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TECHNICAL FEASIBILITY OF ARTIFICIAL RECHARGE OF RECLAIMED WASTEWATER AND ITS HYDROLOGIC IMPACTS ON THE REGIONAL GROUNDWATER SYSTEM

by

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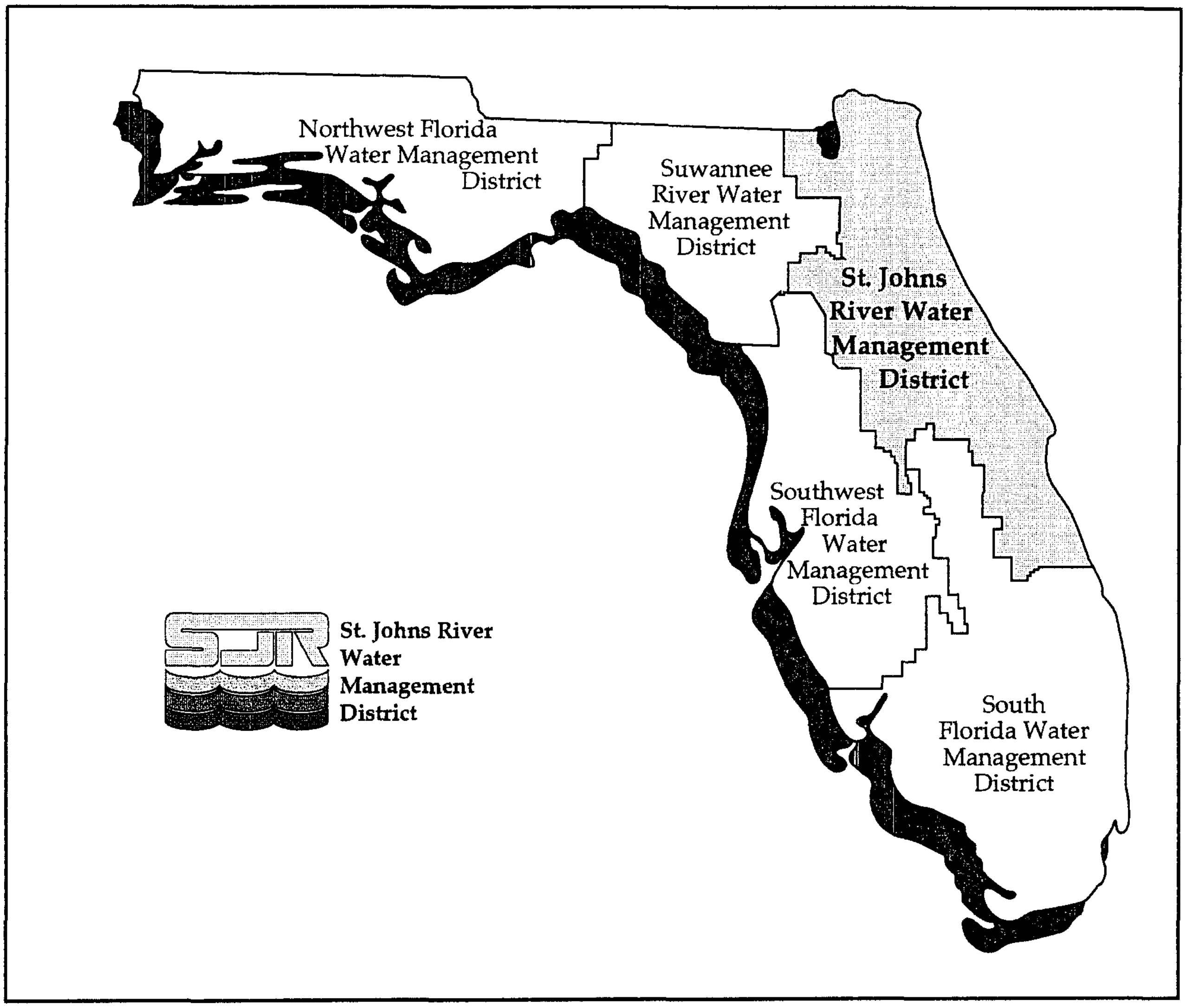

The St. Johns River Water Management District (SJRWMD) was created by the Florida Legislature in 1972 to be one of five water management districts in Florida. It includes all or part of 19 counties in northeast Florida. The mission of SJRWMD is to manage water resources to ensure their continued availability while maximizing environmental and economic benefits. It accomplishes its mission through regulation; applied research; assistance to federal, state, and local governments; operation and maintenance of water control works; and land acquisition and management.

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EXECUTIVE SUMMARY

The population of the St. Johns River Water Management District (SJRWMD) is about 3.44 million, 2.89 million of whom depend on public water supply and about 0.55 million of whom depend on domestic sources (Florence 1994). In SJRWMD, 1,522 million gallons per day (mgd) of freshwater is withdrawn for potable and nonpotable uses. Fresh groundwater comprises about 1,119 mgd, or 75% of this amount. At present, 38% of the groundwater pumpage is used for public water supply. Only a small part of the fresh groundwater pumpage is used for drinking and cooking, and the remaining portion ends up as wastewater. Thus, a large amount of wastewater could be reused or artificially recharged into the groundwater system after treatment.

This study investigated the technical feasibility and hydrologic impacts of artificial recharge with reclaimed wastewater through rapid infiltration basins (RIBs) into the groundwater system. SJRWMD is especially interested in maintaining or increasing the potentiometric head of the Floridan aquifer system and associated spring discharges through the use of artificial recharge with reclaimed wastewater. To evaluate this option, potential artificial recharge sites were identified within the study area using SJRWMD's geographic information system. The study area was divided into seven subregions on the basis of proximity of wastewater treatment plants to the potential recharge sites. Up to 21 potential sites were then selected for artificial recharge of groundwater using RIBs.

GROUNDWATER MODELING

Groundwater modeling was performed to achieve the objectives of this study. The U.S. Geological Survey's (USGS) MODFLOW was used as a tool for performing groundwater flow simulations in this study. The hydrologic impacts of RIBs were evaluated using two pumping scenarios, one for the year 1994 and the other for the year 2010. The hydrologic impacts of artificial recharge through RIBs on the groundwater system were assessed by comparing the differences between the simulations with and without artificial recharge. The simulations without artificial recharge of reclaimed wastewater at the recharge sites or RIBs are considered baseline simulations.

The 2010 groundwater demand (pumpage) was projected to be significantly higher compared to that of 1994. Thus, overall drawdown in the year 2010 was simulated to be greater than that of 1994. From the regional (model area) perspective, the weighted average head differences between 1994 and 2010 were computed to be 1.25, 1.51, and 1.57 feet (ft), respectively, for the surficial, Upper Floridan, and Lower Floridan aquifers.

HYDROLOGIC SIMULATIONS

Five simulations were performed to evaluate the impacts of artificial recharge through RIBs with reclaimed wastewater on the groundwater system. The simulated conditions and results are summarized in Table ES-1.

In the case of Simulation 1, RIBs were simulated at seven artificial recharge sites and all the available reclaimed wastewater (24.6 mgd) was recharged. This first simulation showed that RIBs were unable to accept all available reclaimed water at four of the seven sites because of excessive local mounding of the water table. The main reasons for this condition are hydrogeologic in nature, such as the shallow thickness of the unsaturated zone, the low leakance of the upper confining unit, and low transmissivity of the surficial aquifer at the RIB sites.

Therefore, in Simulation 2, the recharge rates were substantially reduced to avoid surface runoff at the recharge sites. Because of the reduced recharge rates, the mound heights were not as large as in Simulation 1; however, the enhancements in potentiometric head and spring discharge did not differ appreciably from the baseline conditions with no artificial recharge. Only 7.5 mgd of the total available reclaimed water can be effectively recharged by the original seven RIB sites.

In Simulation 3, the original recharge rates were used, but the size of the RIB recharge areas at each of the unsuccessful sites was increased to accommodate the available treated wastewater. However, despite the larger recharge areas, local water mounding was excessive again.

In Simulation 4, the number of RIB recharge sites was increased from seven to 21. Multiple RIB sites were located in subregions in which a single RIB was not successful. The recharge rates were reduced at the RIB sites that experienced flooding and surface runoff conditions. The newly selected sites were placed as far apart as possible to minimize interference with each other. Although this option helped reduce the excessive rising of the water table in many areas, flooding still persisted at some places. Lack of the hydrologic and hydrogeologic conditions necessary to

Table ES-1. Summary of artificial recharge simulations with reclaimed wastewater

Simulation Number	General Description	Recharge Rate (mgd)	Regional Increase in Potentiometric Head (feet) (Year 2010)			Comments
			Surficial Aquifer	Upper Floridan Aquifer	Lower Floridan Aquifer	
1	All available reclaimed water directed to the seven rapid infiltration basin (RIB) sites	24.6	0.54	0.30	0.24	This option is technically infeasible due to excessive groundwater mounding at four of the seven sites
2	Recharged rate reduced in four RIBs to prevent unacceptable groundwater mounding	7.5	0.18	0.08	0.07	Technically feasible recharge rate for 7-RIB configuration is small, and improvement to Upper Floridan aquifer is insignificant
3	RIBs were increased in size to accommodate additional reclaimed water	24.6	0.52	0.28	0.23	Although groundwater mounding is reduced, the increased RIB area is still insufficient to accommodate all reclaimed water without excessive mounding
4	Number of RIB sites is increased from seven to 21	24.6	0.59	0.26	0.21	This option solved the groundwater mounding problem for two of the four unsuccessful sites; however, two sites are still unsatisfactory
4a	Same as Simulation 4 (21 RIB sites); however, reclaimed water recharge rate is reduced	22.5	0.55	0.24	0.19	The total recharge rate is reduced from 24.6 mgd to 22.5 mgd; this is the maximum recharge rate that can be accommodated by the identified RIB site without excessive mounding

Note: mgd = million gallons per day

accommodate and convey the artificially recharged water within the soil profile were responsible for this result.

Simulation 4a is the same as Simulation 4, except that the reclaimed water application rate is reduced as necessary until the computed groundwater mounding is within acceptable limits. The results indicate that the 21 candidate RIB sites appear to effectively recharge 22.5 mgd, or about 91%, of the available reclaimed water (24.6 mgd).

CONCLUSIONS

The estimated increase in potentiometric head under year 2010 pumping conditions is summarized in Table ES-1 for each simulation. In general, the regional increase in aquifer head is directly proportional to the recharge rate. Simulations 1, 3, and 4 are all based on recharge of the full 24.6 mgd of reclaimed water, and the resulting regional increase in potentiometric head is about the same for each case. Each of these options is also technically infeasible because of excessive groundwater mounding.

Simulation 2 represents a recharge rate of only 7.5 mgd. On a regional basis, the increase in potentiometric surface is small (0.08 foot in the Upper Floridan aquifer). On the other hand, Simulation 4a represents the maximum feasible recharge rate when using all 21 candidate RIB sites. The 22.5-mgd recharge rate for Simulation 4a is three times the Simulation 2 recharge rate, and the regional increase in potentiometric head is also about three times (0.24 ft in the Upper Florida aquifer) as great as the Simulation 2 results. However, from a local perspective, head increase in both cases appears to be substantial. In the case of Simulation 2, the water table rises between 2.75 and 15.06 ft at various recharge sites, whereas in the case of Simulation 4a, it varies between 2.77 and 24.66 ft.

Construction of additional RIBs could also have a positive impact on spring flows within the Wekiva River Basin. The simulation results indicate that approximately 70% of the induced recharge will appear as increased spring flow. For example, recharge of 22.5 mgd (Simulation 4a) would increase year 2010 spring flows by 16.2 mgd. However, the study shows that Apopka Spring will significantly benefit from this RIB project because, out of a 70% increase in spring flow, Apopka Spring alone will receive 25%.

The expected decrease in year 2010 spring flow, caused by additional water supply withdrawals, is 68.4 mgd. Therefore, the maximum feasible

RIB configuration investigated in this study could effectively offset 24% of the projected decrease in spring flow.

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INTRODUCTION

Groundwater is the principal source of water supply in the St. Johns River Water Management District (SJRWMD). The use of groundwater in SJRWMD continues to increase with the fast growing development in Florida. If this trend continues, not only the state's population will increase by the year 2010, but the demand for public water supply within SJRWMD will increase also (Figure 1).

As part of its Water Supply Needs and Sources Assessment Project, SJRWMD has evaluated the hydrologic impacts associated with projected groundwater withdrawals through the year 2010 (Vergara 1994). Considering the magnitude of the projected population growth in central Florida, specifically in Orange, Seminole, Volusia, and Lake counties, the increased demand for groundwater could cause significant declines in the potentiometric head in the Floridan aquifer, which could adversely affect spring flows and wetlands and cause saltwater intrusion.

To prevent the deterioration of water resources, SJRWMD is investigating the technical and economic feasibility of alternative water supply strategies (Figure 2). Artificial recharge and reuse of reclaimed water are among the alternatives being considered to offset the adverse impacts due to increased water supply withdrawal within SJRWMD.

PURPOSE AND SCOPE

This study explores the potential of artificial recharge of reclaimed wastewater into the groundwater system to offset the potential adverse hydrologic impacts due to increased groundwater pumpage. Artificial recharge is the process of augmenting recharge to the groundwater flow system through artificial means with waters that are not naturally recharged. In a broad sense, this may be termed as managed recharge of surplus water from various surface sources into the groundwater system.

