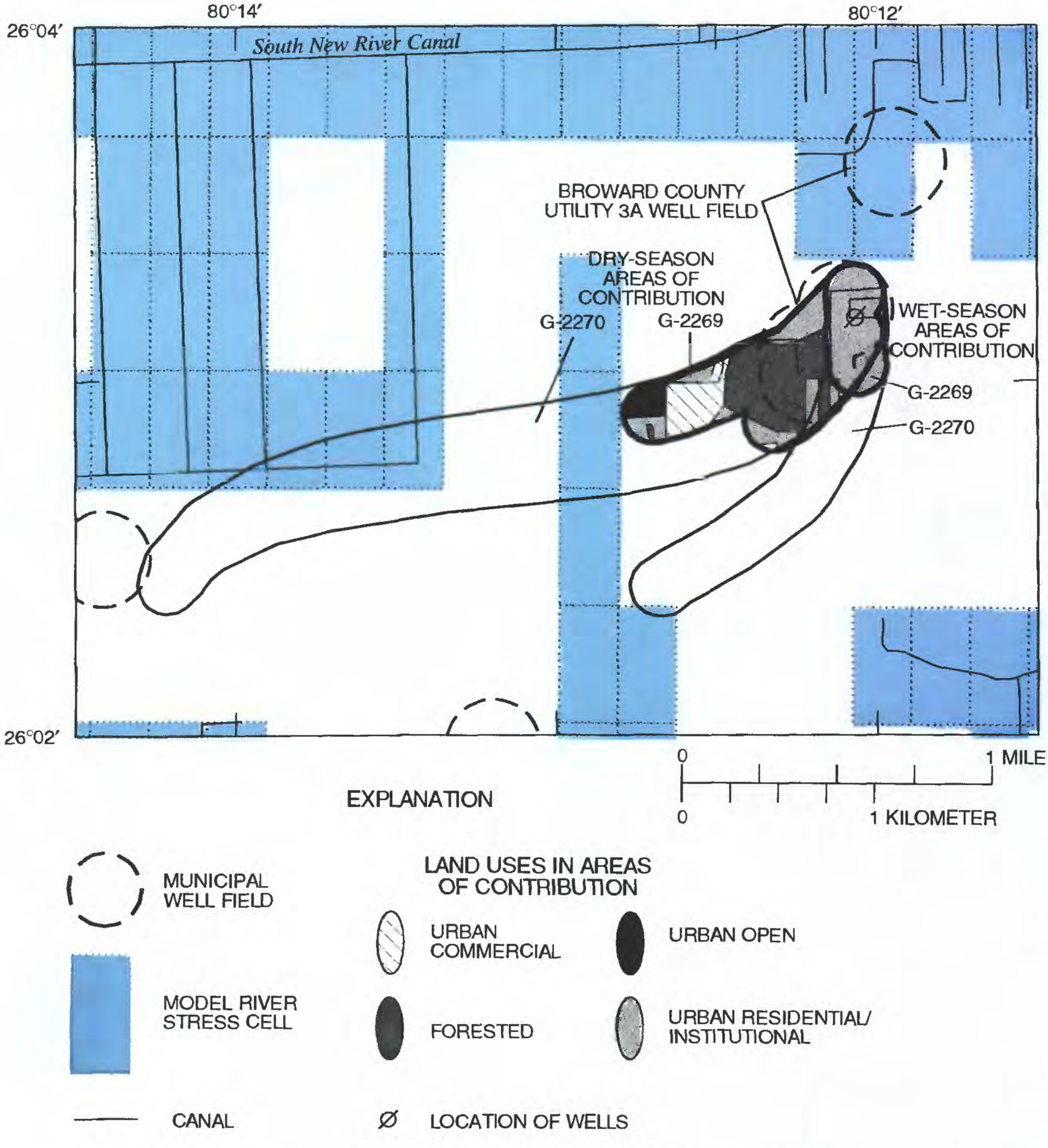

Figure 13. Dry- and wet-season areas of contribution to wells G-2269 and G-2270.

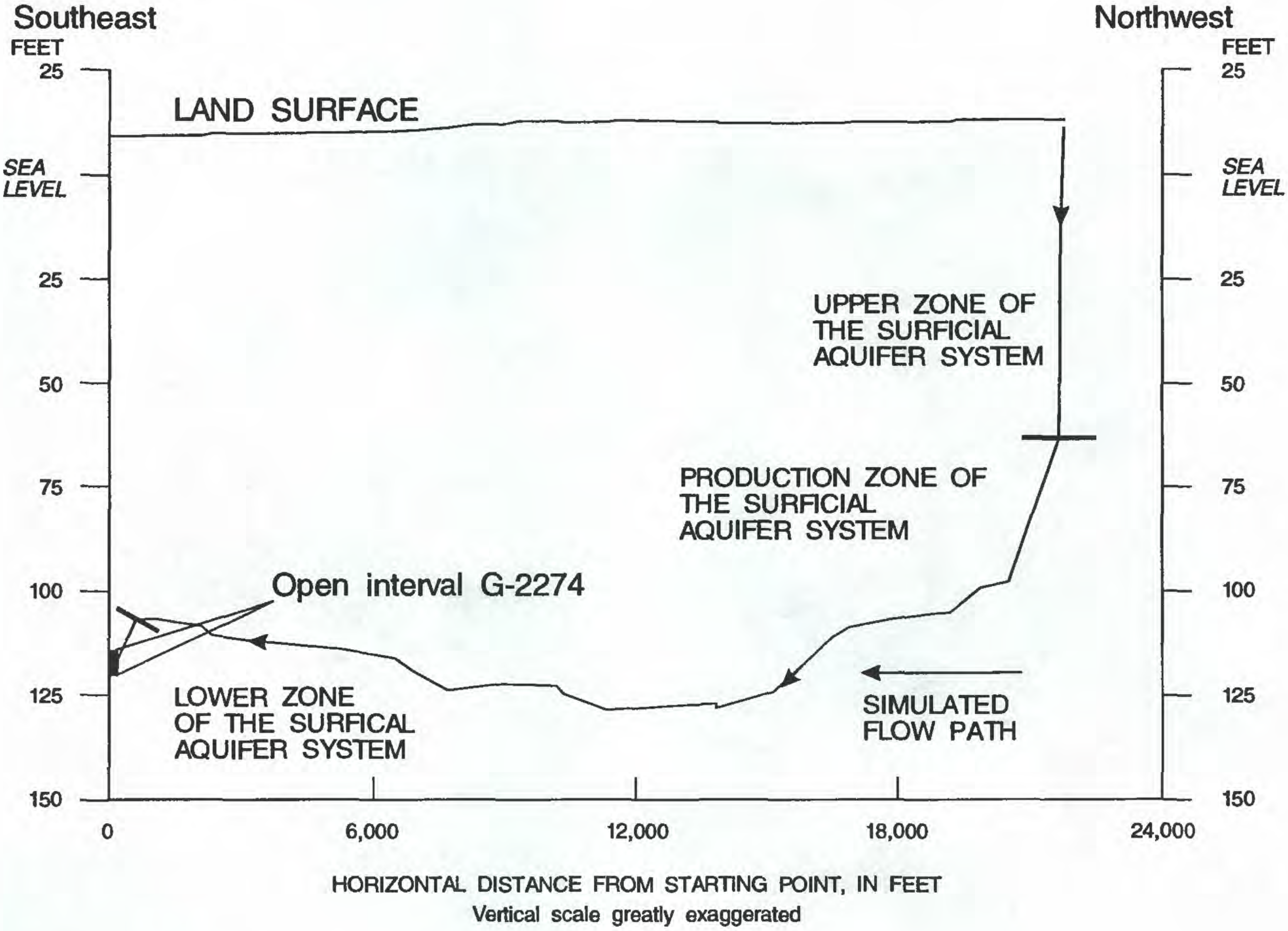

Figure 14. Selected particle pathline leading to well G-2274.

flow patterns between the two sites, an additional well completed in the upper zone of the surficial aquifer system at the Pompano Beach Well Field would probably also be characterized by a short area of contribution, thus, meeting the goals of the network at this site.

Fort Lauderdale Dixie Well Field Site

Well G-2345X, the only well located at the Fort Lauderdale Dixie Well Field site (fig. 1 and table 10), is completed in the production zone of the surficial aquifer system. Ground-water flow to this well is predominantly influenced by pumping at the well field (fig. 4), but also is influenced by pumping at a second municipal well field to the northwest. A major drain exists north of the well, and rivers occur west and south of the well (fig. 15). Simulated wet- and dry-season flow patterns are significantly different at this well.

During the dry season, simulated flow to the well is from the west and a ground-water divide is simulated to the northwest between the two well fields. During the wet season, simulated flow to the well is from the north with ground-water divides occurring to the north between the drain and the Dixie Well Field and to the northwest between the two well fields. However, the closest land use, Urban Open (a golf course), is the same for the simulated contributing areas, regardless of season. The goals of the network would be met at this site with the addition of a well completed in the upper zone of the surficial aquifer system. Because of variations in well-field pumpage and the turning on and off of individual supply wells, the area of contribution to wells within the well field could change significantly over time. Thus, wells located at a site outside of the well field would better meet the goals of the network.