The objectives of this study are as follows:

- To determine the potential impacts of artificial recharge on the potentiometric surface of the Floridan aquifer

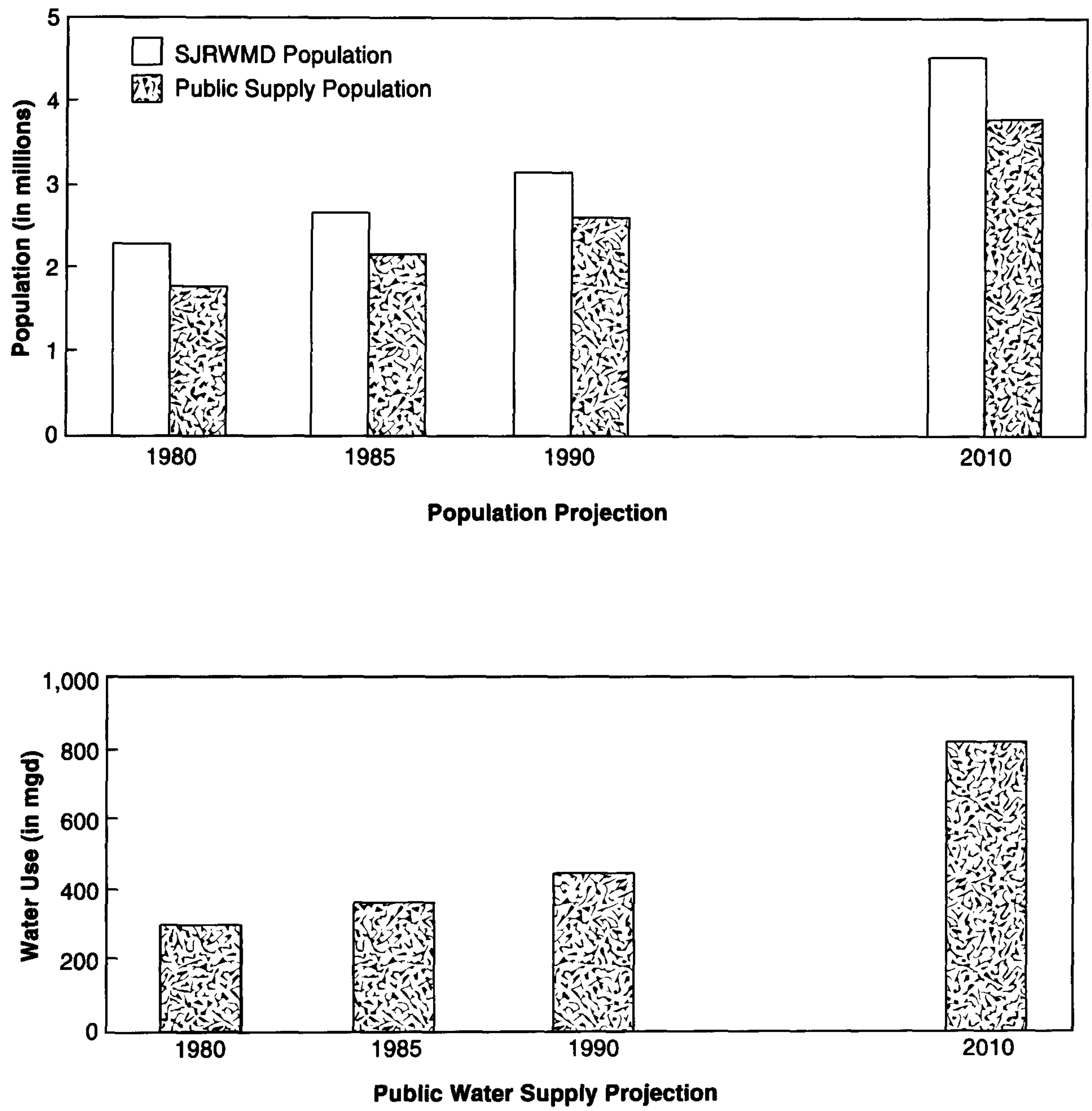

Figure 1. Population and public water supply projections in the St. Johns River Water Management District (Florence 1996)

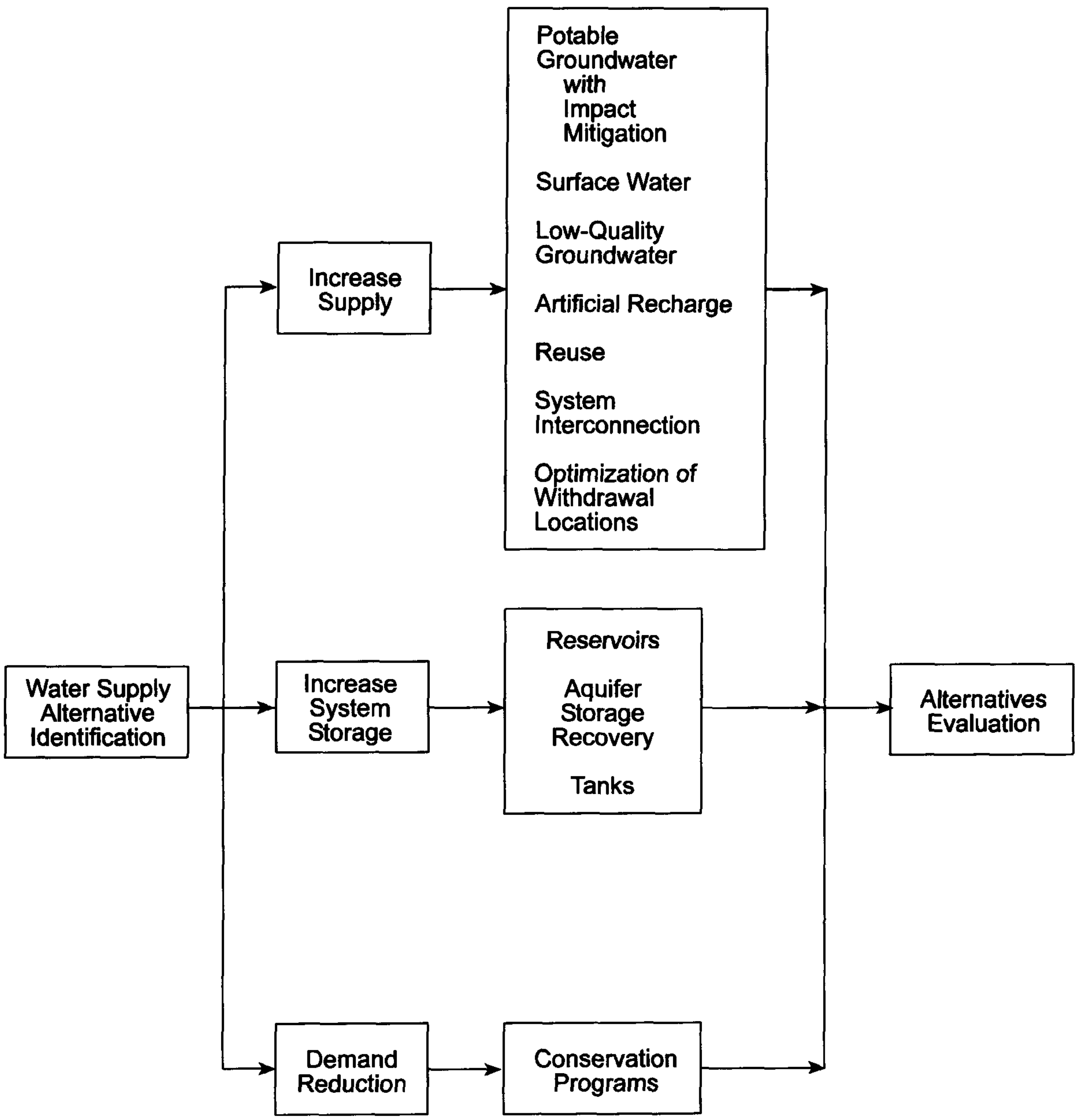

Figure 2. Water supply development options for the St. Johns River Water Management District (CH2M HILL 1997)

- To determine the potential impacts of artificial recharge on the elevation of the water table in the surficial aquifer
- To assess the effectiveness of artificial recharge of reclaimed waste-water into the groundwater system to enhance spring discharges

DESCRIPTION OF THE STUDY AREA

The study area for this evaluation is limited to the priority water resource caution areas (WRCAs) identified by SJRWMD and located in Lake, Orange, Seminole, and Volusia counties (Figure 3). The area selected for this study is shown in Figure 4.

Topography

The topography of the WRCAs ranges from rolling highlands in the western part to flat, swampy lowlands in the eastern part along the St. Johns River. Land surface elevations in the rolling highlands generally range from 100 to 200 feet mean sea level (ft msl), and rise as high as 310 ft msl just west of Lake Apopka in southeastern Lake County. Along the St. Johns River, land surface elevations are generally less than 35 ft msl and the terrain is generally flat and swampy.

Climate

The climate of the study area, which is subtropical humid, is characterized by warm, relatively wet summers and mild, relatively dry winters (Tibbals 1990). The average air temperature is approximately 71 degrees Fahrenheit (°F). Most years have a few days of freezing temperature, but the minimum temperature rarely falls below 20°F. The maximum temperature frequently rises to 90°F.

The average annual rainfall is approximately 51 inches over the study area. Rainfall is unevenly distributed during the year. About 54% of the annual rainfall occurs during four summer months—June through September. Most of the summer rainfall is derived from local showers or thunderstorms that occur randomly. Winter rainfall generally results from large cold fronts that move from the northern states and cause the warm resident air masses to lose their moisture.

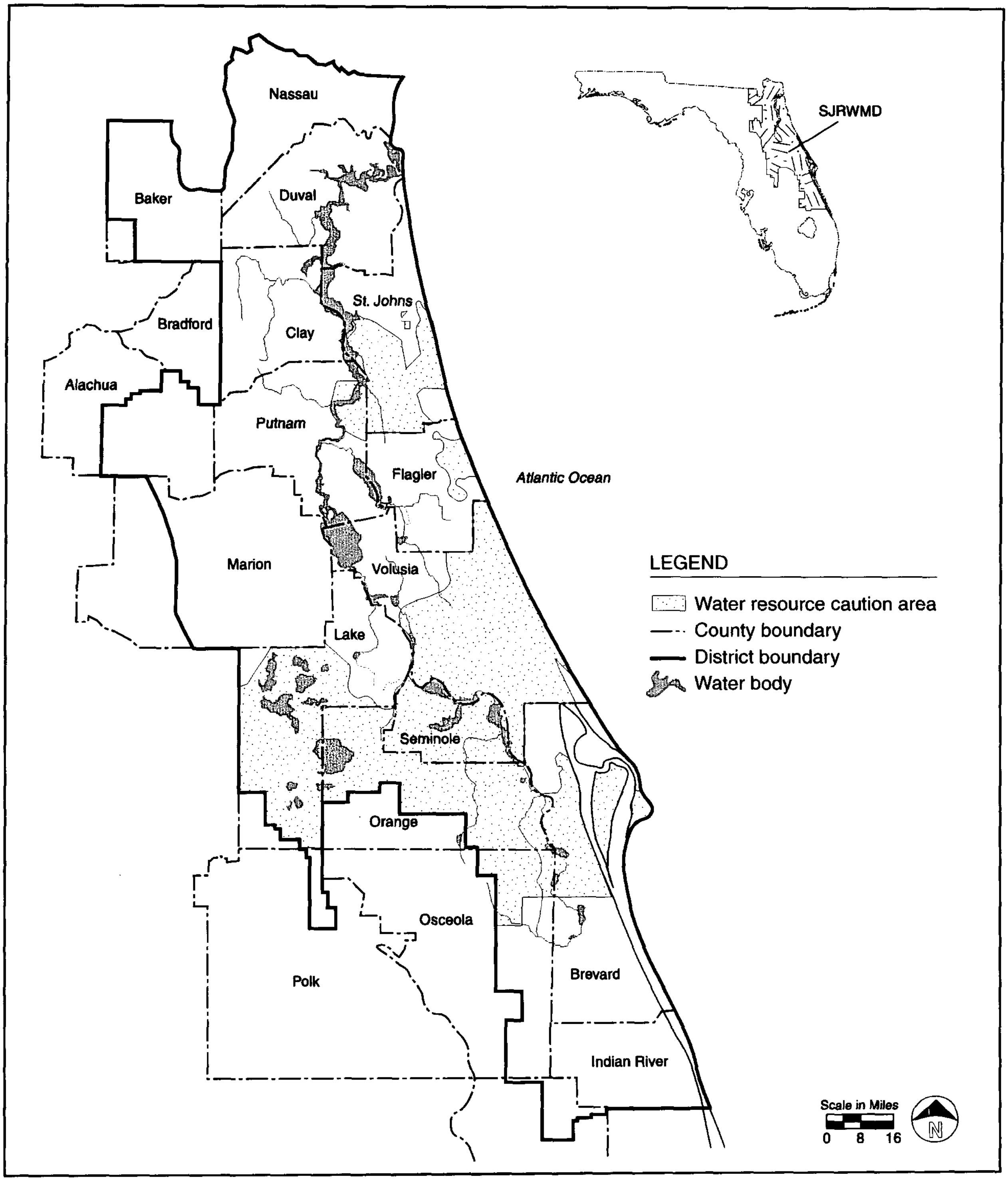

Figure 3. Priority water resource caution areas in the St. Johns River Water Management District (Vergara 1994)

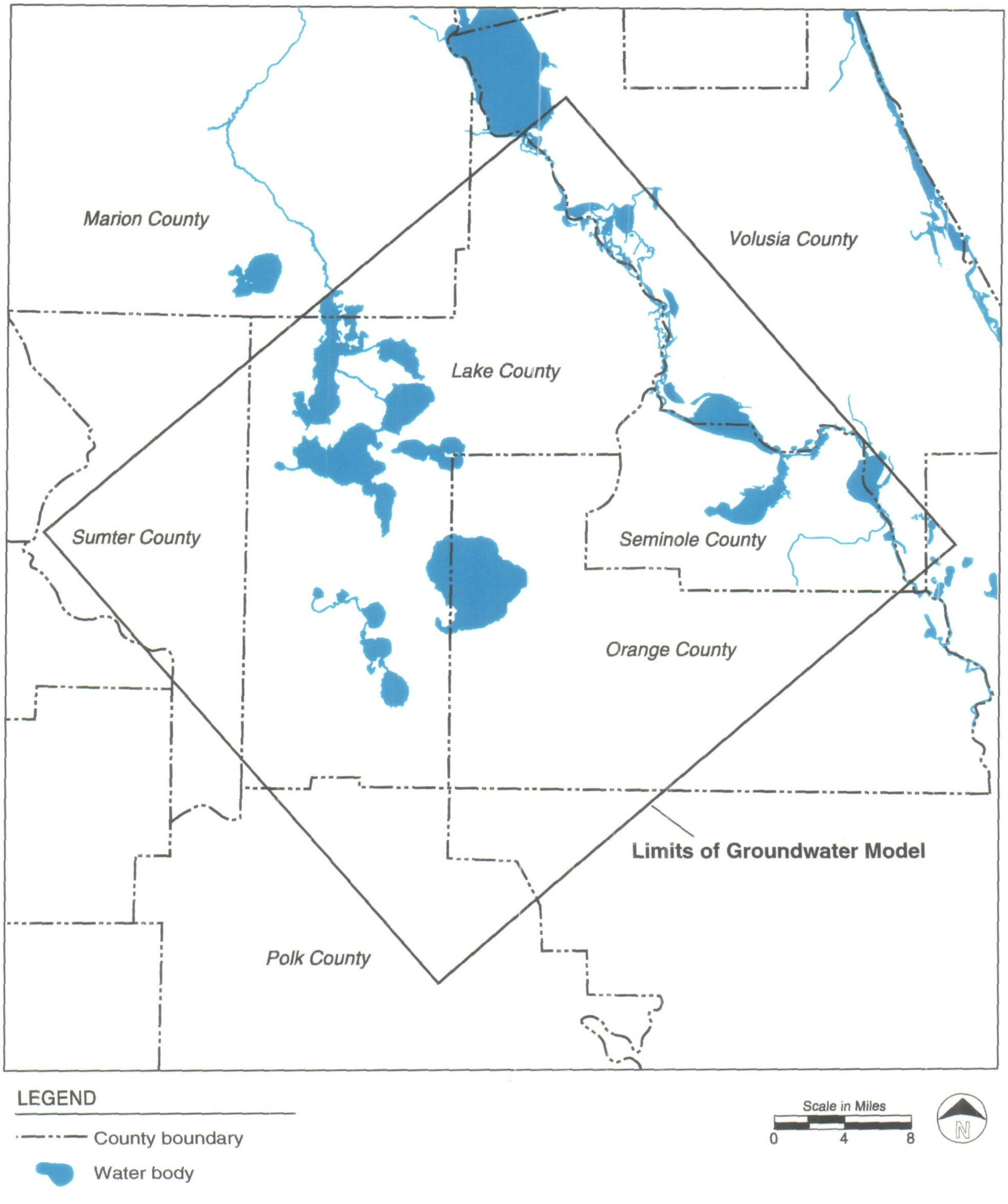

Figure 4. Boundary of study area (groundwater simulation model domain)

The maximum (potential) and minimum (actual) evapotranspiration (ET) rates in the study area are about 47 and 30 inches per year (in/yr), respectively (Tibbals 1990). However, actual ET is always less than potential ET. Thus, ET ranges from 30 to 47 in/yr, depending on the proximity of the water table to the land surface, type of vegetative cover, rainfall, meteorological conditions, and soils.

Hydrogeology

The hydrogeology of the study area is quite complex, with a multiple-layer lithological structure (Figure 5). The most recent comprehensive descriptions of the geology of the Floridan aquifer system are from Miller (1982a, b, c, d, e and 1986) and Tibbals (1990). The study area is underlain mostly by sand, limestone, dolomite, gypsum, anhydrite, and shale, which together may comprise a thickness of several thousand feet (Tibbals 1990). Below those depths are the rocks that comprise the basement complex.

Surficial Aquifer

The uppermost water-bearing formation in the hydrogeologic system is the surficial aquifer. Throughout most of the study area, the surficial aquifer generally consists of fine-to-medium quartz sands that contain varying amounts of silt, clay, and loose shell. In some coastal areas, the surficial aquifer also contains beds of cemented shell or coquina.

Water in the surficial aquifer is unconfined. In the swampy lowlands and flatlands, the water table is generally at or near land surface throughout most of the year. In the rolling highlands, the water table is generally a subdued reflection of the topography, but can be several tens of feet below land surface (GeoTrans 1992). At depths usually less than 50 ft below the water table, the sands of the surficial aquifer generally grade into less permeable clayey or silty sands of the Hawthorn Group, which acts as the overlying confining unit of the Floridan aquifer system (GeoTrans 1992). The thickness of the Hawthorn Group ranges from 0 to 150 ft in the study area (Tibbals 1990).

The surficial aquifer is used as a source of potable supplies, particularly in coastal areas where the Upper Floridan aquifer contains brackish water. In areas other than the coast, the most important function of the surficial aquifer is to store water to maintain the ecosystem and replenish the Upper Floridan aquifer through recharge. The surficial aquifer is little used as a source of water supply in non-coastal areas because, compared

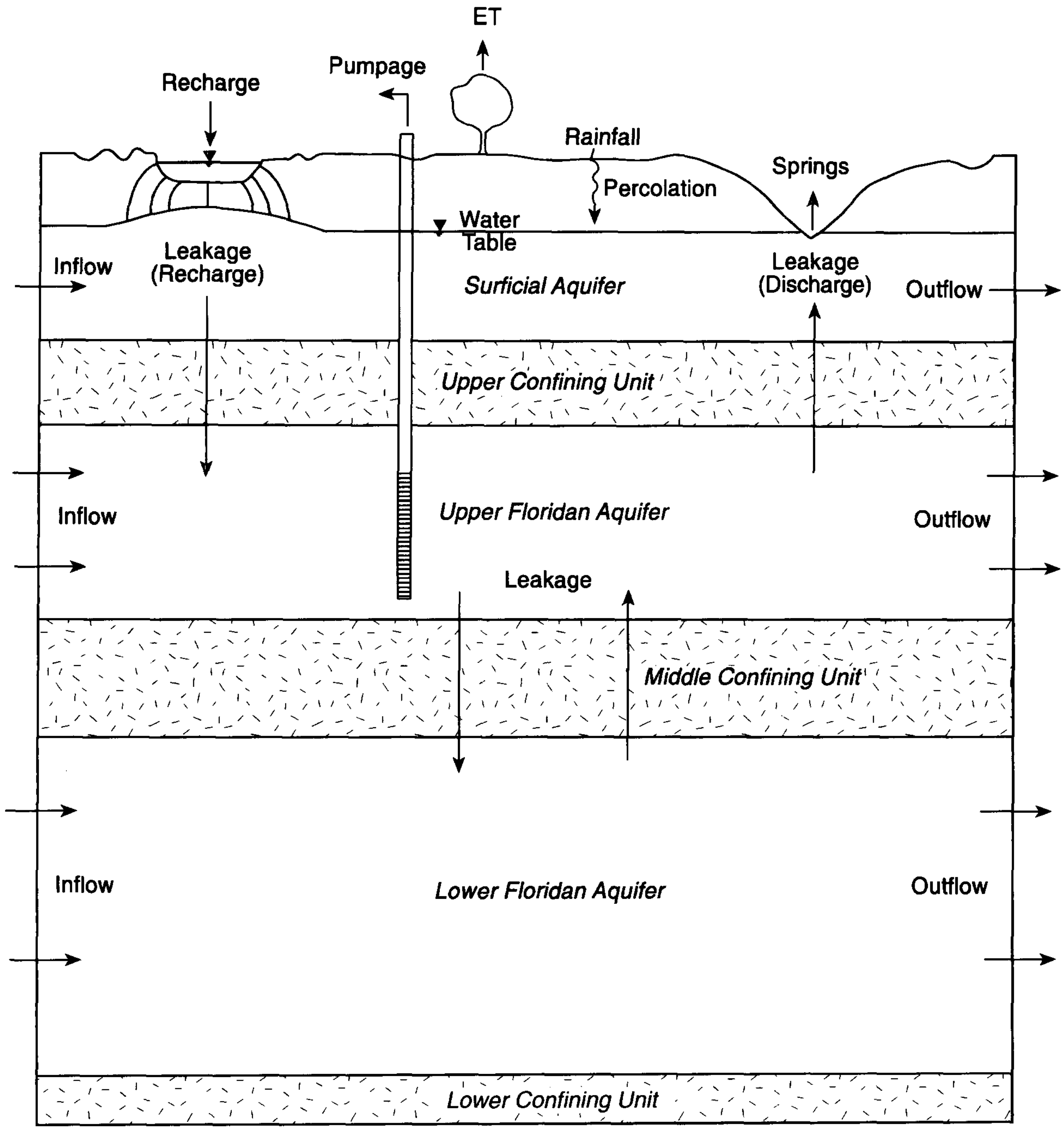

Figure 5. Schematic diagram showing conceptual flow regimes in the subsurface

to the Floridan aquifer system, its permeability and yields to wells are low. Also, the water from the surficial aquifer often contains high concentrations of dissolved iron and is sometimes highly colored.

Hydraulic conductivities of the surficial aquifer have a wide range. Laboratory test values range from 1.0×10^{-5} to 3.4×10^{-1} feet per day (ft/day), with a median of 1.0×10^{-2} ft/day (Phelps 1990). Slug test values range from 3×10^{-2} to 12.8 ft/day, with a median of 2.9×10^{-1} ft/day (McGurk et al. 1989). Pumping test values vary from 4 to 114 ft/day, with an average of 50 ft/day (Gomberg 1980, 1981). Average hydraulic conductivity (50 ft/day) was selected for use in the simulation model of this study area. From a slug test, the value of specific yield for the surficial aquifer was estimated to be 0.25 (Phelps 1990).

Floridan Aquifer System

The Floridan aquifer system is the principal source of water supply in SJRWMD. This aquifer system is comprised of a sequence of limestone and dolomite that ranges in thickness from about 2,000 ft in the northwestern part of the study area to about 2,400 ft in the extreme southwestern part. The elevation of the top of the Floridan aquifer system ranges from +50 to –100 ft msl throughout the project area (GeoTrans 1992). However, the aquifer system does not outcrop in the study area.

The Floridan aquifer system is divided into two highly permeable zones, namely, the Upper Floridan and Lower Floridan aquifers, by a less permeable layer known as the middle confining unit. According to Miller (1986), the average thickness of the Upper Floridan aquifer in the study area is about 350 ft, while the thickness of the Lower Floridan aquifer ranges from 1,300 to 1,500 ft (GeoTrans 1992). The middle confining unit is believed to be thinnest in the western part of the study area, while it is as much as 500 ft thick in southern Seminole County (GeoTrans 1992). The middle semiconfining unit occurs at elevations from 300 to 350 ft below mean sea level (GeoTrans 1992). This unit is leaky and provides impedance to flow between the Upper and Lower Floridan aquifers, which have a head difference typically less than 4 to 5 ft (Tibbals 1990). The Floridan aquifer system is underlain by a low-permeability layer, called the lower confining unit. For groundwater modeling purposes, this layer may be assumed to be impermeable.

Because of the karst nature of the Floridan aquifer, there are many local depressions caused by sinkholes and lakes. Most of the sinkholes are in the high recharge areas, generally where the depth to the top of the Floridan is less than 200 ft (Tibbals 1990). Tibbals (1981) reports that the transmissivities of the Upper Floridan aquifer in the study area vary within a range from 10,000 to 400,000 square feet per day (ft^2/day), and the transmissivities of the Lower Floridan aquifer vary between 30,000 and 130,000 ft^2/day. Tibbals (1990) also reports that the most suitable storage coefficient for both the Upper and Lower Floridan aquifers is 1×10^{-3}.

Recharge/Discharge Rates

The groundwater system in the study area is a multiple-aquifer system with the aquifers separated by confining layers. In such a system, interaquifer water movement occurs because of the head difference between the aquifers. When the elevation of the water table in the surficial aquifer is greater than the potentiometric head of the Upper Floridan aquifer, water from the surficial aquifer flows into the Upper Floridan aquifer. This downward leakage from the surficial aquifer into the Upper Floridan aquifer is called recharge. Conversely, leakage from the Upper Floridan aquifer into the surficial aquifer is called discharge. When the elevation of the water table in the surficial aquifer is less than the potentiometric head in the Upper Floridan aquifer, groundwater flows as discharge from the Upper Floridan aquifer into the surficial aquifer. Such discharge generally occurs in the study area in and around surface water bodies, such as lakes, springs, and rivers.

The surficial aquifer is recharged by local rainfall, irrigation, lakes, ditches, and streams; septic tank effluent; holding pond effluent from wastewater or storm water; and by upward leakage from the Upper Floridan aquifer. The highest rates of recharge occur in the ridge areas, which have little or no surface drainage. Locally, recharge rates in these areas can range from 6 to 18 in/yr (Tibbals 1981; Rutledge 1985). In ridge areas, most of the recharge to the surficial aquifer moves quickly downward to the Upper Floridan aquifer (Phelps 1990). In ridge areas, recharge rates have been estimated to be 8 to 9 in/yr (Phelps 1990).

Water leaves the surficial aquifer as seepage to lakes, ditches, and streams; as evapotranspiration when the water table is near the land surface or within the root zone; as pumpage; and as downward leakage into the Floridan aquifer. High leakage as recharge from the surficial aquifer into the Upper Floridan aquifer occurs in ridge areas. The recharge rates from the surficial aquifer to the Upper Floridan aquifer in these areas range from 0 to 20 in/yr (Tibbals 1990). Leakage as discharge from the Upper Floridan aquifer into the low-lying areas in the surficial aquifer ranges from 0 to 7 in/yr (Tibbals 1990).

The rate of recharge or discharge between the surficial and Upper Floridan aquifers depends on the hydraulic head difference between the aquifers and the leakance of the upper confining unit separating the aquifers (Boniol et al. 1993). This can be defined mathematically as follows:

$$\text{Recharge rate} = \text{hydraulic head difference} \times \text{leakance}$$

where:

$$\text{Hydraulic head difference} = \text{water table elevation} - \text{Upper Floridan aquifer potentiometric head}$$

and

$$\text{Leakance} = \frac{\text{vertical hydraulic conductivity of upper confining unit}}{\text{thickness of upper confining unit}}$$

In the case of negative head difference, the flow occurs upward as discharge rate.

ARTIFICIAL RECHARGE METHODS

A variety of methods have been developed to artificially recharge the groundwater system. Most use variations or combinations of direct surface, direct subsurface, and indirect recharge techniques. SJRWMD is interested in investigating methods of artificial recharge that are technically, environmentally, and economically feasible, as well as acceptable to the communities within SJRWMD.

DIRECT SURFACE

The most widely practiced methods are direct surface techniques, such as surface flooding, ditch and furrow system, basins (e.g., rapid infiltration basins [RIBs]), and stream channel modification. The advantage of groundwater recharge by these direct surface techniques is that it can replenish aquifers in the vicinity of metropolitan and agricultural areas where groundwater overdraft is severe. Also, these methods have the additional benefits of the filtering effect of soils and the transmission of water by aquifers.

DIRECT SUBSURFACE

In contrast to surface recharge techniques, groundwater recharge by direct subsurface injection or by well is practiced where the hydrogeology, topography, or existing land use, such as in urban areas, makes basin recharge impractical or too expensive. Groundwater recharge by wells is particularly effective in creating freshwater barriers in coastal aquifers against saltwater intrusion from the sea. The artificial recharge of reclaimed wastewater by well injection is subject to strict regulations that require tertiary treatment levels for wastewater. Thus, this approach for artificial recharge may be expensive compared to other alternatives.