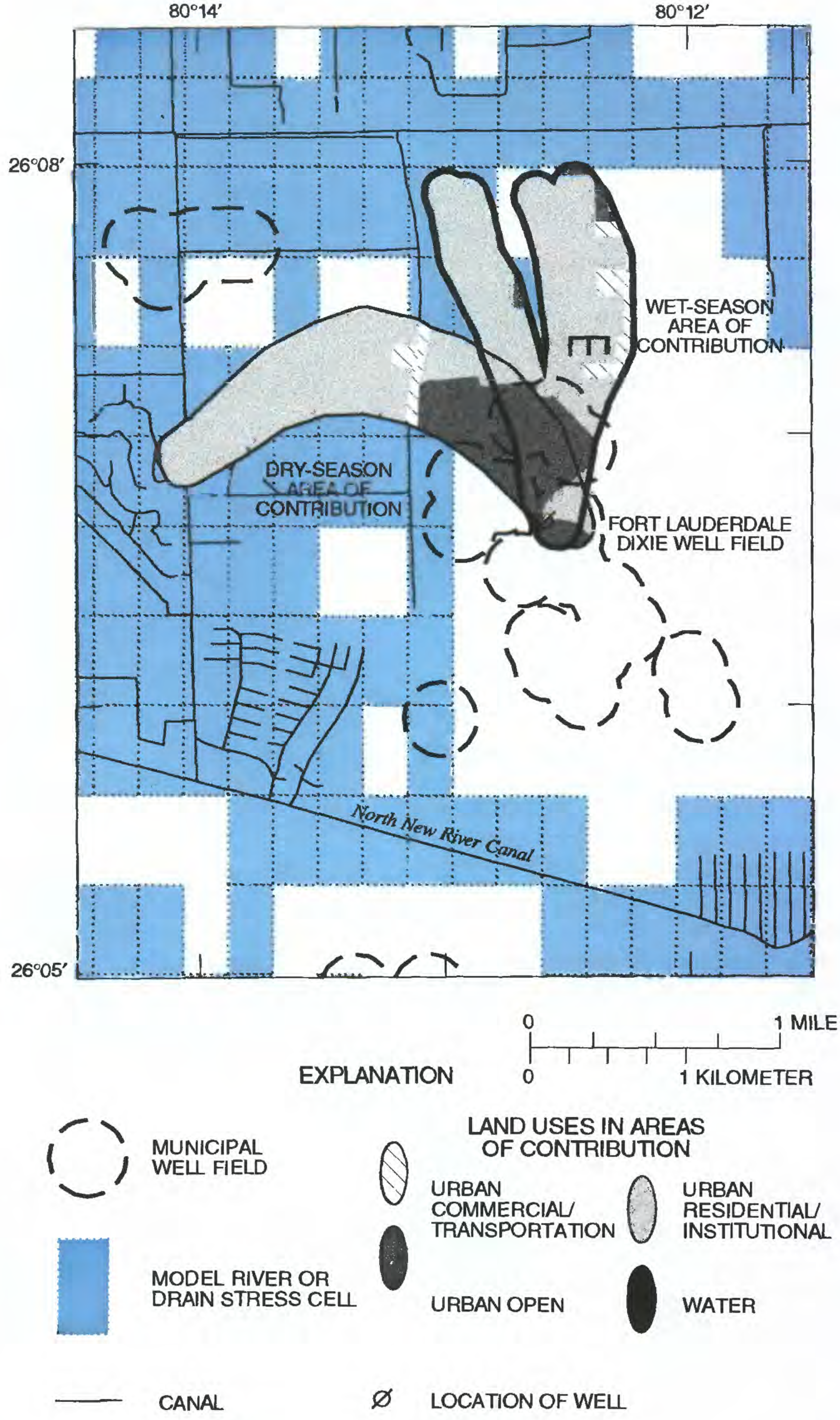

Figure 15. Dry- and wet-season areas of contribution to well G-2345X.

Fort Lauderdale Prospect Well Field Sites

Three well sites are influenced by pumping at the Fort Lauderdale Prospect Well Field (fig. 1 and table 10). The first site consists of wells G-820, G-820A, and G-2275; the second site consists of wells G-2370 and G-2370A; and the third site consists of wells G-2436 and G-2437. The first well site is located at the eastern edge of the water-table depression surrounding the well field (fig. 4). Wells G-820 and G-2275 (fig. 9) are completed in the lower zone of the surficial aquifer system, making the simulated areas of contribution longer and more areally extensive than that for well G-820A (fig. 8) completed in the production zone of the surficial aquifer system. For well G-820A, the simulated length of the area of contribution under wet-season conditions is much shorter than under dry-season conditions, although both areas are in the long-length classification and the direction of the flow paths is similar. Replacing wells G-820 and G-2275 with a well completed in the upper zone of the surficial aquifer system would better meet the goals of the network.

The second well site (represented by wells G-2370 and G-2370A) is located in the water-table depression surrounding the Fort Lauderdale Prospect Well Field. Well G-2370 is completed in the production zone (fig. 8), and well G-2370A is completed in the upper zone (fig. 7). For both wells, the simulated area of contribution is in the medium-length classification, primarily a result of the steep water-table gradient caused by the well field. However, the relative length of the area of contribution for well G-2370A (about 1,400 ft) can be considered sufficiently short and the land uses in the area sufficiently uniform, mostly Urban Commercial (UC) and Urban Open (UO), for these wells to be suitable for network purposes.

The last two wells influenced by the Fort Lauderdale Prospect Well Field are wells G-2436 and G-2437 (the third well site). Well G-2436 is constructed with a 20-ft open interval near the boundary between the upper zone and production zone. During simulations of particle paths, simulated particles in the production zone traveled significantly farther than the particles in the upper zone. Because the lateral hydraulic conductivity of the production zone is greater than that of the upper zone, the source of most of the water in samples from well G-2436 probably is the production zone. Thus, the simulated area of contribution determined by the longer pathlines is more representative of the actual area of contribution to this well (fig. 8). The top of the open interval for well G-2437 is near the top of the lower zone. However, this well might be partly completed in the production zone and would have an area of contribution similar to that of well G-2436. The goals of the network at this site would be better met by replacing well G-2437 with a well completed in the upper zone.

Hollywood Well Field Site

Wells G-2038 and G-2039 are located in the Hollywood Well Field (fig. 1 and table 10). Both wells are completed in the lower zone of the surficial aquifer system where ground-water flow velocity is relatively low. Regional flow probably predominates in the lower zone (fig. 9), and the quality of water sampled from this zone probably does not reflect the influences of current land uses. Well G-2038 is completed near the top of the lower zone and might be completed partly in the production zone of the surficial aquifer system. Because pumping at the municipal well field possibly causes the upconing of water, the source of at least some of the water sampled from well G-2038 might be from the lower zone even if the well were actually completed in the production zone (fig. 16). Replacing the deeper well (G-2039) with a well completed in the upper zone of the surficial aquifer system would better meet the goals of the network.

Sunrise System 2 Well Field Site

Wells G-2366 and G-2366A are located south of the Sunrise System 2 Well Field (fig. 1 and table 10). Well G-2366 is completed in the production zone of the surficial aquifer system, and well G-2366A is completed in the upper zone of the surficial aquifer system. Simulated wet-season particle pathlines leading to the open intervals of both wells are in excess of 30,000 ft as shown by the long area of contribution for well G-2366 (fig. 17). Because of limited areal extent, pumpage from the well field might not be the controlling influence on flow to these wells. A vertical profile of simulated flow paths to these wells (fig. 18) shows upward flow toward the wells, indicating that the river cells adjacent to the well locations are acting as drains, capturing flow from the lower part of the production zone. The actual pathlines leading to the wells might be much different, as was discussed for wells G-2369 and G-2369A at the C.B. Smith Park site. The canal represented by the river cell is much narrower (less than 100 ft) than the 1,000-ft width of the model grid cell and is part of a series of canals that drain into the South New

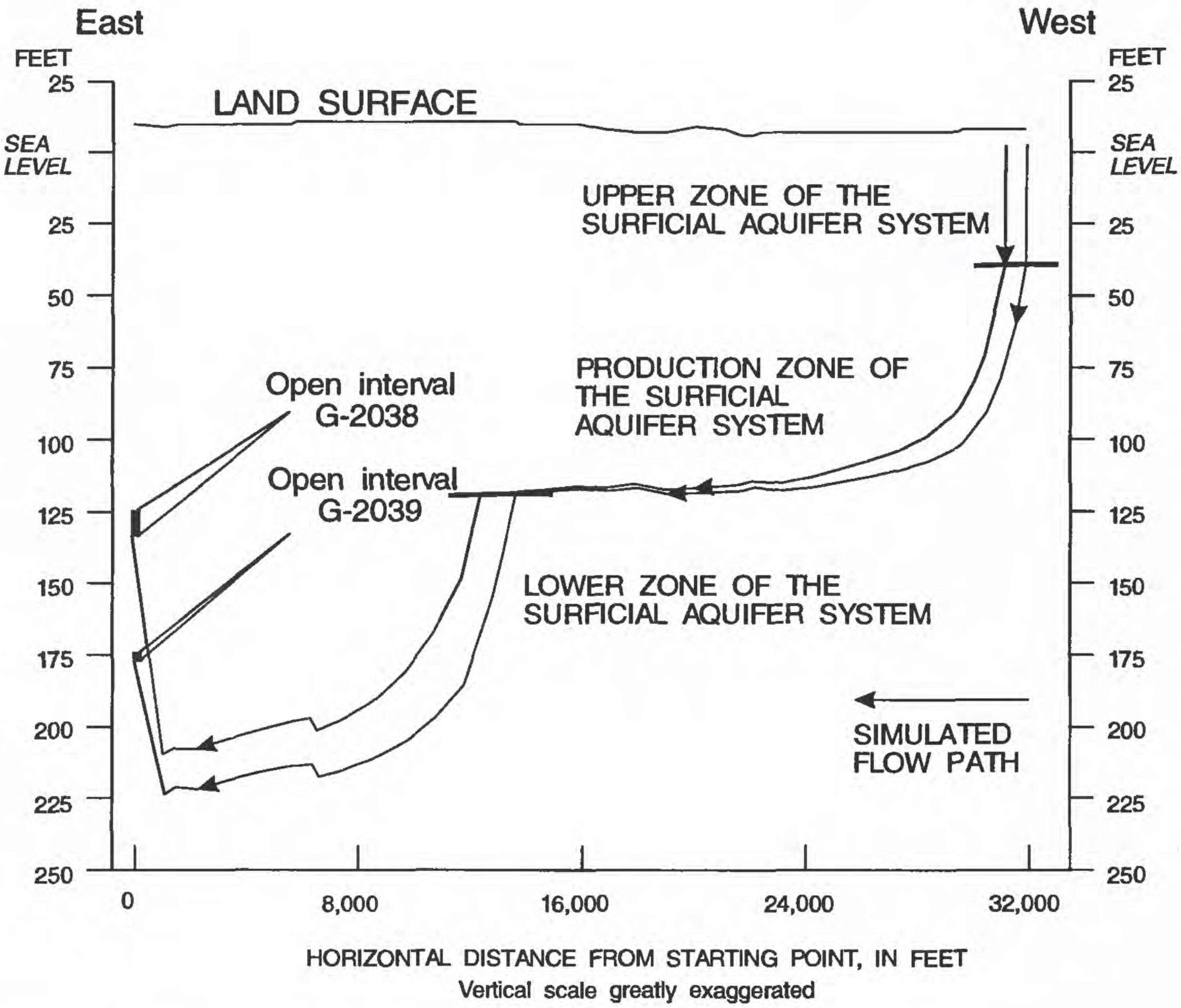

Figure 16. Selected particle pathlines leading to wells G-2038 and G-2039.

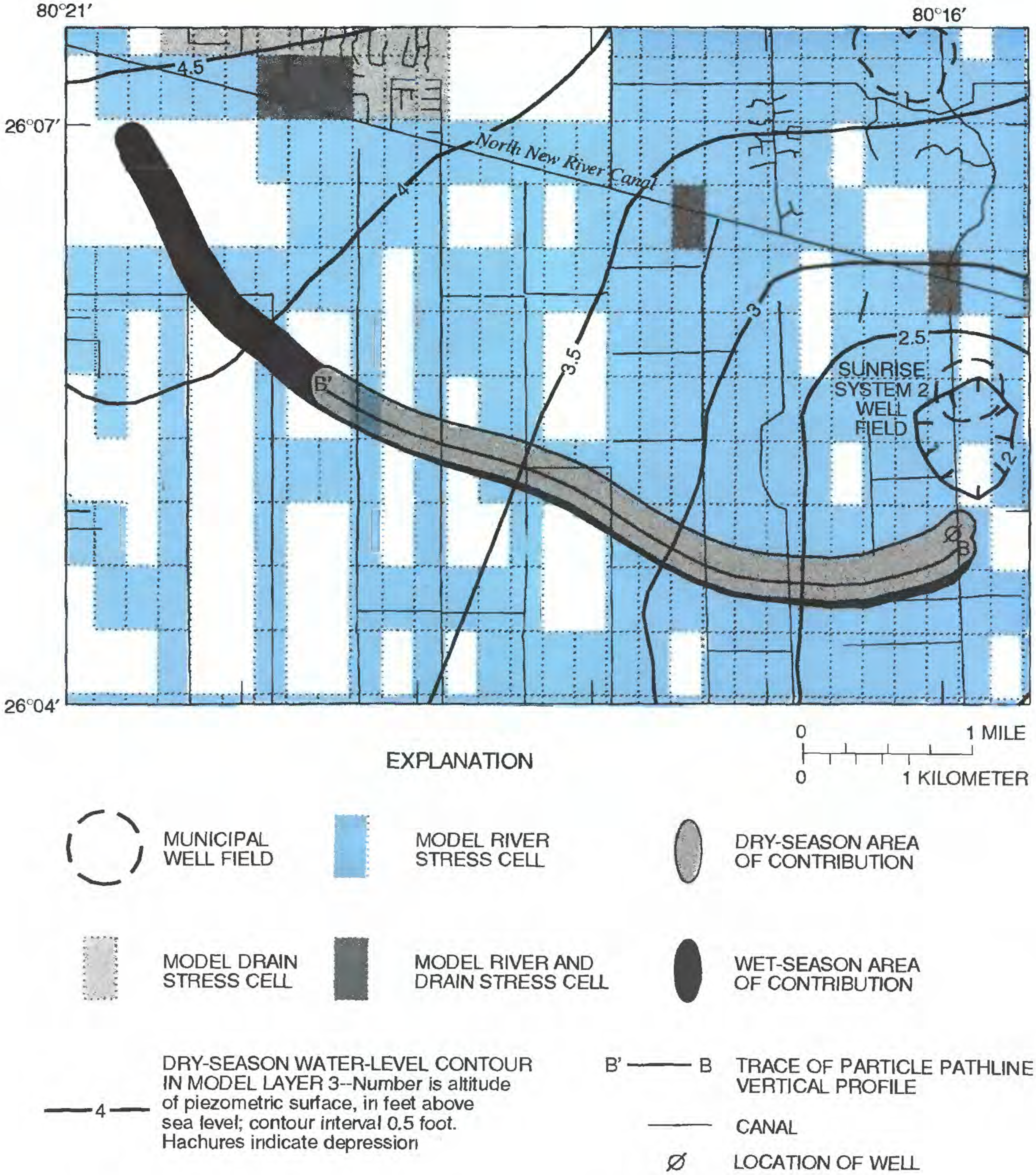

Figure 17. Dry- and wet-season areas of contribution to well G-2366.

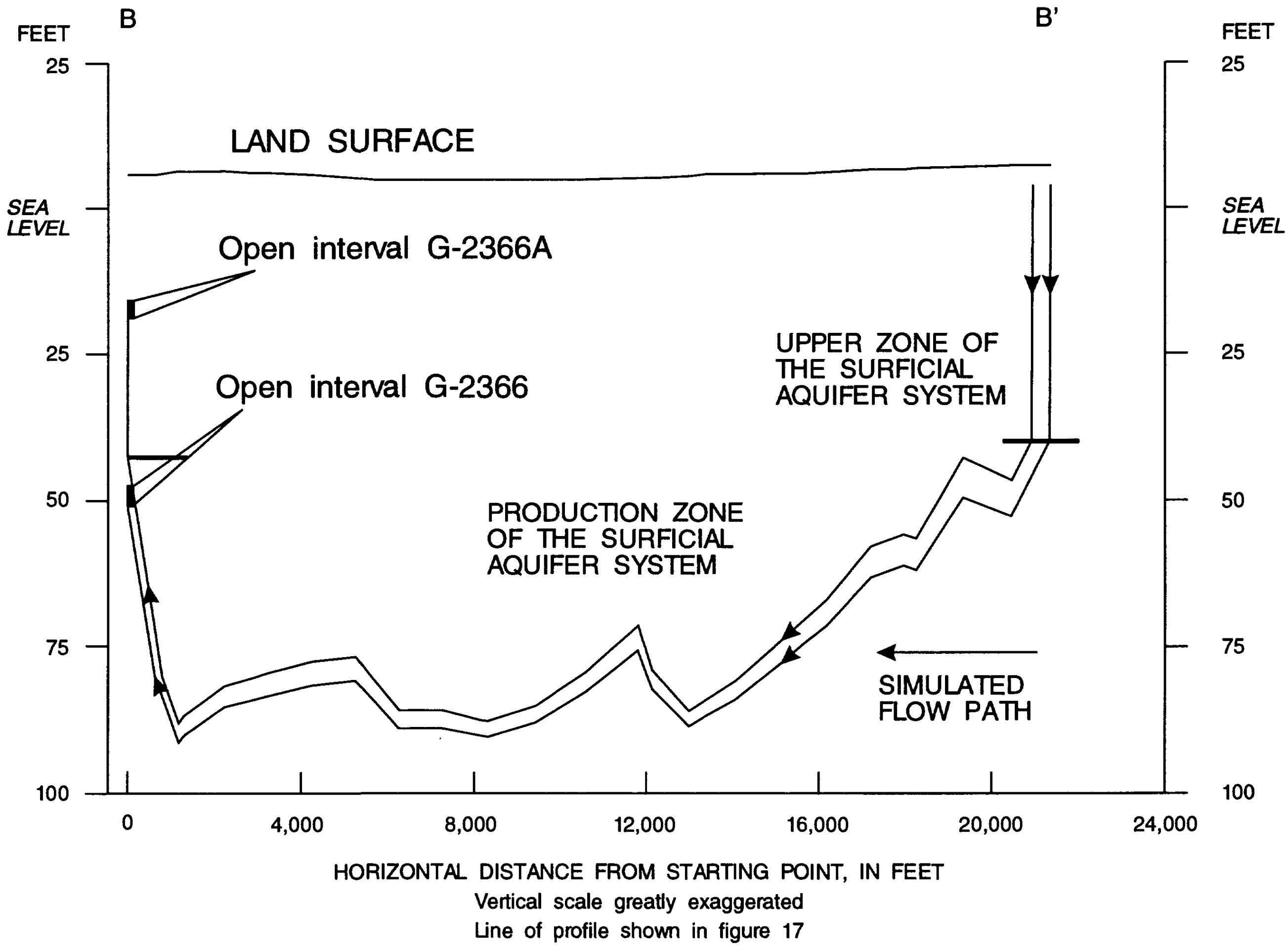

Figure 18. Selected particle pathlines leading to wells G-2366 and G-2366A.

River Canal (fig. 1) south of the site. The simulated particle pathlines may only be representative of flow paths near the canals. A more detailed model is required to more accurately determine the area of contribution to the wells at this site.

Land Use and Sewered or Nonsewered Areas

The land-use and sewered classification method was evaluated for each well site (rather than for each well) and for each representative area of contribution. Although the predominant land use in the area of contribution can vary between wells at the same site, differences only occurred at the Davie Road Extension site (fig. 1 and table 8, wells G-2161 and G-2161A). The land use assigned to this site was the Urban Commercial/Industrial/Transportation category (I), which is the same land use assigned to shallow well G-2161A both at the well and in the area of contribution. At three other sites (wells G-2344A and G-2344B, G-2360 and G-2360A, and G-2366 and G-2366A), the two land-use categories varied between at the well and in the area of contribution. The distributions of the land-use categories Urban Commercial/Industrial/Transportation (I) and Barren/Urban Open (O) are overrepresented when compared to the distributions of these land uses in the study area (table 11). The distributions of the land-use categories Rangeland/Forested Upland/Wetland (G) and Agriculture (A) are underrepresented when compared to the distributions of these land uses in the study area. These land uses represented 19 and 12 percent of the study area, respectively (table 11), at the time the land-use data layer was prepared. However, these percentages have been decreasing as the urban areas have expanded into undeveloped areas.

Differences in the sewered classification, between at the well and in the area of contribution, only occurred at well G-2269 – sewered at the well and nonsewered in the area of contribution (table 8). This well was assigned to the sewered category, resulting in no wells that were different (sewered or nonsewered) both at the well and in the area of contribution. Thus, using either method of classification (at the well or predominant land use in the area of contribution), 69 percent of the well sites are in sewered categories and 31 percent are in nonsewered categories (table 12). This distribution corresponds closely to the percentage of sewered and nonsewered areas in the study area. Therefore, no changes are required to the network to monitor sewered and nonsewered areas.

Table 11. Distribution of combined land-use categories by site

Land-use code	Land-use category	Percentage of land use of total study area	Site location		Predominant in area of contribution	
			Number of sites	Percentage of sites	Number of sites	Percentage of sites
A	Agriculture	12	1	3	2	7
G	Rangeland/Forested Upland/Wetland	19	4	14	4	14
H	Water	4	0	0	0	0
I	Urban Commercial/ Industrial/Transportation	14	8	28	6	21
O	Barren/Urban Open	13	6	21	5	17
R	Urban Residential/ Institutional	38	10	34	12	41

Table 12. Distribution of sewered and nonsewered areas by site

Category	Percentage of total study area	Site location		Predominant in area of contribution	
		Number of sites	Percentage of sites	Number of sites	Percentage of sites
Nonsewered	40	9	31	9	31
Sewered	60	20	69	20	69

Relation Between Water Quality and Land Use

An assessment of the relation between water quality at the wells in the DNRP ground-water quality monitoring network and the corresponding land use was accomplished using the mean concentration of eight constituents (table 13). A USGS program to sample water from wells in the DNRP ground-water quality monitoring network was conducted from April 1983 to July 1984. Sampling times were selected to represent yearly minimum water levels (April), rising water levels (June and July), and yearly maximum water levels (September and October) (Waller and Cannon, 1986, p. 2). Not all wells were sampled every time, and not all water-quality constituents were determined for each water sample during each round of sampling. One to five analyses of major-ion concentrations were available for 53 wells, and one to two analyses of trace-metal concentrations were available for 42 wells. No water-quality data were available for three wells (G-2156A, G-2436, and G-2437). A summary of the USGS water-quality data used in this report is given in table 13. Data from the DNRP sampling program were not available for this report. Box plots were used to visually compare the median and ranges of concentrations for six of the water-quality constituents to the predominant land use in the area of contribution and to the land use at the well.

Constituents that naturally occur in water from the surficial aquifer system and which are generally not used as indicators of contamination were not included in the assessment of the relation to land use. These constituents include calcium, iron, magnesium, manganese, potassium, sodium, bicarbonate, and sulfate; all except manganese naturally occur in relatively large concentrations. Chloride, which is used as an indicator of saltwater intrusion and which also naturally occurs in relatively large concentrations, also was not included in this assessment.