Before the recent concerns about trace organics and viruses in drinking water, several groundwater recharge projects were developed and operated with apparent success using secondary effluent in spreading basins (Asano 1985). However, because of the increasing concern that low concentrations of stable organics and heavy metals may cause long-term health effects and because of the potential presence of pathogenic organisms in reclaimed wastewater, groundwater recharge with reclaimed wastewater normally requires further treatment following conventional secondary treatment.

Thus, the stringent requirements of pre-application treatment are important factors in planning, designing, and managing groundwater recharge with reclaimed wastewater. These may include disinfection, chemical oxidation, coagulation, flocculation, clarification, filtration, air stripping, ion exchange, activated carbon adsorption, and reverse osmosis or other membrane separation processes. However, in the case of the RIB method, when a soil-aquifer system is used for treating wastewater and controlled underground movement and sample collection of the water exist, the requirements for pretreatment of groundwater recharge could be less stringent. An optimum combination of pretreatment, soil-aquifer treatment, and post-treatment of renovated water should be included.

INDIRECT RECHARGE

The remaining indirect groundwater recharge methods involve special cases in which potable water supply is provided by riverbank or sand dune filtration of generally polluted river water. This method of treatment is practiced in Europe, particularly in Germany and the Netherlands (Asano 1985). The water filtered through the riverbanks traverses an aquifer to an extraction point at some distance from the riverbank.

RAPID INFILTRATION BASIN

Rapid infiltration basins for artificial recharge operate at several locations in Florida. However, this method still needs to be tested for effectiveness in SJRWMD, as well as for its overall impact on the groundwater system. RIBs have gained public acceptance in SJRWMD, particularly in the Orlando and Palm Coast areas, where reclaimed wastewater is stored in surface water storage tanks for nonpotable uses, particularly for the irrigation of agricultural and horticultural crops. The surplus water, not used for irrigation, is discharged into RIBs to recharge the groundwater system.

The RIB method of groundwater recharge provides an effective mechanism of wastewater treatment. However, despite the cleansing capability of RIBs, the wastewater must still be treated to meet Florida Department of Environmental Protection (FDEP) standards before it can be recharged into the aquifer system at a RIB site. Groundwater recharge with reclaimed wastewater presents a wide spectrum of technical and health challenges that must be carefully evaluated. The following four factors of water quality are particularly significant (California State Water Resources Control Board 1975):

- Microbiological quality
- Total mineral content
- Presence of a heavy metal mineral toxicant
- Concentration of stable organic substances

METHODOLOGY

The primary objective of this study is to assess the hydrologic impacts of artificial recharge of reclaimed wastewater into the groundwater system using RIBs. The potential for using artificial recharge to improve regional groundwater conditions has technical, environmental, and legal and institutional ramifications. In this study, the most difficult task is identifying suitable sites for RIBs, which have several technical and nontechnical challenges.

For this investigation, groundwater modeling was used to simulate the regional groundwater flow system. The following steps were implemented:

1. Develop technical and legal criteria for site selection.
2. Identify potential RIB sites within the study area using a geographic information system (GIS).
3. Divide the study area into subregions on the basis of the location and availability of reclaimed water from wastewater treatment plants.
4. Use a groundwater flow model to simulate the effects of RIBs in the study area for a number of artificial recharge scenarios and to evaluate potential impacts on the groundwater flow system.

SITE-SELECTION CRITERIA

Site selection involves the consideration of physical siting criteria, recharge water (source) availability and quality, legal and institutional issues, artificial recharge methods, and potential costs and benefits.

To find suitable locations for RIB sites within the study area, the following technical and legal/institutional selection criteria were considered:

- **Technical Criteria**
  - **Soil infiltration capacity and permeability.** Infiltration capacity and permeability of soils above the water table should be sufficiently high to convey the treated water discharged to a

recharge basin. The vertical hydraulic conductivity of a soil profile in this search was considered to be at least 5 ft/day.

- **Leakance value of the confining layer.** The leakance of the confining unit should be sufficiently high to best use the difference in head associated with the water mound caused by artificial recharge. The minimum leakance value at a recharge site was assumed to be 1.0×10^{-4}/day.

- **Thickness of the surficial layer.** The surficial layer should be thick enough to accommodate and dissipate the recharged water. The minimum thickness of the surficial aquifer at a recharge site was assumed to be 50 ft.

- **Thickness of the vadose zone.** The vadose zone should be thick enough to accommodate the groundwater mound above the baseline water table at a recharge site, as well as to cleanse the suspended materials and other impurities from the recharge water. The minimum thickness of the vadose zone at a recharge site was assumed to be 20 ft.

- **Hydraulic potential at RIB recharge sites.** The recharge site should be located in the recharge zone where water table elevations of the surficial aquifer are much higher than the potentiometric head of the Floridan aquifer. At a recharge site, this head difference was assumed to be at least 35 ft.

- **Legal/Institutional Criteria**

  - **Proximity of wellfields.** A wellfield should be at least 500 ft away from the recharge site to comply with FDEP regulations (62-521, *Florida Administrative Code* [*F.A.C.*]).

  - **Residence time.** According to the Environmental Protection Agency's (EPA) recommendations, the residence time of recharged water should be at least one year to reach a wellfield from the point of recharge (EPA 1992).

  - **Minimum areal extent.** The areal extent of a recharge site should be sufficient to prevent the seepage (saturated infiltration) rate from being exceeded by the recharge water supply rate.

- **Location.** The location of a recharge site should be acceptable to the communities, with minimal impacts on ecology and environment.

SITE IDENTIFICATION

A GIS search was conducted to identify sites suitable for RIBs that best satisfy the site selection criteria. ARC/INFO was used to perform GRID analyses and applicable overlying coverage. The GIS platform consisted of a SUN Sparcstation using SunOs 4.13 (UNIX) running ARC/INFO 6.1 (ESRI 1992). The methodology was an overlay procedure in the GRID module of ARC/INFO.

To identify the appropriate locations for the artificial recharge of groundwater, particularly through RIBs, the initial GIS search used a single criterion. In each subsequent GIS application, criteria were added to eliminate areas not fulfilling the current requirements. Eventually, the areas that fulfilled all the criteria for RIB sites were identified.

In the first application, a GIS search delineated the gross areas that satisfied two criteria: (1) surficial aquifer more than 50 ft thick and (2) areal extent of an isolated patch of area more than 10 acres.

In the second application, additional selection criteria were applied so that the previously delineated areas could be further evaluated to identify those with the greatest recharge potential. The additional criteria were (1) the leakance value of the upper confining unit should be at least 0.0013/day and (2) a buffer of at least 500 ft should be between a recharge site and a production well or wellfield. The average residence time through the buffers was computed to be 10 years. However, FDEP regulations require a minimum buffer of 500 ft (62-521, *F.A.C.*) and EPA (1992) recommends a minimum residence time of 1 year.

In the third application, two more criteria were imposed: (1) the thickness of the surficial aquifer should be at least 100 ft and (2) the thickness of the unsaturated zone above the water table should be at least 20 ft.

In the fourth application, saturated infiltration capacity was added to identify the areas in which moderate infiltration rates range from 10 to 15 inches per hour and the high infiltration capacity exceeds 16 inches per hour. The delineated areas remaining were also divided into categories on the basis of two sets of leakance values: one set ranges from 1.0x 10^{-4} to 1.3x10^{-4}/day, and the other set ranges from 1.3x10^{-4} to 1.6x10^{-4}/day.

Among the other factors considered were the proximity of lakes, availability of treatment facilities, length of transmission pipes, and the distance between RIB sites in the study area.

After applying the criteria above, the areas that meet the selection criteria for potential artificial recharge were identified (Figure 6). Seven artificial recharge sites with the greatest recharge potential and most proximal to the wastewater treatment plants were selected for hydrologic evaluation (Figure 7). The average hydrogeologic characteristics of the recharge sites are provided in Table 1.

ALLOCATION OF RECLAIMED WASTEWATER

To calculate the availability of reclaimed wastewater for each recharge site, the model area was divided into seven subregions, one for each recharge site (Figure 7). The locations of the reclaimed wastewater treatment plants were overlaid on the study area map using GIS methods (Brandes 1996). The available reclaimed water from the treatment plants located in each subregion were added to determine the quantity available for artificial recharge at each site. The reclaimed wastewater available at site Nos. 1, 2, 3, 4, 5, 6, and 7 were computed to be 41,575; 320,032; 119,243; 375,376; 251,855; 1,855,000; and 314,685 cubic feet per day (ft^3/day), respectively. Thus, the total reclaimed water available is about 24.6 million gallons per day (mgd) (Brandes 1996).

MODELING

For this effort, both conceptual and numerical models were developed to further evaluate the areas identified as being potentially suitable for artificial recharge. These models and their functions are described below.

Conceptual Model

To help conceptualize the physical processes of groundwater flow in the subsurface system, a schematic diagram of the components of the groundwater flow regime and their interrelationship within the model domain are shown in Figures 5 and 8. Ultimately, this conceptual model was translated into a numerical groundwater flow model.