Constituent Group 1

Constituent group 1 is based on water samples from 53 wells that were analyzed for dissolved solids, total organic carbon, nitrite, nitrite plus nitrate, and orthophosphate. Dissolved solids concentration is a general indicator of water quality, with a nonmandatory U.S. Public Health Service standard of 500 mg/L (milligrams per liter) (Hem, 1985, p. 212). Sources of organic carbon in ground water are both natural and anthropogenic. Organic soils, a source of natural organic carbon in ground water in southern Florida, are prevalent in the southwestern parts of the study area (Pendelton and others, 1984). Synthetic organic compounds, an anthropogenic source of organic carbon, are used for agricultural, industrial, and residential purposes. However, some of these synthetic compounds are volatile and are frequently evaporated from a water sample during the sampling procedure. This probably occurred during the procedure used to sample total organic carbon at wells used for this study. Elevated nitrite, nitrite plus nitrate, and orthophosphate concentrations are often the result of anthropogenic influences, such as waste disposal (septic tanks and farm animal waste) and the application of synthetic fertilizers (Hem, 1985, p. 124-126).

The median dissolved-solids concentration at wells classified as Urban Commercial/Industrial/Transportation (I) was 302 mg/L, which is lower than the median values that correspond to other land-use categories (fig. 19). However, the range of dissolved-solids concentrations for this land-use category is large. Mean dissolved-solids concentrations in

Table 13. Summary statistics for water-quality data

[Values in parentheses indicate laboratory code for given constituent. The < symbol indicates less than the value]

Well number	Dissolved solids, in milligrams per liter (70301)				Total organic carbon, milligrams per liter (00680)			
	Mean	Minimum	Maximum	Number of analyses	Mean	Minimum	Maximum	Number of analyses
G-820	207.7	207	208	3	4.00	2.5	5.0	4
G-820A	294.3	287	300	3	6.67	4.0	9.6	3
G-1272A	394.3	323	430	3	10.10	8.3	11.0	3
G-2038	325.0	325	325	1	8.00	7.0	9.0	2
G-2039	359.8	342	375	4	9.63	8.7	11.0	4
G-2156	383.0	383	383	1	8.88	5.6	12.0	4
G-2160	276.5	274	281	4	11.57	8.8	15.0	4
G-2160A	147.0	126	171	4	8.02	6.5	9.3	4
G-2161	404.5	391	413	4	16.75	13.0	20.0	4
G-2161A	119.0	110	131	4	8.43	6.0	11.0	4
G-2269	342.3	339	347	3	11.63	6.0	16.0	4
G-2270	380.5	379	382	2	9.20	6.0	12.0	4
G-2274	381.5	371	392	2	17.00	16.0	18.0	2
G-2275	302.5	296	309	4	6.20	4.0	9.1	3
G-2344A	323.5	317	339	4	10.73	7.9	15.0	4
G-2344B	203.5	198	209	2	3.40	3.0	3.8	2
G-2345X	307.5	275	320	4	12.38	9.5	17.0	4
G-2355	555.5	547	564	2	14.00	11.0	17.0	2
G-2355A	564.5	549	580	2	28.00	21.0	35.0	2
G-2356	402.0	382	426	4	17.50	15.0	21.0	4
G-2356A	390.5	379	406	4	13.25	11.0	17.0	4
G-2357	408.5	393	414	4	14.75	13.0	17.0	4
G-2357A	394.8	384	400	4	16.50	14.0	20.0	4
G-2358	659.0	640	678	2	26.25	23.0	30.0	4
G-2358A	453.8	432	475	4	24.25	23.0	28.0	4
G-2359	408.5	404	413	2	14.75	12.0	17.0	4
G-2359A	421.0	398	451	4	15.25	14.0	17.0	4
G-2360	254.3	242	276	4	7.82	6.9	9.0	4
G-2360A	97.0	89	105	2	25.50	24.0	27.0	2
G-2361	470.8	457	477	4	18.50	15.0	24.0	4
G-2361A	385.7	362	411	3	19.33	17.0	21.0	3
G-2363	398.5	361	436	2	14.67	13.0	16.0	3
G-2363A	544.7	490	579	3	16.25	14.0	20.0	4
G-2364	326.5	309	362	4	15.25	11.0	19.0	4
G-2364A	294.5	272	317	2	13.00	9.0	17.0	2
G-2365	421.0	413	429	3	19.33	18.0	20.0	3
G-2365A	395.7	380	404	3	15.67	11.0	25.0	3
G-2366	471.0	466	479	4	39.75	31.0	45.0	4
G-2366A	445.7	438	454	3	31.00	25.0	35.0	3
G-2367	465.3	457	479	3	21.67	17.0	25.0	3
G-2367A	448.0	444	452	2	23.67	23.0	25.0	3
G-2368	399.0	399	399	1	23.00	23.0	23.0	1
G-2368A	476.0	456	496	2	24.00	22.0	26.0	2
G-2369	401.0	390	410	4	29.50	23.0	34.0	4
G-2369A	400.3	364	442	4	27.50	19.0	33.0	4
G-2370	370.8	358	381	4	15.25	11.0	21.0	4
G-2370A	253.8	218	280	4	10.65	7.6	14.0	4
G-2372	506.5	490	523	2	10.50	7.0	14.0	2
G-2372A	338.0	334	342	2	25.00	23.0	27.0	2
G-2373	534.5	533	536	2	29.00	26.0	32.0	2
G-2373A	518.5	482	555	2	30.50	29.0	32.0	2
G-2374	385.5	379	392	2	15.00	13.0	17.0	2
G-2374A	319.5	308	331	2	27.00	25.0	29.0	2

Table 13. Summary statistics for water-quality data (Continued)

Well number	Nitrite, in milligrams per liter (00615) Detection limit is <0.01 milligram per liter				Nitrite + nitrate, in milligrams per liter (00630) Detection limit is <0.02 milligram per liter			
	Mean	Minimum	Maximum	Number of analyses	Mean	Minimum	Maximum	Number of analyses
G-820	0.010	<0.01	0.01	4	0.620	<0.02	2.40	4
G-820A	.010	<.01	.01	3	.020	<.02	.02	3
G-1272A	.010	<.01	<.01	3	.020	<.02	<.02	3
G-2038	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2039	.010	<.01	<.01	4	.020	<.02	<.02	4
G-2156	.010	<.01	<.01	4	.020	<.02	<.02	4
G-2160	.010	<.01	.01	4	.020	<.02	<.02	4
G-2160A	.010	<.01	.01	4	.020	<.02	<.02	4
G-2161	.010	<.01	.01	4	.020	<.02	<.02	4
G-2161A	.010	<.01	.01	4	.020	<.02	<.02	4
G-2269	.010	<.01	.01	4	.020	<.02	<.02	4
G-2270	.010	<.01	.01	4	.020	<.02	<.02	4
G-2274	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2275	.010	<.01	.01	4	.020	<.02	.02	4
G-2344A	.010	<.01	<.01	4	.020	<.02	<.02	4
G-2344B	.010	<.01	.01	2	.020	<.02	.02	2
G-2345X	.010	<.01	.01	4	.020	<.02	<.02	4
G-2355	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2355A	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2356	.010	<.01	<.01	4	.020	<.02	<.02	4
G-2356A	.010	<.01	<.01	4	.020	<.02	<.02	4
G-2357	.010	<.01	.01	4	.020	<.02	<.02	4
G-2357A	.010	<.01	.01	4	.020	<.02	<.02	4
G-2358	.010	<.01	<01	4	.020	<.02	.02	4
G-2358A	.010	<.01	.01	4	.020	<.02	<.02	4
G-2359	.010	<.01	.01	4	.020	<.02	.02	4
G-2359A	.010	<.01	<.01	4	.020	<.02	.02	4
G-2360	.010	<.01	<.01	4	.020	<.02	.02	4
G-2360A	.010	.01	.01	2	.020	<.02	.02	2
G-2361	.010	<.01	<..01	4	.020	<.02	<.02	4
G-2361A	.013	<.01	.02	3	.023	<.02	.03	3
G-2363	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2363A	.010	<.01	<.01	3	.020	<.02	<.02	3
G-2364	.010	<.01	.01	4	.020	<.02	<.02	4
G-2364A	.010	<.01	.01	2	.020	<.02	<.02	2
G-2365	.010	<.01	.01	4	.020	<.02	<.02	4
G-2365A	.010	<.01	.01	5	.020	<.02	<.02	5
G-2366	.010	.01	.01	4	.020	<.02	<.02	4
G-2366A	.010	.01	.01	3	.020	<.02	<.02	3
G-2367	.010	<.01	.01	4	.020	<.02	<.02	4
G-2367A	.010	<.01	<.01	3	.020	<.02	<.02	3
G-2368	.010	<.01	<.01	1	.020	<.02	<.02	1
G-2368A	.090	.08	.10	2	.515	.45	.58	2
G-2369	.010	<.01	.01	4	.020	<.02	<.02	4
G-2369A	.018	.01	.04	4	.260	<.02	.98	4
G-2370	.010	<.01	<.01	4	.020	<.02	<.02	4
G-2370A	.010	<.01	.01	4	.020	<.02	.02	4
G-2372	.010	<.01	<.01	2	.020	<.02	<.02	2
G-237A	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2373	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2373A	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2374	.010	<.01	<.01	2	.020	<.02	<.02	2
G-2374A	.010	<.01	<.01	2	.020	<.02	<.02	2

Table 13. Summary statistics for water-quality data (Continued)

Well number	Orthophosphate, in milligrams per liter (70507) Detection limit is <0.01 milligram per liter				Chromium, in micrograms per liter (01034) Detection limit is <1 microgram per liter			
	Mean	Minimum	Maximum	Number of analyses	Mean	Minimum	Maximum	Number of analyses
G-820	0.037	0.02	0.08	4	1	<1	<1	1
G-820A	.550	.35	.85	3	1	<1	<1	1
G-1272A	.037	<.01	.08	3	1	<1	<1	1
G-2038	.015	.01	.02	2	--	--	--	--
G-2039	.022	.02	.03	4	23	23	23	1
G-2156	.010	<.01	.01	4	1	1	1	1
G-2160	.020	.02	.02	4	1	<1	<1	1
G-2160A	.030	.03	.03	4	26	26	26	1
G-2161	.022	.02	.03	4	25	25	25	1
G-2161A	.047	.04	.06	4	24	24	24	1
G-2269	.058	.05	.07	4	24	24	24	1
G-2270	.015	.01	.02	4	22	22	22	1
G-2274	.140	.13	.15	2	1	<1	<1	2
G-2275	.117	.05	.21	4	14	14	14	1
G-2344A	.025	.01	.03	4	1	<1	<1	1
G-2344B	.015	<.01	.02	2	--	--	--	--
G-2345X	.045	.02	.07	4	23	23	23	1
G-2355	.015	.01	.02	2	1	<1	<1	1
G-2355A	.030	.02	.04	2	2	2	2	1
G-2356	.030	.02	.04	4	1	<1	<1	1
G-2356A	.027	.02	.03	4	1	<1	<1	1
G-2357	.030	<.01	.04	4	1	<1	<1	1
G-2357A	.100	.02	.18	4	1	<1	<1	1
G-2358	.015	<.01	.02	4	1	<1	<1	1
G-2358A	.020	.01	.03	4	1	<1	<1	1
G-2359	.015	.01	.02	4	1	<1	<1	1
G-2359A	.035	.03	.05	4	1	<1	<1	1
G-2360	.375	.22	.48	4	1	<1	<1	1
G-2360A	1.400	1.30	1.50	2	--	--	--	--
G-2361	.020	.01	.03	4	20	20	20	1
G-2361A	.030	.02	.04	3	1	1	1	1
G-2363	.015	.01	.02	2	21	21	21	1
G-2363A	.010	.01	.01	3	20	20	20	1
G-2364	.020	.02	.02	4	23	23	23	1
G-2364A	.010	.01	.01	2	--	--	--	--
G-2365	.018	.01	.03	4	20	20	20	1
G-2365A	.022	<.01	.03	5	3	3	3	1
G-2366	.063	.06	.07	4	1	<1	<1	1
G-2366A	.080	.07	.09	3	1	<1	<1	1
G-2367	.045	.02	.11	4	2	2	2	1
G-2367A	.063	.05	.07	3	--	--	--	--
G-2368	.010	.01	.01	1	7	7	7	1
G-2368A	.025	.02	.03	2	1	<1	<1	1
G-2369	.027	.02	.04	4	1	<1	<1	1
G-2369A	.018	.01	.02	4	25	25	25	1
G-2370	.025	.02	.03	4	23	23	23	1
G-2370A	.032	.02	.05	4	22	22	22	1
G-2372	.010	.01	.01	2	--	--	--	--
G-237A	.010	.01	.01	2	--	--	--	--
G-2373	.015	.01	.02	2	--	--	--	--
G-2373A	.015	.01	.02	2	--	--	--	--
G-2374	.015	.01	.02	2	--	--	--	--
G-2374A	.015	.01	.02	2	--	--	--	--

Table 13. Summary statistics for water-quality data (Continued)

Well number	Lead, in micrograms per liter (01051) Detection limit is <1 microgram per liter				Zinc, in micrograms per liter (01092) Detection limit is <10 microgram per liter			
	Mean	Minimum	Maximum	Number of analyses	Mean	Minimum	Maximum	Number of analyses
G-820	4.0	4	4	2	55	20	90	2
G-820A	7.0	7	7	1	80	80	80	1
G-1272A	2.0	2	2	1	50	50	50	1
G-2038	--	--	--	--	--	--	--	--
G-2039	3.0	3	3	2	230	200	260	2
G-2156	3.0	1	5	2	25	10	40	2
G-2160	1.5	1	2	2	15	10	20	2
G-2160A	1.5	1	2	2	25	10	40	2
G-2161	2.5	1	4	2	25	20	30	2
G-2161A	9.0	4	14	2	20	<10	30	2
G-2269	2.5	2	3	2	30	<10	50	2
G-2270	4.0	3	5	2	20	10	30	2
G-2274	3.0	1	5	2	70	50	90	2
G-2275	5.5	4	7	2	25	20	30	2
G-2344A	3.5	2	5	2	30	10	50	2
G-2344B	--	--	--	--	--	--	--	--
G-2345X	20.0	7	33	2	20	10	30	2
G-2355	2.0	2	2	2	20	10	30	2
G-2355A	2.5	2	3	2	125	10	240	2
G-2356	3.0	1	5	2	25	20	30	2
G-2356A	1.5	1	2	2	15	10	20	2
G-2357	4.5	2	7	2	40	10	70	2
G-2357A	3.0	2	4	2	55	10	100	2
G-2358	2.5	2	3	2	25	10	40	2
G-2358A	4.0	4	4	2	25	10	40	2
G-2359	2.5	2	3	2	30	20	40	2
G-2359A	4.5	3	6	2	110	20	200	2
G-2360	3.5	3	4	2	70	50	90	2
G-2360A	--	--	--	--	--	--	--	--
G-2361	85.0	70	100	2	30	10	50	2
G-2361A	3.0	3	3	1	60	60	60	1
G-2363	5.0	4	6	2	65	10	120	2
G-2363A	4.0	3	5	2	65	10	120	2
G-2364	2.5	<1	4	2	15	10	20	2
G-2364A	--	--	--	--	--	--	--	--
G-2365	4.0	4	4	1	90	90	90	1
G-2365A	3.0	3	3	1	150	150	150	1
G-2366	7.5	3	12	2	25	10	40	2
G-2366A	2.0	2	2	1	10	10	10	1
G-2367	2,751.5	3	5,500	2	60	30	90	2
G-2367A	--	--	--	--	--	--	--	--
G-2368	7.5	3	12	2	45	20	70	2
G-2368A	3.0	3	3	1	10	10	10	1
G-2369	6.5	4	9	2	60	40	80	2
G-2369A	5.0	5	5	2	120	60	180	2
G-2370	2.0	1	3	2	130	10	250	2
G-2370A	4.0	3	5	2	15	10	20	2
G-2372	--	--	--	--	--	--	--	--
G-237A	--	--	--	--	--	--	--	--
G-2373	--	--	--	--	--	--	--	--
G-2373A	--	--	--	--	--	--	--	--
G-2374	--	--	--	--	--	--	--	--
G-2374A	--	--	--	--	--	--	--	--

water samples from 5 of the 15 wells in this land-use category were greater than the overall median value of 394 mg/L for all wells. Additionally, 5 of the 15 wells classified as Urban Commercial/Industrial/Transportation (I) at the well are classified as Urban Residential/Institutional (R) in the area of contribution. Accordingly, the relation between land use and dissolved-solids concentration is unclear.

The land-use categories Agriculture (A), Rangeland/Forested Upland/Wetland (G), and Barren/Urban Open (O) at the well and in the area of contribution correspond to the highest median total organic carbon concentrations in water samples from the wells (fig. 19). This relation between total organic carbon concentration and land use can be explained, at least in part, by noting the areal distribution of total organic carbon (fig. 20). Water samples from 16 wells in the study area had mean total organic carbon concentrations greater than 20 mg/L (fig. 20, table 13), with 11 of these wells being in the southwestern part of the study area where organic soils are prevalent. Additionally, mean total organic carbon concentrations at all 14 wells in this part of the area were at least 15 mg/L or greater (fig. 20). None of the seven well sites in the southwestern part of the study area correspond to land-use category (I), either at the well or in the area of contribution. The (I) land-use category is characterized by the lowest median total organic carbon concentration, both at the well and in the area of contribution. Additional information is needed to determine the source of elevated total organic carbon concentrations at those wells located in areas not affected by organic soils.

Water samples from only three wells contained nitrite and nitrite plus nitrate at concentrations significantly above the detection limit. Box plots were not produced for these two constituents. Three of four water samples from well G-820 contained nitrite plus nitrate at concentrations below the detection limit of 0.02 mg/L, and the fourth water sample contained a nitrite plus nitrate concentration of 2.40 mg/L. Nitrite concentrations in water sampled from well G-820 were below the detection limit. Only water samples from two other wells (G-2369A and G-2368A) contained nitrite and nitrite plus nitrate at concentrations significantly above the detection limit. Two of four water samples from well G-2369A and two water samples from well G-2368A contained elevated concentrations of nitrite and nitrite plus nitrate. The only classification in common for wells G-2369A and G-2368A is aquifer zone (upper zone). This result is consistent with the conclusion reached by Radell and Katz (1991, p. 11) that nitrate concentrations decrease significantly with depth in the study area.

Three land-use categories (A, O, and I) at the well and in the area of contribution correspond to higher median concentrations for orthophosphate compared to median concentrations related to the other two land-use categories (R and G) (fig. 21). Mean concentrations of orthophosphate in water samples from 19 of 28 wells, represented by the (A), (O), and (I) categories for land use at the well, were above the median concentration (0.025 mg/L) determined for all wells (fig. 22). Mean concentrations of orthophosphate in water samples from 17 of 23 wells, represented by the (A), (O), and (I) categories for land use in the area of contribution, were also above the median concentration determined for all wells (fig. 22). A relation seems to exist between orthophosphate concentration and land-use categories with only (G) and (R) land uses generally not corresponding to elevated concentrations of orthophosphate in ground water.

Constituent Group 2

Constituent group 2 is based on water samples from 42 wells that were analyzed for the trace metals chromium, lead, and zinc. Trace metals occur naturally in ground water in very low concentrations. Elevated concentrations of trace metals are an indication of contamination from an anthropogenic source, such as local contamination from surface sources or from well-casing material (Radell and Katz, 1991, p. 13).

Chromium concentrations in water samples from 20 of 42 wells were above the detection limit of 1 µg/L (microgram per liter). Mean chromium concentrations for water samples from five wells (G-2039, G-2269, G-2270, G-2275, and G-2370) completed with iron casing significantly exceeded the detection limit (tables 7 and 13), indicating a possible relation between casing type and chromium concentration, contrary to results reported by Radell and Katz (1991, p. 16). The Barren/Urban Open (O) category is the only land-use category that corresponds to a median chromium concentration greater than 5 µg/L (fig. 23). All of the wells in this land-use category were completed with polyvinyl chloride (PVC) casing. However, mean chromium concentrations significantly exceeded the detection limit for water samples from wells completed with PVC casing in all land-use categories, except for Agriculture (A), which contains only four wells at two sites. Thus, no