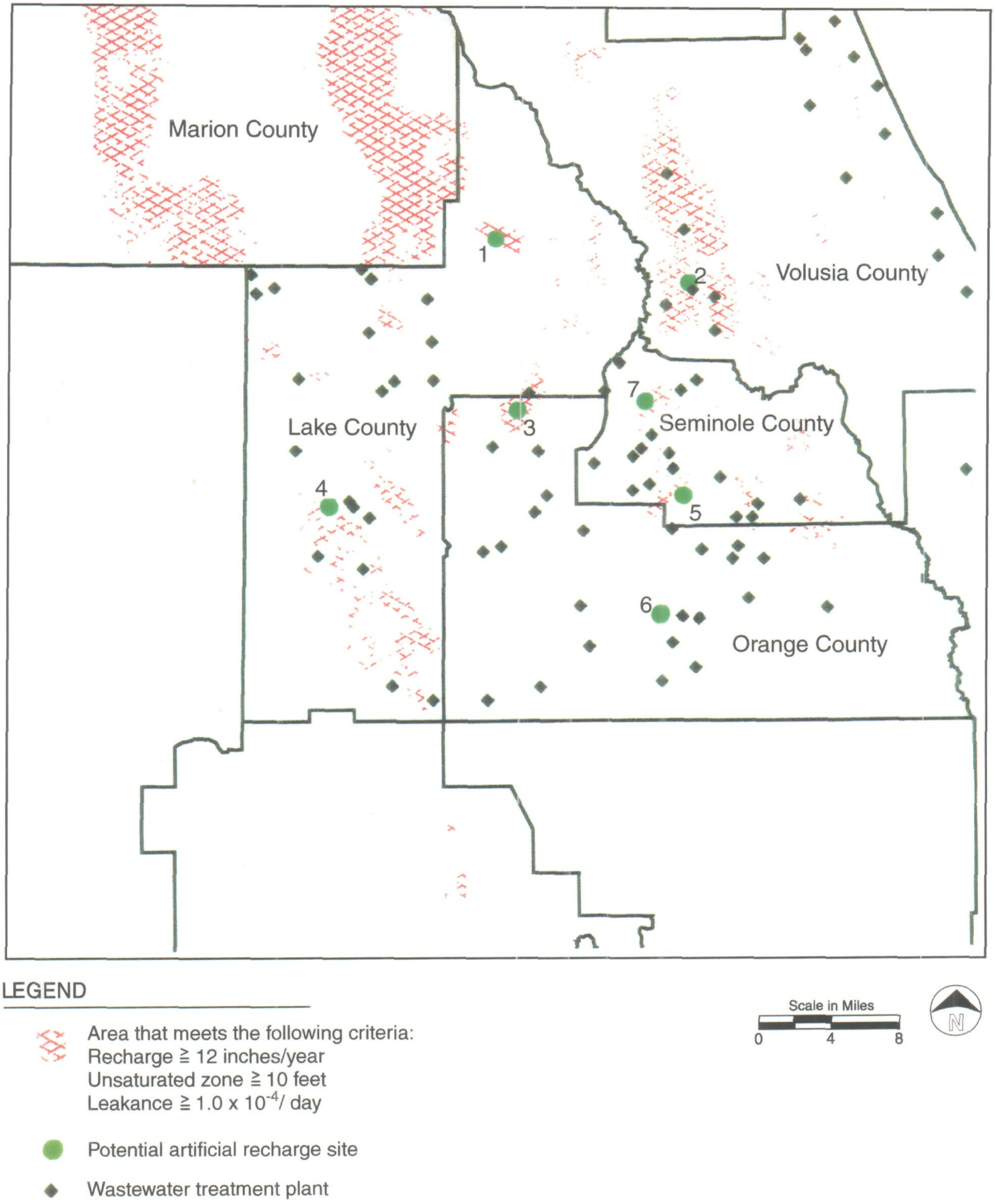

Figure 6. Potential recharge areas obtained through GIS search

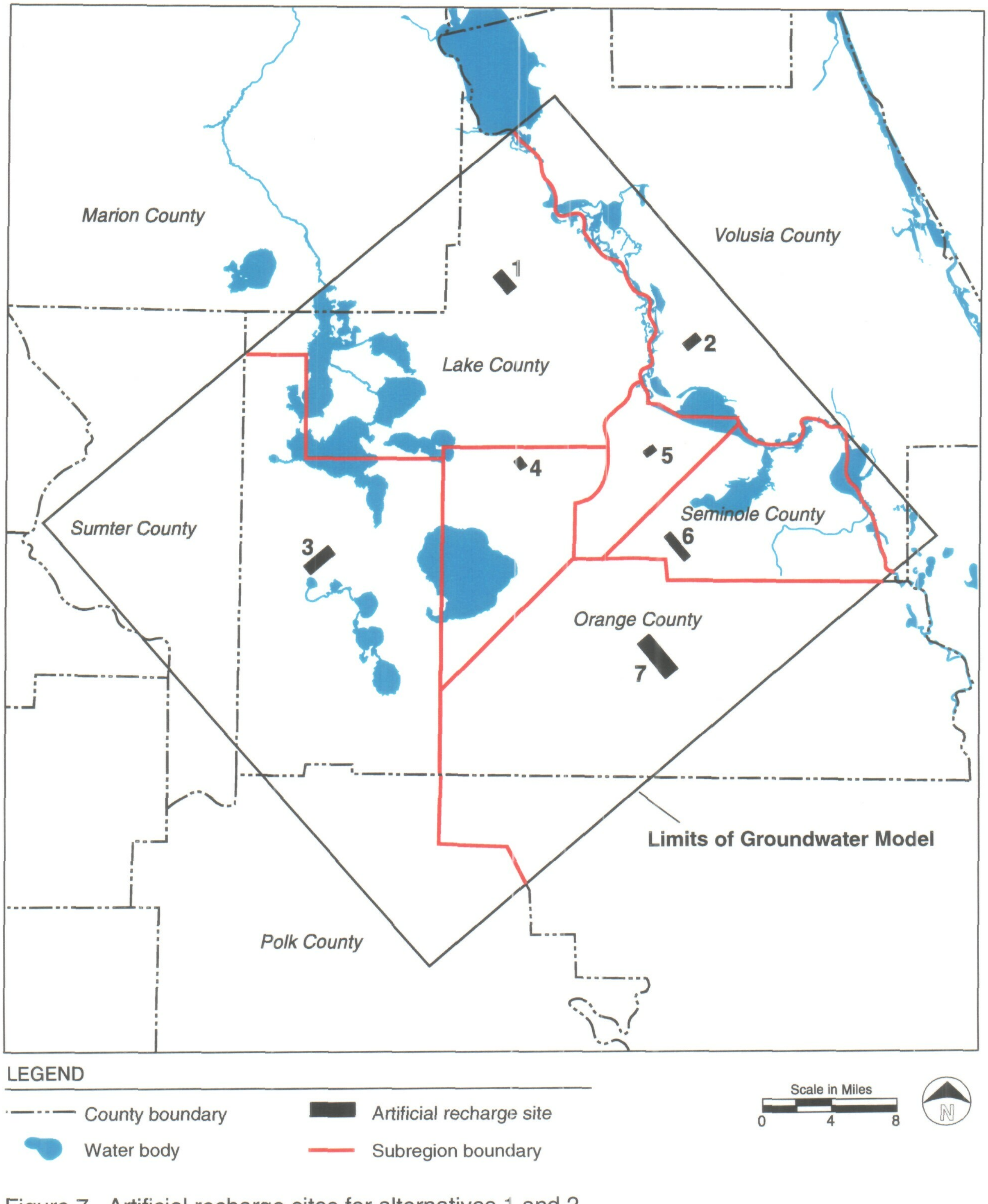

Figure 7. Artificial recharge sites for alternatives 1 and 2

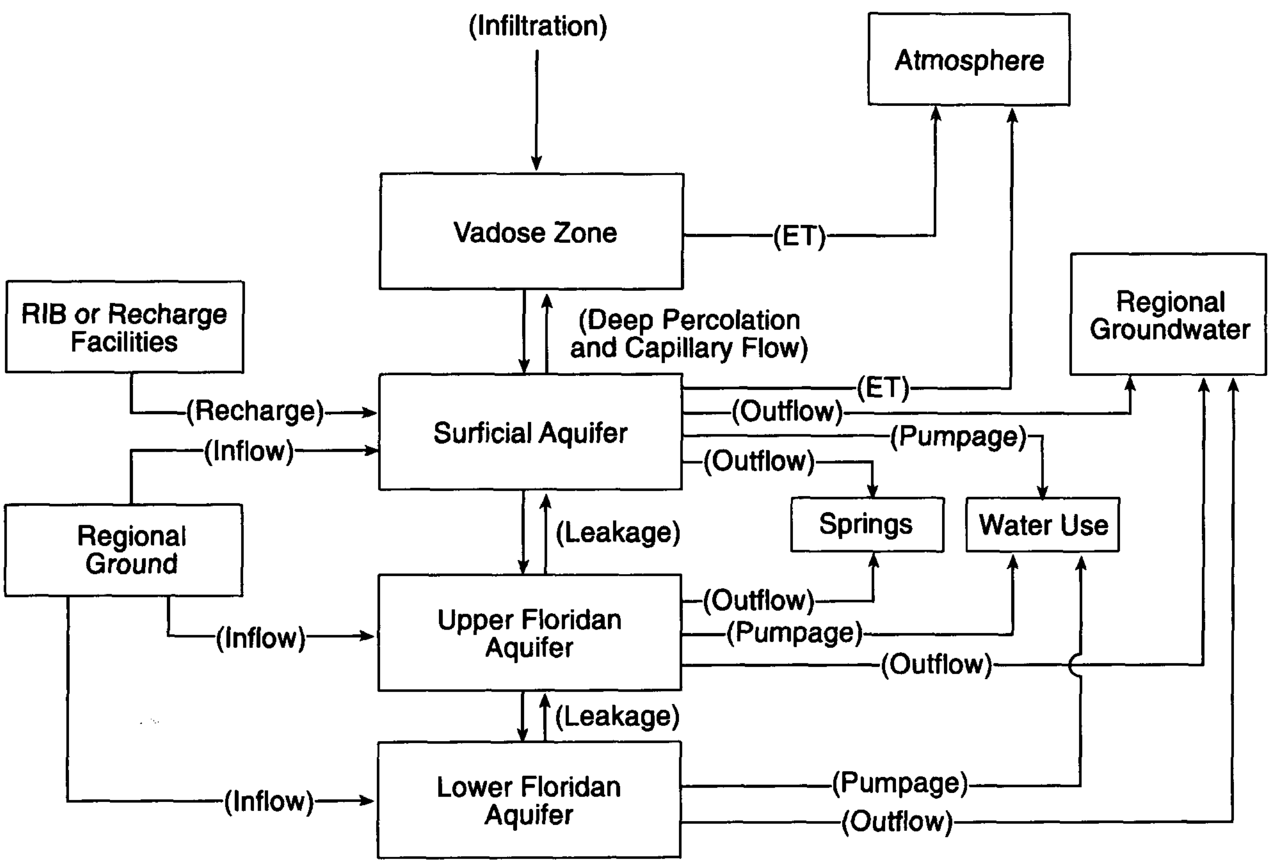

Figure 8. Line diagram of groundwater flow regimes in the study area

Table 1. Hydrogeologic characteristics at recharge sites

Site Number	Land Surface Elevation (ft msl)	Bottom Elevation of Surficial Layer (ft msl)	Hydraulic Conductivity of Surficial Layer (ft/day)	Transmissivity of Upper Floridan Aquifer (ft^2/day)	Transmissivity of Lower Floridan Aquifer (ft^2/day)
1	94.00	19.57	50.00	200,000	60,000
2	82.00	41.64	50.00	100,000	30,000
3	128.00	51.76	50.00	300,000	60,000
4	120.00	43.77	50.00	200,000	60,000
5	81.00	50.00	50.00	40,000	60,000
6	102.00	50.00	50.00	40,000	300,000
7	100.00	21.42	50.00	200,000	570,000

Note: ft msl = feet mean sea level
ft/day = feet per day
ft2/day = square feet per day

Figures 5 and 8 show that the model domain is a multi-aquifer system consisting of the vadose zone, surficial aquifer, upper confining unit, Upper Floridan aquifer, middle confining unit, Lower Floridan aquifer, and the lower confining unit in a sequence from the ground surface to the bedrock.

Hydraulic stress in an aquifer may transmit from layer to layer within the system. While the confining units impede the flow of water from one aquifer into another, water is still transmitted between the layers. Although the hydrogeologic properties in an individual layer may not change substantially from point to point, each layer in a multi-aquifer system is still more or less anisotropic and heterogeneous.

Figures 5 and 8 also show that the groundwater and the surface water systems are linked by the vadose zone. Water, as artificial recharge from RIBs, areal recharge from rainfall, and ponding water from low-lying areas, flows through the unsaturated soil profile (vadose zone) into the groundwater system. The surficial aquifer not only receives water from the land surface, but also loses water as a result of evapotranspiration, direct pumpage, and spring discharge processes. Also, the exchange of water as a gain or loss between surface water bodies, such as rivers, canals, lakes, and ponds, and the groundwater zone always occurs on the basis of hydrologic conditions.

Numerical Model

Simulation of a complex interaquifer flow regime cannot be achieved by performing analytical modeling of individual aquifers because the aquifers are integrated in a single, multi-aquifer system. Thus, for this application, all the aquifers have been viewed simultaneously as a single integrated system in a numerical model.

In this modeling effort, the U.S. Geological Survey (USGS) finite difference code, called MODFLOW (McDonald and Harbaugh 1988), was used for groundwater flow analysis in the multi-aquifer system (Figures 5 and 8). Steady-state analysis was performed for all the simulations, each with a set of boundary conditions representing the hydrologic condition of the aquifer system.

GROUNDWATER FLOW MODEL

All the sites selected for simulating the impact of artificial recharge of groundwater are located within the WRCAs, particularly in Volusia, Seminole, Orange, and Lake counties. These recharge sites are also located within the regional groundwater flow model domain (Figure 4) developed by GeoTrans (1992) for SJRWMD to simulate groundwater flow in the Wekiva River Basin. For this reason, the same model domain as that used for the Wekiva River Basin was used in this study. This model domain consists of three aquifers—the surficial, Upper Floridan, and Lower Floridan—and two aquitards, called the upper and middle confining units (Figure 5).

The domain is discretized into 38 columns and 35 rows. The maximum and minimum spacings between the grid lines along the x axis are 21,120 and 2,640 ft, respectively, and along the y axis are 21,210 and 2,640 ft, respectively. The vertical spacings are the cell-specific thickness of the aquifers and confining units. However, the confining units are integrated with the adjacent aquifers in terms of input data, without being considered independent layers.

INITIAL CONDITIONS

Groundwater flow simulations for various recharge scenarios were performed for steady-state flow conditions. Unlike a transient simulation, a steady-state simulation is concerned with space only, not with time. During steady-state modeling, the simulated output is the outcome of a given set of boundary conditions, where the inflow is equal to the outflow, without changing the volume of water in storage within the model domain over time. Regardless of the initial condition, a steady-state simulation for a given set of boundary conditions always ends with a specific solution in terms of primary variable(s). In this steady-state analysis, regardless of the initial condition, there will be a set of outputs in terms of hydraulic head for each set of boundary conditions. A reasonable initial guess is essential to help a steady-state solution converge and to avoid lengthy computational time.

For this modeling effort, the initial guess for hydraulic head in the aquifers, required for the input files, was developed on the basis of the hydrologic data, particularly the water levels and potentiometric head observed in the field from 1993 through 1995.

The sources of the data were USGS potentiometric surface maps of the Floridan aquifer, USGS well data, SJRWMD observation well data, lake and river stages, and a regression analysis showing the relationship between the land surface and water table elevations in the surficial aquifer (Boniol et al. 1993). In this study, the initial guess (or background hydraulic condition) generally represents the field data for the years 1993 through 1995. In the case of missing data at any grid cell or cells, the data around the cells of interest were interpolated to fill out the missing data point.

As an illustration, the background hydraulic condition for the Upper Floridan aquifer is shown in Figure 9. Note that the background hydraulic condition was used in this study to simulate the response of the aquifers to the hydraulic stresses caused by regional groundwater withdrawals and artificial recharge. This modeling effort is designed to simulate the response of the various aquifers to the man-made hydraulic stresses on the aquifer system, such as groundwater withdrawals and artificial recharges, *not* to simulate the hydrologic conditions in a specific year.

BOUNDARY CONDITIONS

During the modeling process, hydraulic conditions affecting the flow regime in the model domain were represented in terms of hydraulic head and/or recharge into, or discharge from, the aquifer system. The boundary conditions used for modeling were developed to best fit the conceptual model of groundwater flow regime in the study area. These boundary conditions were different from those used by GeoTrans (1992).

In the GeoTrans model, the surficial aquifer was assumed to be inactive and a head-dependent source boundary, while the model domain was assumed to be surrounded by a no-flow boundary. For the conceptual model used in this study, the surficial aquifer was active, allowing groundwater to flow freely both horizontally and vertically in the hydraulically stressed aquifer system. The surrounding model domain boundary was also active, allowing regional groundwater to flow in and out of the various aquifers within the model domain according to the hydraulic gradient.

Areal recharge from the land surface was assigned to the surficial aquifer separately through the recharge package in MODFLOW. Point recharge

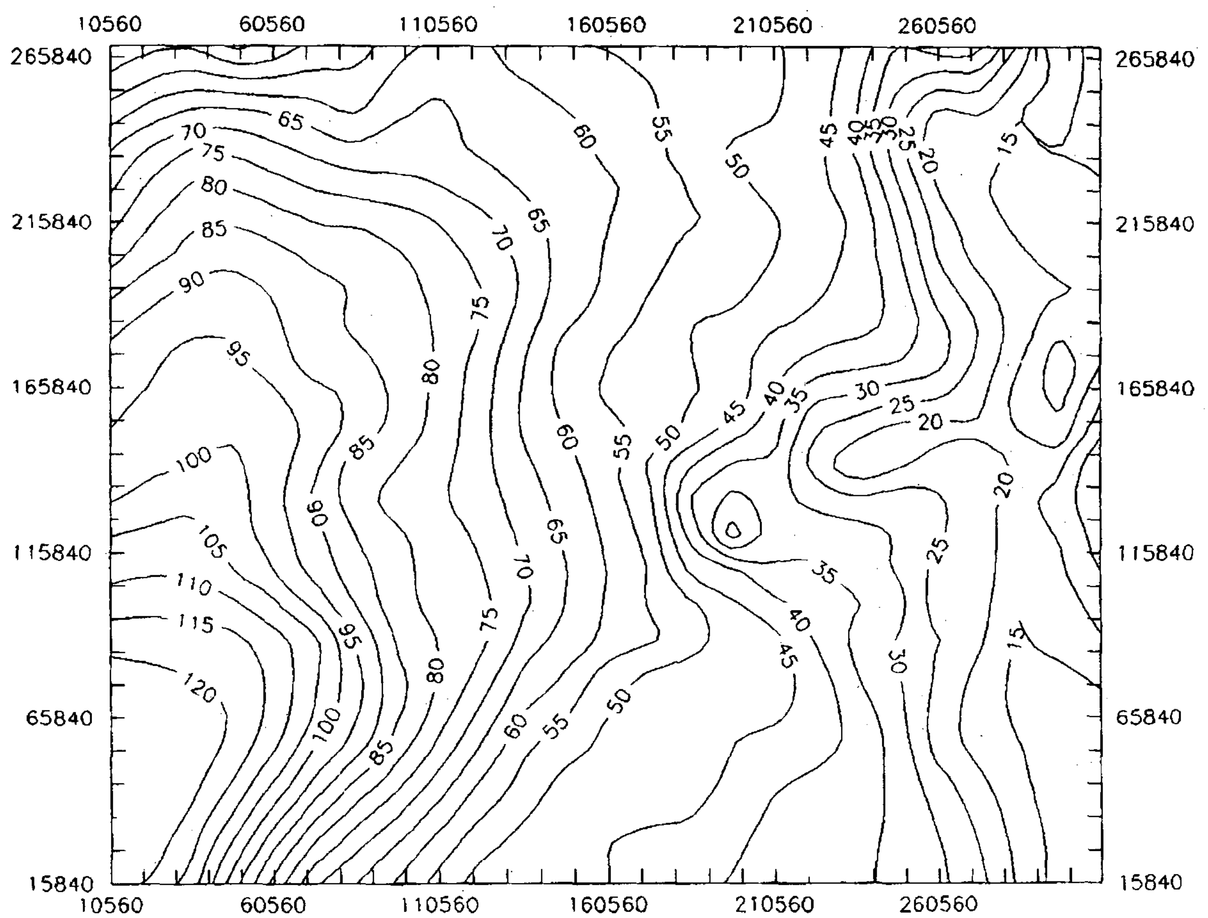

Figure 9. Initial potentiometric head used in modeling for the Upper Floridan aquifer

and discharge at various points in various aquifers within the aquifer system were represented by the well package in MODFLOW. Artificial recharge to the surficial aquifer at RIB sites was also considered to be point recharge and was also incorporated in the well package. The areal extent of a RIB was represented by a single grid cell or by a cluster of grid cells at the RIB site.