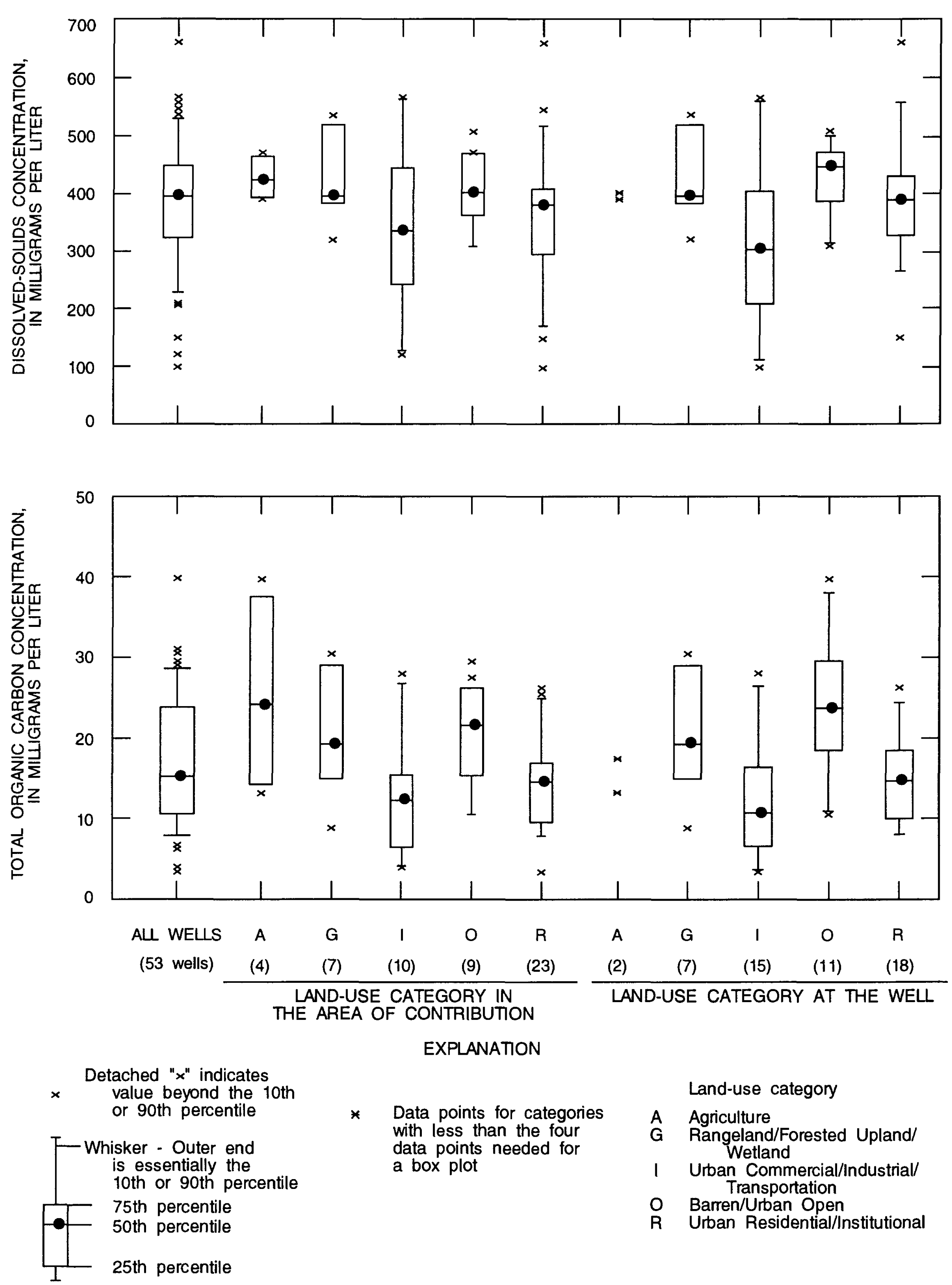

Figure 19. Box plots of dissolved-solids and total organic carbon concentrations in ground water in the study area by land-use category at the well and in the area of contribution.

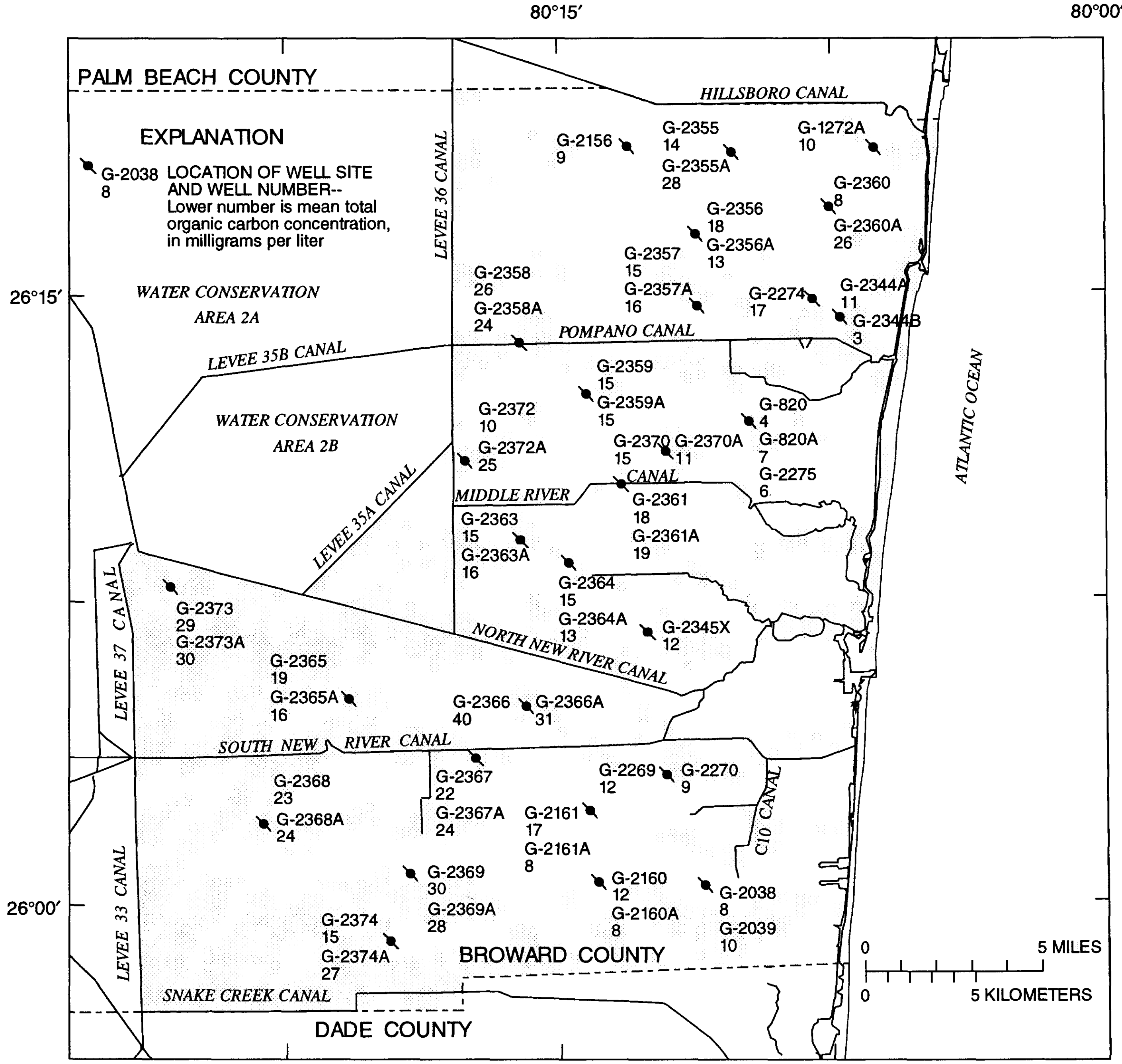

Figure 20. Eastern Broward County showing total organic carbon concentrations in the surficial aquifer system.

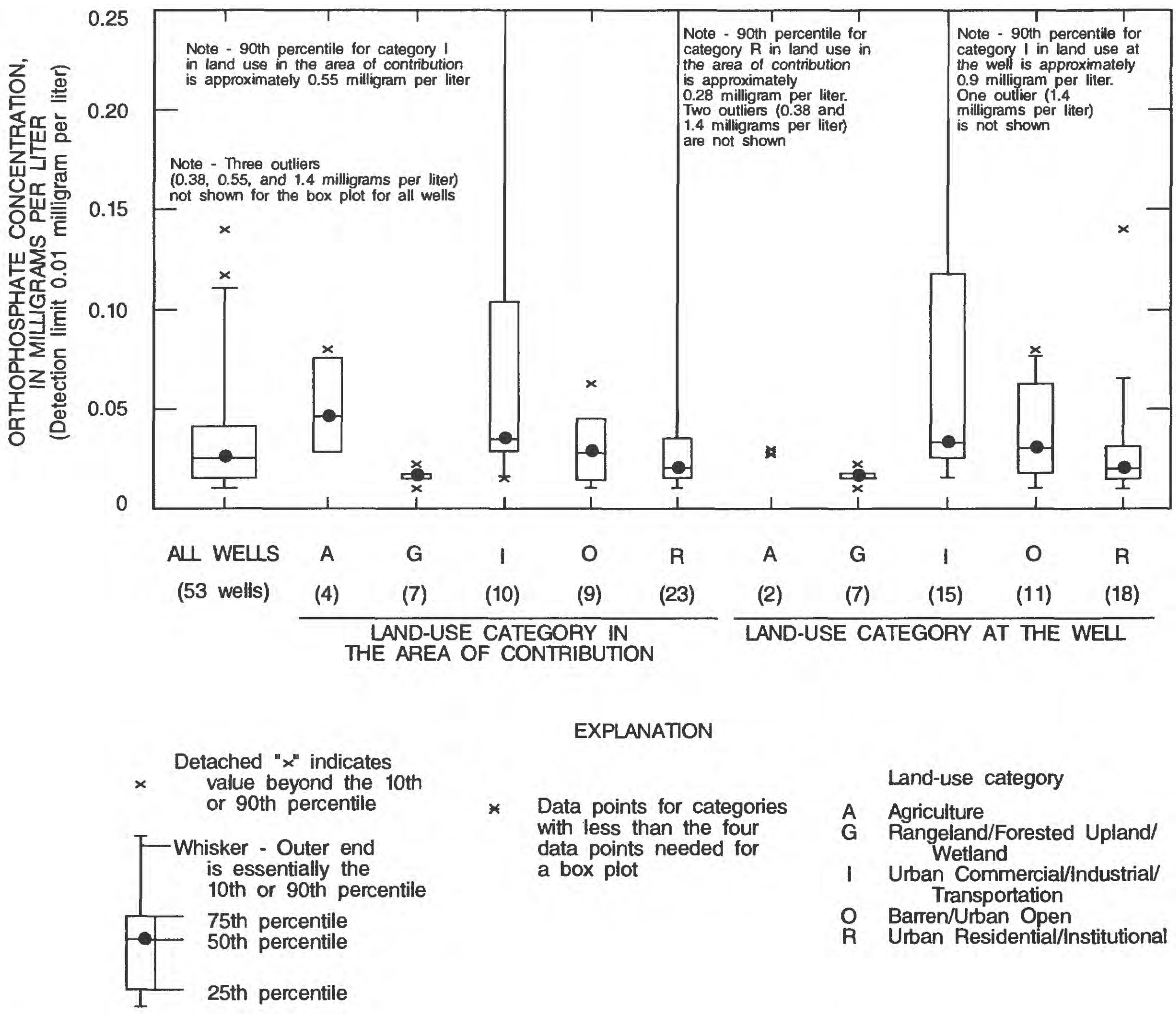

Figure 21. Box plot of orthophosphate concentrations in ground water in the study area by land-use category at the well and in the area of contribution.

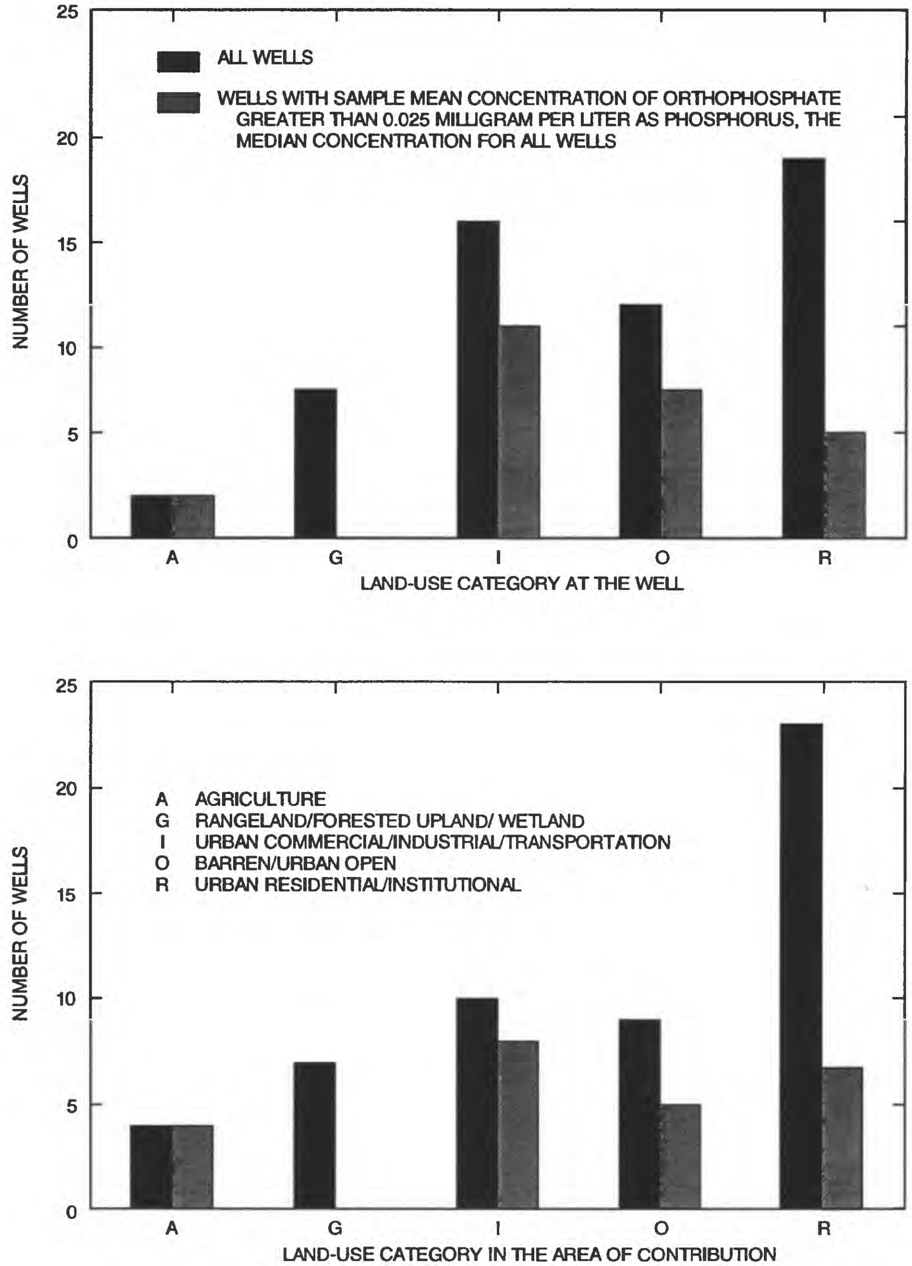

Figure 22. Histograms of orthophosphate concentrations in the study area by land-use category at the well and in the area of contribution.

relation between chromium concentration and land use is apparent.

The land-use categories Urban Commercial/Industrial/Transportation (I) and Barren/Urban Open (O) at the well and in the area of contribution correspond to higher median lead concentrations in water samples from wells than the categories of Agriculture (A), Rangeland/Forested Upland/Wetland (G), and Urban Residential/Institutional (R) (fig. 23). Mean concentrations of lead in water samples from 14 of 21 wells in the (I) and (O) land-use categories at the well and from 11 of 16 wells in the (I) and (O) land-use categories in the area of contribution were above the median concentration (3.25 µg/L) for all wells (fig. 24). The (I) land-use category corresponding to elevated lead concentrations is reasonable because of the land-use activities associated with this category; however, the elevated concentrations related to the (O) land-use category are more difficult to explain. One possible explanation is the proximity of these wells to canals. Lead concentrations in samples of canal water have been reported to be higher than in samples of ground water (Radell and Katz, 1991, p. 16). Five of the six wells (G-2361, G-2361A, G-2367, G-2369, and G-2369A) sampled for lead concentrations in the (O) land-use category are located near canals, and the two wells (G-2361 and G-2367) that contained the highest lead concentrations are in this category.

Median zinc concentrations in water samples from wells varied between the predominant land-use categories in the area of contribution, ranging from 20 to 90 µg/L. Three land-use categories (G, I, and O) correspond to median zinc concentrations above the median concentration of 30 µg/L for all wells. Mean zinc concentrations related to the (A) land-use category (median of 20 µg/L and maximum of 25 µg/L) were below the median concentration for all wells. The median zinc concentration related to the (R) land-use category is equal to the overall median concentration (fig. 25). These results are similar to those previously discussed for lead concentrations. As was the case with lead concentrations, the proximity of canals to the wells located in the (O) land-use category is a factor that should be considered when evaluating the relation of zinc concentrations in ground water to land use.

SUMMARY AND CONCLUSIONS

The DNRP ground-water quality monitoring network in Broward County, which consists of 56 wells at 29 sites, was established in 1983 to determine areal, vertical, and seasonal variations in water quality in the Biscayne aquifer and to identify areas where contamination is or might be evident. A recent study was conducted to evaluate the design of the DNRP network in relation to monitoring vertical variations and land-use effects on water quality and to assess the relation between water-quality constituents and land use. Hydrogeologic and statistical approaches were used in the study to determine whether the goals of the network are being met. Adding, replacing, or moving wells at 10 of 29 sites could result in a network which better meets the goals.

The hydrogeologic approach was used to determine the area of contribution to each well. The wells were assigned to classes based on selected land-use characteristics of the well site and of the area of contribution as well as other criteria, such as contributing interval to the well, the seasonal variation in areas of contribution, and whether or not the area is sewered. The distribution of land-use categories affecting the wells was compared to the distribution of land-use categories within the study area to determine if land-use categories being monitored by the network were representative of the entire study area. The statistical approach was used to determine whether or not correlations exist between selected water-quality constituents and land use.

To monitor the vertical variations in water quality in the Biscayne aquifer, one well should be completed in the upper zone of the surficial aquifer system and one well in the production zone of the surficial aquifer system at each site. An initial evaluation of the wells at each site indicates that 14 of the 29 sites meet the criteria to monitor the top two zones of the surficial aquifer system. Of the remaining 15 sites, 6 sites had no well monitoring the upper zone, 7 sites had no well monitoring the production zone, and 2 sites had wells monitoring only the lower zone of the surficial aquifer system. Because of the uncertainty in the aquifer zone boundaries, all of the sites except one can be considered to have a well in the production zone, but seven sites can still be considered to be without a well completed in the upper zone. The relative length of the area of contribution and other factors were evaluated at these sites to determine any changes required to better meet the goal of monitoring vertical variations in water quality. Variations exist between the simulated wet- and dry-season areas of contribution for seven wells at five sites. These variations are not considered

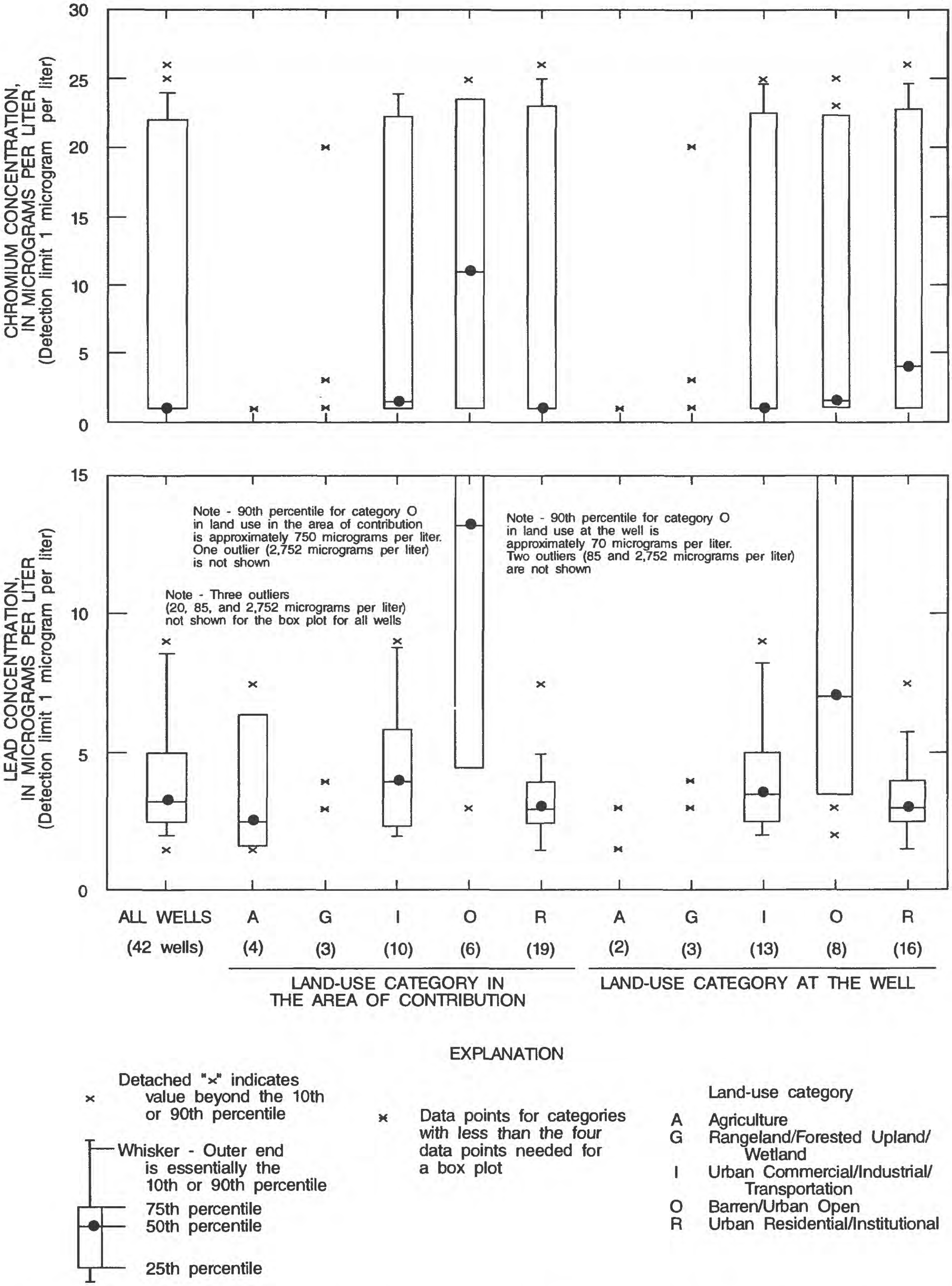

Figure 23. Box plots of chromium and lead concentrations in ground water in the study area by land-use category at the well and in the area of contribution.