The vertical peripheral walls, or boundaries, of the model domain were activated by assigning specified head to represent the approximate field conditions. Major lakes and water bodies were represented with grid cells, with specified heads in the surficial aquifer. The springs were defined by the drainage package in MODFLOW, in which water can only discharge. The boundary conditions represented by specified head are called Dirichlet boundary conditions, while external recharge into, or withdrawals from, the aquifer system is called flux (or Nuemann) boundary conditions. The bottom face of the model domain being bounded by a low-permeability confining unit was assumed to be a no-flow boundary.

INPUT

For this modeling effort, the input files, particularly those that involve parameters and basic data developed by GeoTrans (1992) were used directly, with no modifications. These basic data include the areal extent of model domain, the number and size of rows and columns, the transmissivity values of the Floridan aquifer, and the leakance values of the confining units. The major changes in the remaining input files were the incorporation of the surficial layer as an active unconfined aquifer and replacement of initial and peripheral boundary conditions to fit the present modeling requirements.

The recharge package was also added to each set of the input files for each of the pumping scenarios to incorporate water exchange between the surficial aquifer and land surface. Also, alternative well packages were used for various artificial recharge conditions. For example, in the case of baseline simulations, the baseline well packages for the pumping scenarios of 1994 and 2010 were updated and used to simulate the baseline potentiometric head in various aquifers, when no artificial recharge was included in the well packages. When simulating artificial recharge, RIBs for each alternative simulation were added to update the well files of baseline conditions. As a result, the difference between the simulations with and without artificial recharge indicated the impacts of artificial recharge on the groundwater flow system.

In this model, the areal extent of a RIB that was to provide artificial recharge was represented by the areal extent of the grid cells encompassing the RIB. Also in this model, a RIB was represented as a point source; however, in the case of a site-specific model with finer grids, a RIB may be big enough to be considered a distributed source.

The MODFLOW input files used in the modeling process are basic (BAS), block-centered-flow (BCF), well (WEL), recharge (RCH), drain (DRN), and strongly implicit procedure packages (SIP).

SIMULATIONS AND RESULTS

The objective of the simulations is to determine the response of the groundwater flow system to the artificial recharge of reclaimed wastewater. A series of simulations was performed until the simulated hydrologic conditions reached acceptable levels, in particular, maximizing the potential of the groundwater flow system and minimizing environmental hazards.

Two pumping scenarios, one for 1994 and the other for 2010, were compared to assess the effects of RIBs in the groundwater flow system in the study area. In both the cases, all the input files were the same, except for the groundwater withdrawal scenarios for the respective year. The 1994 pumping scenario was considered to simulate the hydrologic impacts of artificial recharge of groundwater under a recent pumping condition. The projected 2010 pumping scenario reflected additional stress on the Upper Floridan aquifer, creating a hydrologic condition that might use recharged water from the RIBs more effectively. Two baseline simulations and five artificial recharge simulations were performed to evaluate the potential hydraulic response in the groundwater flow system as well as the effects on spring discharges.

BASELINE SIMULATIONS

The baseline simulations in this study represent the hydrologic conditions of the aquifer system for all boundary and initial conditions, except the use of reclaimed water for artificial recharge of groundwater. The baseline simulations were performed for two pumping scenarios: one for 1994 and the other for 2010. Because the projected groundwater withdrawals for the year 2010 are much higher than for 1994, it is likely that the overall (model area average) drawdown for 2010 would be greater than that for 1994. The overall drawdown in an aquifer is the sum of all the drawdowns at grid cells multiplied by their respective cell areas and divided by the total area of the model domain. Mathematically, the overall (mean) drawdown can be defined as

$$\bar{D} = \frac{\sum_{i=1}^{n} D_i A_i}{\sum_{i=1}^{n} A_i} \qquad (1)$$

where:

$\bar{D}$ = overall (mean) drawdown
D_i = drawdown at cell i
A_i = area of cell i
n = number of cells in the model area

The overall (mean) drawdowns for 2010 were computed to be 1.25, 1.51, and 1.57 ft greater in the surficial, Upper Floridan, and Lower Floridan aquifers, respectively, compared to those for 1994.

Although the study area baseline potentiometric head for 1994 is greater than that for 2010, this may not be the case for site-specific conditions. For example, in the vicinity of Wekiva Falls, west of the Wekiva River near State Road 46, the potentiometric head for 2010 is greater than that for 1994. At this site, an artesian well discharging at the rate of 12.75 mgd was simulated in 1994, while for the year 2010, the well was assumed to be plugged.

BASIC SIMULATION (SIMULATION 1)

The basic simulation (Simulation 1) was the first test to determine the feasibility of the RIB method at all seven of the artificial recharge sites. At these sites, all the available reclaimed wastewater was recharged through the RIBs into the surficial layer during the test. The artificial recharge rates at Sites 1, 2, 3, 4, 5, 6, and 7 were 41,575; 320,032; 119,243; 375,376; 251,855; 1,855,090; and 314,685 ft^3/day, respectively, into the surficial aquifer. These recharge rates total 24.6 mgd, which is equal to the total reclaimed water available for artificial recharge. The recharge rates and other features at the RIB sites are summarized in Table 2.

The simulation of artificial recharge using reclaimed wastewater created groundwater mounds in the water table at the RIB sites. This local mounding above the baseline water table elevation at Sites 2, 4, 5, and 6 was 28.43, 33.53, 40.19, and 79.37 ft, respectively, for the 1994 pumping scenario, and 21.05, 33.97, 45.36, and 83.91 ft, respectively, for the 2010 pumping scenario (Table 2). These results show that mound heights at four of the seven sites exceeded the land surface for both the 1994 and

Table 2. Rapid infiltration basin site scenarios and simulated mound heights for Simulation 1

Basic Simulation (Simulation 1)							
Subregion	Land Surface Elevation (ft msl)	Depth to Water Table Without Recharge (feet)	Area (acres)	Recharge Rate (ft^3/day)	1994 Mound Height (feet)	2010 Mound Height (feet)	Remarks
1	94.0	11.91	1,280	41,575	2.78	2.79	
2	82.0	21.07	720	320,032	28.43	21.05	Mound height too high
3	128.0	52.52	1,920	119,243	6.49	6.80	
4	120.0	21.46	480	375,376	33.53	33.97	Mound height too high
5	81.0	18.46	320	251,855	40.19	45.36	Mound height too high
6	102.0	44.06	1,440	1.86×10^6	79.37	83.91	Mound height too high
7	100.0	11.02	3,840	314,685	10.49	10.62	

Note: ft msl = feet mean sea level
ft^3/day = cubic feet per day

2010 scenarios. This means that the thickness of the vadose zone and the transmissivity of the surficial layer are not sufficient to transmit all the available artificially recharged water away from RIB Sites 2, 4, 5, and 6. Thus, the RIBs in the vicinity of Sites 2, 4, 5, and 6 may cause surface runoff and flooding. If a groundwater mound remains in close proximity to the bottom of the RIB basin, the RIB may lose its capability to cleanse impurities from the water because of the lack of flow through a deep, unsaturated zone. Thus, a mound should be well below the bottom of a RIB.

In this simulation option, the overall regional enhancements in potentiometric head of the surficial, Upper Floridan, and Lower Floridan aquifers were computed to be 0.53, 0.28, and 0.23 ft, respectively, for 1994 and 0.54, 0.30, and 0.24 ft, respectively, for 2010. Tables 3 and 4 present the regional increase in hydraulic head for all simulated recharge conditions for the 1994 and 2010 pumping conditions, respectively. The simulation results indicate that little difference exists in the regional effects of artificial recharge for the two pumping scenarios evaluated.

In Simulation 1, the simulated water table in the surficial aquifer at the RIB recharge sites exceeded the land surface in many areas, which would

Table 3. Regional increase of hydraulic head in the model area for 1994 pumping scenario

Aquifer	Increase in Hydraulic Head (feet)				
	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 4a
Surficial	0.53	0.17	0.51	0.58	0.54
Upper Floridan	0.28	0.08	0.27	0.25	0.23
Lower Floridan	0.23	0.06	0.21	0.20	0.18

Table 4. Regional increase of hydraulic head in the model area for 2010 pumping scenario

Aquifer	Increase in Hydraulic Head (feet)				
	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 4a
Surficial	0.54	0.18	0.52	0.59	0.55
Upper Floridan	0.30	0.08	0.28	0.26	0.24
Lower Floridan	0.24	0.07	0.23	0.21	0.19

cause surface runoff. Thus, the simulated water table in the surficial aquifer may not be realistic and additional simulations are necessary to reflect realistic hydrologic conditions that would not have significant adverse environmental impacts.

ALTERNATIVE SIMULATIONS

The results of the basic simulation indicate that the seven sites identified could not handle all the available treated wastewater without creating undesirable hydrologic conditions. For this reason, the quantities of water applied to the RIB sites were modified until the simulated hydrologic conditions were acceptable. To achieve this objective, five additional simulations were performed, the results of which follow.

Simulation 2

Simulation 2 is the same as the basic simulation (Simulation 1), except the recharge rates were reduced to 1/3, 1/3, 1/4, and 1/8, respectively, of the initial amounts used for Simulation 1 at Sites 2, 4, 5, and 6 (Table 5). The total effective recharge rate for Simulation 2 is 7.5 mgd. The simulated mound heights for this option were computed to be 2.75, 10.88, 6.43, 12.6, 13.59, 15.06, and 10.15 ft for the 1994 pumping scenario and 2.75, 11.19, 6.72,

Table 5. Recharge rates and areas at various artificial recharge sites

Subregion	Simulation 1		Simulation 2		Simulation 3		Simulation 4		Simulation 4a	
	Area (acres)	Rech. Rate (ft^3/day)	Area (acres)	Rech. Rate (ft^3/day)	Area (acres)	Rech. Rate (ft^3/day)	No. of Sites	Rech. Rate (ft^3/day)	No. of Sites	Rech. Rate (ft^3/day)
1	1,280	41,575	1,280	41,575	1,280	41,575	1	41,575	1	41,575
2	720	320,032	720	106,677	1,440 (2)*	320,032	3	320,032	3	320,032
3	1,920	119,243	1,920	119,243	1,920	119,243	1	119,243	1	119,243
4	480	375,376	480	125,125	1,920 (3)*	375,376	3	375,376	3	312,813
5	320	251,855	320	62,964	1,600 (4)*	251,855	4	251,855	4	214,078
6	1,440	1.86×10^6	1,440	231,886	1,920 (2)*	1.86×10^6	8	1.86×10^6	8	1.86×10^6
7	3,840	314,685	3,840	314,685	3,840	314,685	1	314,685	1	157,432

Note: ft^3/day = cubic feet per day
Rech. = recharge

*Indicates number of cells at the recharge sites with multiple cells.

12.81, 18.08, 17.43, and 10.28 ft for the 2010 pumping scenario at Sites 1, 2, 3, 4, 5, 6, and 7, respectively (Tables 6 and 7).

These mound heights are smaller than those associated with Simulation 1, primarily because of the reduced recharge rates at Sites 2, 4, 5, and 6. The simulated results of this option demonstrate that although mound heights reduced were considerable, enhancement of the potentiometric head of the aquifers and of spring discharge are low compared to that of Simulation 1. The regional improvements in head of the surficial, Upper Floridan, and Lower Floridan aquifers compared to baseline conditions were computed to be 0.17, 0.08, and 0.06 ft, respectively, for 1994, and 0.18, 0.08, and 0.07 ft, respectively, for 2010 (Tables 3 and 4).

Simulation 3

Simulation 3 is the same as Simulation 1, except the RIBs that had groundwater mounds higher than land surface were increased in size. Figure 10 shows the location of the expanded artificial recharge sites. The intent of Simulation 3 was to reduce the groundwater mound heights by expanding the recharge areas so that the mounds could be accommodated within the soil profile. The recharge areas and recharge rates are shown in Table 5.

With this option, the recharge areas at Sites 2, 4, 5, and 6 were increased from 720, 480, 320, and 1,440 acres to 1,440, 1,920, 1,600, and 1,920 acres, respectively. Despite the larger areal extent of the recharge areas, the new mound heights at Sites 2, 4, 5, and 6 were computed to be 19.01, 16.16, 13.62, and 75.14 ft (Table 6), respectively, compared to 28.43, 33.53, 40.19, and 79.37 ft, respectively, for Simulation 1 for the 1994 condition. Similar values were also computed for the 2010 pumping scenario (Table 7). Although the mound heights are reduced to some extent, they still appear to be too high at many sites.

Using Simulation 3, the average regional enhancement in potentiometric head in the surficial, Upper Floridan, and Lower Floridan aquifers was computed to be 0.51, 0.27, and 0.21 ft, respectively, for the 1994 pumping scenario, and 0.52, 0.28, and 0.23 ft, respectively, for the 2010 pumping scenario (Tables 3 and 4).

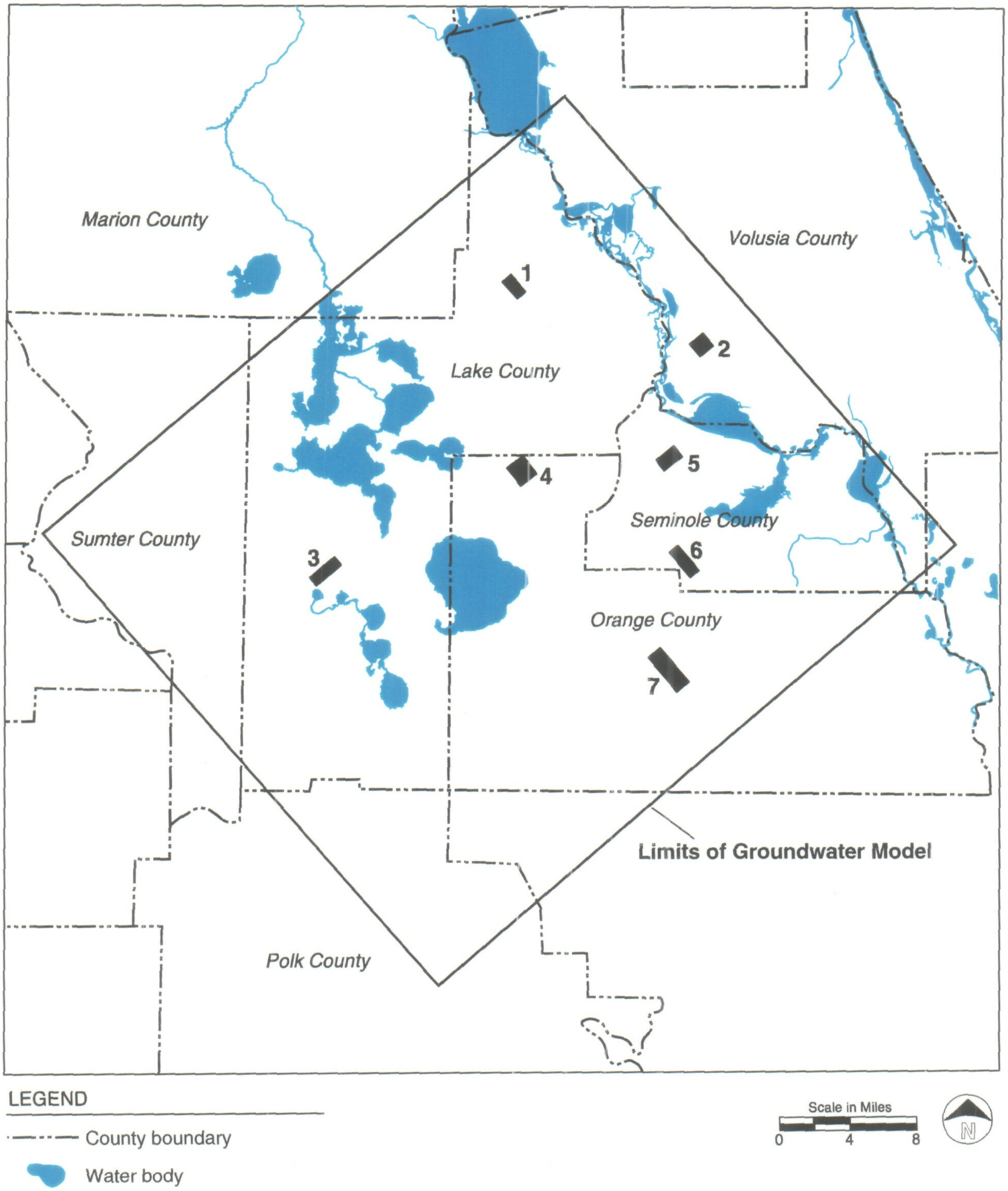

Figure 10. Artificial recharge sites for alternative 3

Table 6. Groundwater mound heights in the surficial aquifer at rapid infiltration basin sites for 1994 pumping scenario

Site	Land Surface Elevation (feet msl)	Depth to Water Table Without Recharge (feet)	Groundwater Mound Heights (feet) at Artificial Recharge Sites				
			Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 4a
1	94.0	11.91	2.78	2.75	2.78	2.77	2.77
2	82.0	21.07	28.43	10.88	19.01	11.87 (3)*	11.87
3	128.0	52.52	6.49	6.43	6.49	6.56	6.56
4	120.0	21.46	33.53	12.6	16.16	20.0 (3)*	12.62
5	81.0	18.46	40.19	13.59	13.62	21.61 (4)*	18.16
6	102.0	44.06	79.37	15.06	75.14	26.43 (8)*	26.44
7	100.0	11.02	10.49	10.15	10.55	11.19	6.25

Note: msl = mean sea level

**Indicates number of artificial recharge sites within each subregion.*

Table 7. Groundwater mound heights in the surficial aquifer at rapid infiltration basin sites for 2010 pumping scenario

Site	Land Surface Elevation (feet msl)	Depth to Water Table Without Recharge (feet)	Groundwater Mound Heights (feet) at Artificial Recharge Sites				
			Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 4a
1	94.0	12.21	2.79	2.75	2.79	2.78	2.78
2	82.0	22.99	21.05	11.19	20.46	12.14 (3)*	12.14 (3)*
3	128.0	55.12	6.80	6.72	6.80	6.79	6.78
4	120.0	22.86	33.97	12.81	17.35	20.27 (3)*	12.90 (3)*
5	81.0	23.82	45.36	18.08	17.69	24.68 (4)*	17.68 (4)*
6	102.0	50.76	83.91	17.43	66.85	28.01 (8)*	27.90 (8)*
7	100.0	13.49	10.62	10.28	10.68	11.31	6.31

Note: msl = mean sea level

*Indicates number of artificial recharge sites within each subregion.

Simulation 4

To avoid excessive mound heights, 21 RIB sites instead of seven were selected within the model area domain, as illustrated in Figure 11. As a result, the number of RIB recharge sites in Subregions 2, 4, 5, and 6 were increased from a single site to three, three, four, and eight sites, respectively. The multiple sites were located as far away from each other as possible in the subregions to prevent interference of the mounding effect in the surficial aquifer. The recharge rate for a subregion with multiple sites was equally divided among the newly selected sites within that subregion.

The recharge rates and RIB locations for Sites 1, 3, and 7, where the simulated mound heights were found to be acceptable, were unchanged. Clearly this option was selected to reduce the water mound heights by distributing the point recharge throughout the study area at a greater number of sites.

Maximum mound heights for each subregion are reported in Tables 6 and 7 for 1994 and 2010 conditions, respectively. For Simulation 4, the mound heights in Subregions 4 and 5, only, were unsatisfactory. Unfavorable site characteristics, such as shallow depth to the water table, low transmissivity of the surficial layer, and low leakance of the upper confining unit, are the probable causes for the poor hydrologic conditions in those subregions. The overall enhancement in the potentiometric head of the surficial, Upper Floridan, and Lower Floridan aquifers was computed to be 0.58, 0.25, and 0.20 ft, respectively, for the 1994 pumping scenario, and 0.59, 0.26, and 0.21 ft, respectively, for the 2010 pumping scenario (Tables 3 and 4).

Simulation 4a

Simulation 4a is the same as Simulation 4, except the reclaimed water application rate is reduced as necessary until the computed groundwater mounding is within acceptable limits. The results indicate that the 21 candidate RIB sites can effectively recharge 22.5 mgd, or about 91%, of the available reclaimed water. This represents the estimated maximum, technically feasible artificial recharge rate at the 21 identified RIB sites.

The overall enhancement in the potentiometric head of the surficial, Upper Floridan, and Lower Floridan aquifers was computed to be 0.54, 0.23, and 0.18 ft, respectively, for the 1994 pumping scenario and 0.55,

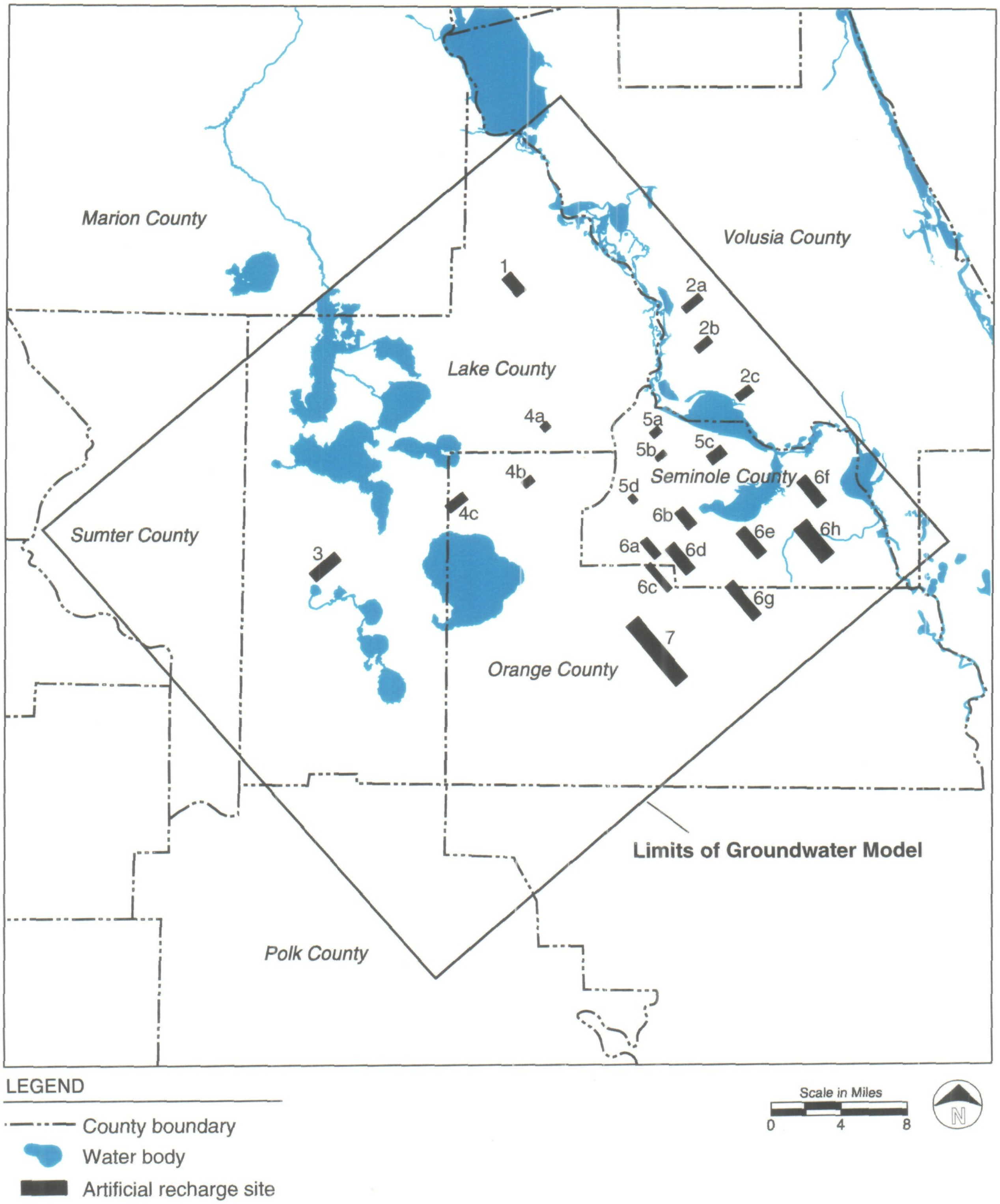

Figure 11. Artificial recharge sites for alternatives 4 and 4a

0.24, and 0.19 ft, respectively, for the 2010 pumping scenario (Tables 3 and 4).

IMPROVEMENT IN THE 2010 HYDRAULIC POTENTIAL

As stated earlier, the overall model area weighted average drawdowns for 2010 as a result of increased pumpage were 1.25, 1.51, and 1.57 ft greater in the surficial, Upper Floridan, and Lower Floridan aquifers, respectively, than the same values for 1994. This increase in regional drawdown can be offset in part by the artificial recharge scenarios evaluated in this report. Of the five scenarios evaluated, only two simulations (2 and 4a) are technically feasible. The remaining three simulations result in unacceptable groundwater mounding. The drawdown offset or recovery that could be achieved by implementation of the feasible RIB alternatives is summarized in Table 8.

For Simulation 2, which recharges 7.5 mgd at seven RIB locations, the areawide drawdown recoveries are relatively small, ranging from about 14.4% in the surficial aquifer to 4.5% in the Lower Floridan aquifer. For simulation 4a, which recharges 22.5 mgd at 21 RIB sites, the regional drawdown recoveries are more significant, ranging from 44% in the surficial aquifer to 12.1% in the Lower Floridan aquifer. Since the recharge is applied directly to the surficial aquifer, the recoveries (local and regional) are greatest in this hydrologic unit. Conversely, the recoveries are lowest in the Lower Floridan aquifer.

IMPACTS ON SPRING FLOWS

Consequently, the change in potentiometric head in the aquifer system caused by artificial recharge of groundwater also affects the spring discharge within the region. The discharge of a spring depends on cavern configurations and the head difference between the discharge point of the spring and the head of the aquifer contributing water to the spring. The 24 springs in the model area, have a total historic median discharge of 693.50 cubic feet per second (cfs) (from 1929 to 1993) and an estimated median discharge of 587.70 cfs for the 2010 pumping condition (Vergara 1994; Rao and Clapp 1996).

Table 8. Effect of technically feasible artificial recharge scenarios in year 2010

Simulated Condition	Regional Change in Potentiometric Head (feet)		
	Surficial Aquifer	Upper Floridan Aquifer	Lower Floridan Aquifer
Baseline 2010 additional drawdown compared with 1994 condition	1.25	1.51	1.57
2010 potentiometric head increase for Simulation 2 (7.5-mgd artificial recharge rate)	0.18	0.08	0.07
2010 potentiometric head increase for Simulation 4a (22.5-mgd artificial recharge rate)	0.55	0.24	0.19
	Drawdown Recovery (percent)		
2010 potentiometric head increase for Simulation 2 (7.5-mgd artificial recharge rate)	14.4	5.3	4.5
2010 potentiometric head increase for Simulation 4a (22.5-mgd artificial recharge rate)	44.0	15.9	12.1

Note: mgd = million gallons per day

Simulation 1

Using Simulation 1, the total spring discharges within the region were computed to be 715.16 and 615.58 cfs, respectively, for the years 1994 and 2010. In other words, the artificial recharge associated with Simulation 1 increased the total spring discharge for 1994 by 21.66 cfs, and for 2010 by 27.88 cfs. Thus, Simulation 1 enhanced the total spring discharge by 3.12 and 4.74%, respectively, for the years 1994 and 2010. The simulated discharges of individual springs within the model domain for the years 1994 and 2010 are shown in Tables 9 and 10, respectively.