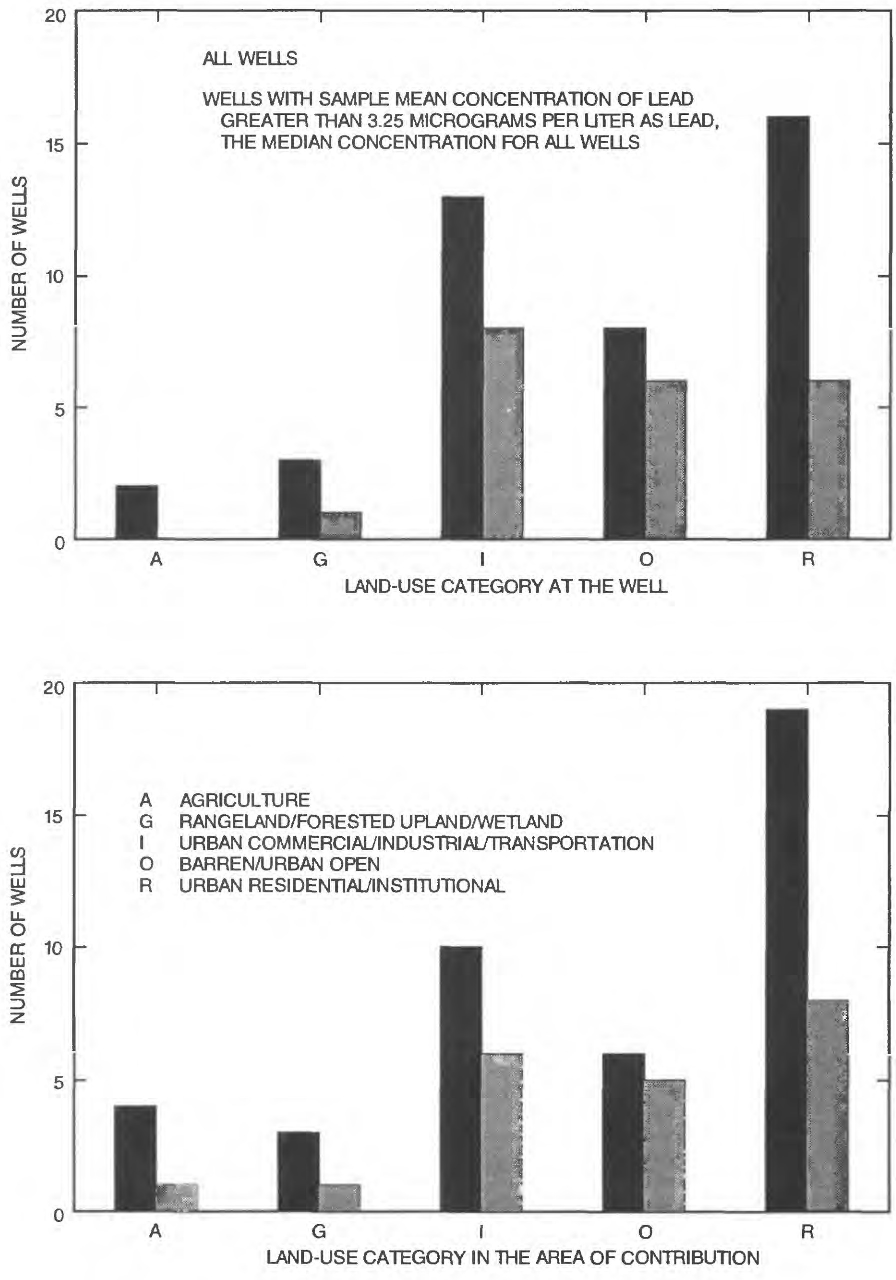

Figure 24. Histograms of lead concentrations in the study area by land-use category at the well and in the area of contribution.

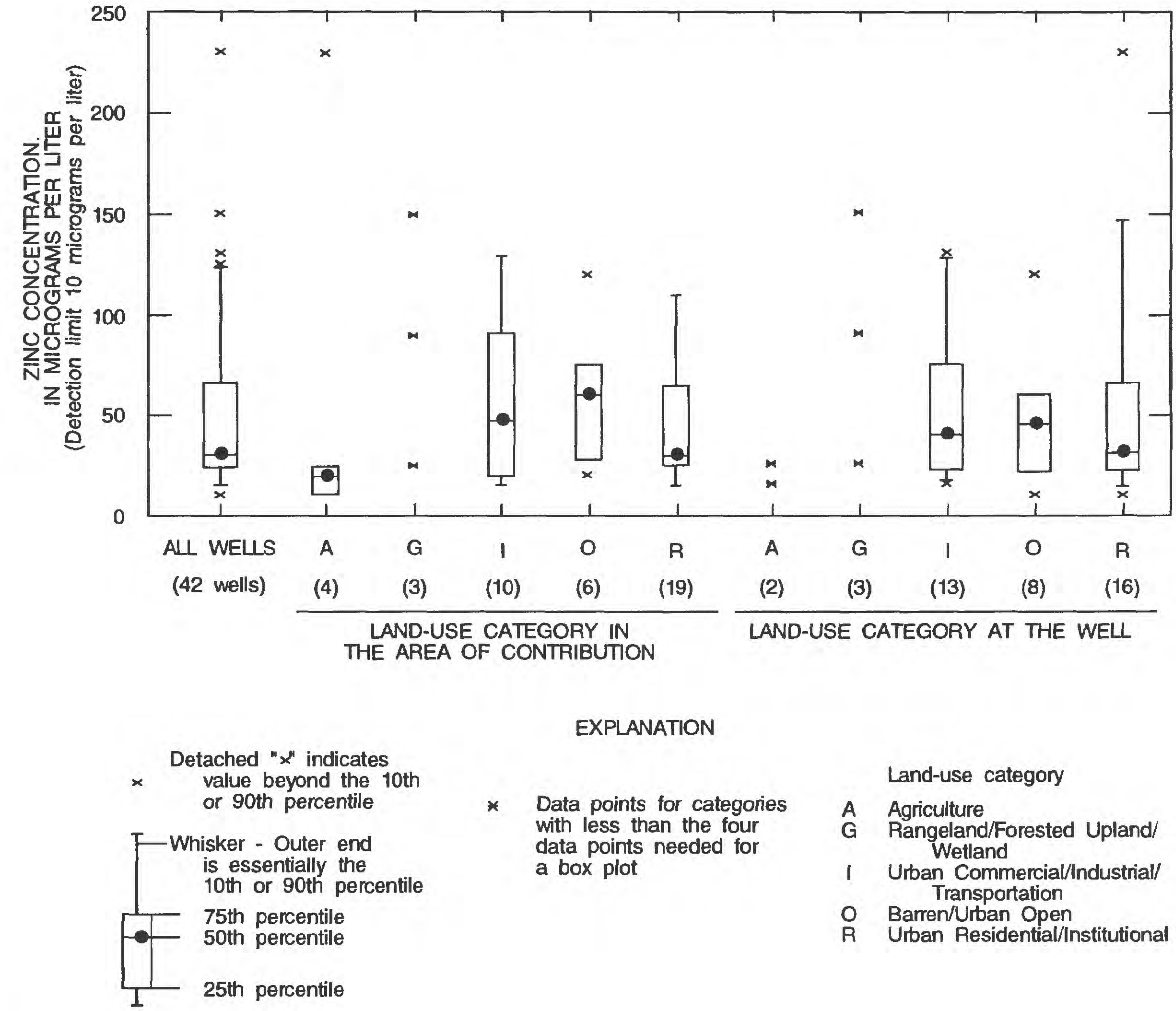

Figure 25. Box plot of zinc concentrations in ground water in the study area by land-use category at the well and in the area of contribution.

significant for the analyses because of the lack of variations in the land-use and sewered classifications in the vicinity of the areas of contribution.

To monitor the effects of land use on ground-water quality, wells should have an area of contribution which can be easily defined, allowing the land uses that might affect the quality of water sampled from wells to be determined. The accuracy in predicting the area of contribution increases with a decrease in the length of the area. A total of 18 wells at 16 sites were in the short area of contribution category, and 3 wells at 3 other sites were at the low end of the medium area of contribution category. Only 1 of these 19 sites had no wells monitoring the upper zone, and replacing a well completed in the lower zone with a well completed in the upper zone would better meet the goals of the network. The 10 sites not in the group of 19 sites were evaluated to determine what changes, if any, are needed to better meet the goals of the network. Stresses on the ground-water flow system, including drainage canals and well fields, have a significant effect on the length of the area of contribution at these sites. Six of these sites had no well monitoring the upper zone. The goals of the network are better met by adding a well completed in the upper zone, or replacing a well completed in the lower zone with one completed in the upper zone. The proximity to model drain cells affected the length of the area of contribution for wells at two of the remaining four well sites. These two sites require additional analysis to more accurately determine the area of contribution. The final two well sites were considered to meet the goals of the network because the land uses in the area of contribution were sufficiently uniform.

The land-use and sewered classifications were evaluated for each well site to determine if the distributions of the categories within these classifications were similar to the distribution of the categories in the study area. For land use, the Urban Commercial/Industrial/Transportation category and the Barren/Urban Open category were overrepresented. The Rangeland/Forested Upland/Wetland category and the Agriculture category were underrepresented. For the sewered classification, the distributions of the two categories by site, sewered and nonsewered, closely matched the distributions for the study area.

Dissolved-solids concentrations might have a relation to land use at the well based on the Urban Commercial/Industrial/Transportation category having a lower median value than the other categories. However, the variation between land use at the well and in the area of contribution for five of the wells in the Urban Commercial/Industrial/Transportation category indicated that the lower median dissolved-solids concentration for the wells in this land-use category might be due to a factor other than land use at the well. A spatial analysis of total organic carbon concentrations indicated that elevated concentrations might be related to organic soils.

Elevated nitrite, nitrite plus nitrate, and orthophosphate concentrations are often associated with anthropogenic influences. Concentrations of nitrite and nitrite plus nitrate were above the detection limit in some water samples from only two wells at two different sites and in all water samples from one additional well. Orthophosphate concentrations were determined to be related to land use; elevated levels being associated with the Agriculture, Barren/Urban Open, and the Urban Commercial/Industrial/Transportation land-use categories.

Concentrations of trace metals above background levels are also associated with anthropogenic sources. Chromium concentrations significantly exceeded the detection limit in water samples from five wells completed with iron casing, indicating a possible relation between chromium concentration and casing type. However, no relation between chromium concentration and land use is apparent. Lead and zinc concentrations were both related to land use, with the Urban Commercial/Industrial/Transportation category and the Barren/Urban Open category having been associated with higher concentrations of these metals. Canals were considered a possible source of the elevated concentrations of lead and zinc for wells in the Barren/Urban Open land-use category.

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