The total estimated median spring discharge without artificial recharge in 2010 is 105.8 cfs less than the historic median (Vergara 1994). The artificial recharge of various alternatives can reduce this overall springflow difference to various extents. For example, in 2010, the artificial recharge associated with Simulation 1 would increase the total spring discharge by 27.88 cfs, which in turn would reduce the difference in spring discharge between 1994 and 2010 from 105.8 to 77.92 cfs. Thus, there may be a 26.35% recovery in the difference in total spring discharge for 1994 and 2010 using Simulation 1.

Table 9. Spring discharge with and without artificial recharge of groundwater for 1994 pumping scenario

Spring	Historical Median and Required Minimum Q (cfs and %)	Simulation 1 Discharge Q (cfs and %)	Simulation 2 Discharge Q (cfs and %)	Simulation 3 Discharge Q (cfs and %)	Simulation 4 Discharge Q (cfs and %)	Simulation 4a Discharge Q (cfs and %)
1. Apopka	36.00 (100.00) —	40.25 (111.81)	37.67 (104.65)	40.45 (112.36)	39.81 (110.57)	39.48 (109.7)
2. Blue (Lake County)	3.00 (100.00) —	3.06 (101.88)	3.03 (101.13)	3.06 (101.88)	3.06 (101.88)	3.06 (101.72)
3. Holiday Spring and Creek	3.60 (100.00) —	3.68 (102.30)	3.65 (101.35)	3.68 (102.30)	3.69 (102.44)	3.67 (102.23)
4. Alexander Spring and Creek	138.20 (100.00) —	138.37 (100.12)	138.30 (100.07)	138.37 (100.12)	138.36 (100.11)	138.35 (100.10)
5. Camp La-No-Che	0.90 (100.00) —	0.93 (103.11)	0.91 (101.47)	0.93 (103.15)	0.93 (102.84)	0.93 (102.6)
6. Messant	14.90 (100.00) 12.00	15.22 (102.17)	15.00 (100.67)	15.23 (102.19)	15.22 (102.14)	15.19 (101.96)
7. Seminole	35.80 (100.00) 34.00	36.88 (103.02)	36.15 (100.98)	36.95 (103.20)	36.94 (103.19)	36.84 (102.92)
8. Blue	158.40 (100.00) —	161.42 (101.90)	159.36 (100.61)	161.55 (101.99)	160.46 (101.30)	160.28 (101.19)
9. Gemini	8.50 (100.00) —	8.76 (103.04)	8.56 (100.75)	8.73 (102.65)	8.71 (102.51)	8.69 (102.3)
10. Rock	60.90 (100.00) 53.00	63.68 (104.56)	61.72 (101.35)	63.56 (104.36)	62.79 (103.10)	62.63 (102.84)
11. Witherington	(100.00) —	4.84 (102.89)	4.74 (100.77)	4.83 (102.81)	4.80 (102.18)	4.79 (101.99)
12. Wekiva	67.80 (100.00) 62.00	69.14 (101.98)	68.11 (100.46)	69.16 (102.01)	68.85 (101.55)	68.76 (101.42)
13. Clifton	1.70 (100.00) —	1.85 (108.70)	1.72 (101.30)	1.81 (106.37)	1.81 (106.38)	1.80 (105.84)
14. Miami	4.70 (100.00) 4.00	4.82 (102.61)	4.73 (100.58)	4.83 (102.67)	4.80 (102.08)	4.79 (101.9)
15. and 16. Sanlando and Palm	43.50 (100.00) 22.00	47.90 (110.11)	44.29 (101.83)	48.21 (110.83)	46.97 (107.97)	46.67 (107.29)
17. Starbuck	14.50 (100.00) 13.00	16.97 (117.02)	14.92 (102.93)	16.94 (116.82)	16.42 (113.24)	16.26 (112.11)
18. Lake Jesup	1.00 (100.00) —	1.11 (110.50)	1.02 (101.52)	1.07 (107.47)	1.06 (106.40)	1.05 (105.85)

Table 9—*Continued*

Spring	Historical Median and Required Minimum Q (cfs and %)	Simulation 1 Discharge Q (cfs and %)	Simulation 2 Discharge Q (cfs and %)	Simulation 3 Discharge Q (cfs and %)	Simulation 4 Discharge Q (cfs and %)	Simulation 4a Discharge Q (cfs and %)
19. Island	6.10 (100.00) ——	6.29 (103.15)	6.14 (100.73)	6.26 (102.56)	6.25 (102.49)	6.24 (102.28)
20. Alexander Creek	30.00 (100.00) ——	30.09 (100.30)	30.05 (100.16)	30.09 (100.30)	30.08 (100.27)	30.07 (100.25)
21. Lake Jesup	5.60 (100.00) ——	5.84 (104.21)	5.64 (100.69)	5.79 (103.32)	5.90 (105.42)	5.87 (104.96)
22. St. Johns River	8.90 (100.00)	9.07 (101.96)	8.93 (100.34)	9.04 (101.58)	9.23 (103.74)	9.20 (103.42)
23. Lake Harney, North	20.20 (100.00) ——	20.20 (100.00)	20.20 (100.00)	20.20 (100.00)	20.20 (100.00)	20.20 (100.00)
24. Lake Harney, South	24.60 (100.00) ——	24.81 (100.86)	24.64 (100.14)	24.77 (100.70)	25.29 (102.79)	25.23 (102.55)
Total discharge (including Apopka)	693.50 (100.00)	715.16 (103.12)	699.50 (100.86)	715.48 (103.17)	711.62 (102.61)	710.07 (102.39)
Total discharge (excluding Apopka)	657.50 (100.00)	674.91 (102.65)	661.92 (100.66)	675.03 (102.67)	671.81 (102.18)	670.59 (101.99)
Enhancement in discharge (including Apopka)	——	21.66 (3.12%)	6.00 (0.86%)	21.98 (3.17%)	18.12 (2.61%)	16.57 (2.39%)

Note: cfs = cubic feet per second
—— = projection not available

Figures in parentheses indicate the discharge in percent compared with the historical median discharge.

Table 10. Spring discharge with and without artificial recharge of groundwater for 2010 pumping scenario

Spring	2010 Discharge and Required Minimum Discharge Q (cfs and %)	Simulation 1 Discharge Q (cfs and %)	Simulation 2 Discharge Q (cfs and %)	Simulation 3 Discharge Q (cfs and %)	Simulation 4 Discharge Q (cfs and %)	Simulation 4a Discharge Q (cfs and %)
1. Apopka*	21.30 (100.00) ——	31.44 (147.62)	25.10 (117.86)	31.87 (149.60)	30.18 (141.67)	29.42 (138.11)
2. Blue* (Lake County)	0.90 (100.00) ——	0.96 (106.67)	0.94 (104.17)	0.96 (107.08)	0.96 (107.08)	0.95 (106.48)
3. Holiday Spring and Creek*	1.60 (100.00) ——	1.69 (105.85)	1.65 (103.35)	1.69 (105.79)	1.70 (106.09)	1.69 (105.57)
4. Alexander Spring and Creek	134.60 (100.00) ——	134.77 (100.12)	134.70 (100.07)	134.77 (100.12)	134.75 (100.12)	134.74 (100.11)
5. Camp La-No-Che	0.80 (100.00) ——	0.83 (103.61)	0.81 (101.70)	0.83 (103.65)	0.83 (103.29)	0.83 (103.01)
6. Messant	14.00 (100.00) 12.00	14.32 (102.29)	14.10 (100.71)	14.32 (102.31)	14.32 (102.26)	14.29 (102.07)
7. Seminole	31.80 (100.00) 34.00	32.86 (103.33)	32.14 (101.08)	32.92 (103.53)	32.92 (103.51)	32.82 (103.21)
8. Blue*	132.90 (100.00) ——	135.57 (102.01)	133.75 (100.64)	135.69 (102.10)	134.73 (101.37)	134.57 (101.25)
9. Gemini*	6.80 (100.00) ——	7.03 (103.38)	6.86 (100.84)	7.00 (102.95)	6.99 (102..81	6.97 (102.57)
10. Rock*	49.10 (100.00) 53.00	51.75 (105.40)	49.89 (101.61)	51.64 (105.17)	50.91 (103.69)	50.76 (103.38)
11. Witherington*	3.80 (100.00) ——	3.93 (103.44)	3.84 (100.93)	3.93 (103.35)	3.90 (102.62)	3.89 (102.4)
12. Wekiva	58.80 (100.00) 62.00	60.11 (102.22)	59.11 (100.52)	60.13 (102.26)	59.83 (101.75)	59.74 (101.6)
13. Clifton*	1.10 (100.00) ——	1.22 (110.58)	1.12 (101.59)	1.19 (107.75)	1.19 (107.82)	1.18 (107.15)
14. Miami*	3.90 (100.00) 4.00	4.02 (103.01)	3.93 (100.67)	4.02 (103.07)	3.99 (102.40)	3.98 (102.2)
15. and 16. Sanlando and Palm*	36.40 (100.00) 22.00	41.86 (115.00)	37.39 (102.73)	42.24 (116.04)	40.73 (111.90)	40.36 (110.88)
17. Starbuck*	7.40 (100.00) 13.00	9.84 (132.91)	7.82 (105.70)	9.80 (132.45)	9.31 (125.75)	9.15 (123.55)
18. Lake Jesup*	0.70 (100.00) ——	0.79 (112.93)	0.71 (101.88)	0.76 (109.21)	0.76 (107.94)	0.76 (107.26)

Table 10—*Continued*

Spring	2010 Discharge and Required Minimum Discharge Q (cfs and %)	Simulation 1 Discharge Q (cfs and %)	Simulation 2 Discharge Q (cfs and %)	Simulation 3 Discharge Q (cfs and %)	Simulation 4 Discharge Q (cfs and %)	Simulation 4a Discharge Q (cfs and %)
19. Island	5.90 (100.00) —	6.08 (103.12)	5.94 (100.73)	6.05 (102.52)	6.05 (102.48)	6.04 (102.27)
20. Alexander Creek	29.20 (100.00) —	29.29 (100.30)	29.25 (100.17)	29.29 (100.30)	29.28 (100.28)	29.27 (100.26)
21. Lake Jesup*	4.20 (100.00) —	4.40 (104.77)	4.23 (100.79)	4.36 (103.77)	4.46 (106.18)	4.44 (105.65)
22. St. Johns River	7.00 (100.00) —	7.15 (102.09)	7.03 (100.36)	7.12 (101.69)	7.28 (104.01)	7.26 (103.67)
23. Lake Harney, North*	15.90 (100.00)	15.90 (100.00)	15.90 (100.00)	15.90 (100.00)	15.90 (100.00)	15.90 (100.00)
24. Lake Harney, South*	19.60 (100.00) —	19.77 (100.89)	19.63 100.15)	19.74 (100.72)	20.17 (102.90)	20.12 (102.65)
Total discharge (including Apopka)	587.70 (100.00)	615.58 (104.74)	595.85 (101.39)	616.21 (104.85)	611.12 (103.98)	612.7 (104.25)
Total discharge (excluding Apopka)	566.40 (100.00)	584.14 (103.13)	570.74 (100.77)	584.34 (103.17)	580.94 (102.57)	582.51 (102.84)
Enhancement in discharge (including Apopka)	—	27.88 (4.74%)	8.15 (1.39%)	28.51 (4.85%)	23.42 (3.98%)	25.0 (4.25%)

Note: cfs = cubic feet per second
—— = projection not available

Figures in parentheses indicate the discharge in percent compared to the 2010 median discharge.

*Spring discharge is 15 (or more than 15) percent less than the historical median (Vergara 1994).

Simulation 2

For Simulation 2, which represents the maximum recharge attainable with the seven RIB configurations, total spring discharge was computed to be 699.50 and 595.85 cfs for the years 1994 and 2010, respectively, which is about 0.86 and 1.39% greater, respectively, than that of baseline conditions (Tables 9 and 10). Because of the artificial recharge associated with Simulation 2, the increase in total spring discharge is 8.15 cfs, or 5.3 mgd, in the year 2010 compared to the 2010 baseline condition. Thus, the difference between the values for total spring discharge in 1994 and 2010 was reduced by 7.7 cfs, to 97.65 cfs. These simulation results indicate that artificial recharge appears to be an efficient method of springflow augmentation. Simulation 2 provides a 7.5 mgd recharge rate, of which 5.3 mgd, or about 70% of the total, contributes to direct springflow increase. However, of this 70% contribution, 32% is attributed to Apopka Spring alone.

Simulation 3

For Simulation 3, total spring discharges were computed to be 3.17 and 4.85% greater than baseline conditions for the years 1994 and 2010, respectively (Tables 9 and 10). Using this artificial recharge option, total spring discharge in 2010 is increased by 28.51 cfs. Therefore, the difference in total spring discharge for 1994 and 2010 was reduced from 105.8 cfs to 77.29 cfs, or 27%.

Simulation 4

For Simulation 4, total spring discharges were computed to be 2.61 and 3.98% greater than baseline conditions for the years 1994 and 2010, respectively (Tables 9 and 10). Using this option, the increase in the total spring discharge is 23.42 cfs in 2010; and the improvement in the total spring discharge between 1994 and 2010 is 22.13%. Thus, the difference between the 1994 and 2010 total spring discharge will be reduced to 83.67 cfs.

Simulation 4a

Simulation 4a is the same as Simulation 4, except that the reclaimed water application rate is reduced to 22.5 mgd. This is the maximum recharge rate that can be accommodated by the 21 RIB configurations without unacceptable groundwater mounding occurring.

For Simulation 4a, total spring discharges were computed to be 710.1 and 612.7 cfs for the years 1994 and 2010, respectively, which are about 2.4 and 4.3% greater, respectively, than their baseline conditions (Tables 9 and 10). Because of the artificial recharge associated with Simulation 4a, the increase in total spring discharge is 25.0 cfs, or 16.2 mgd, in the year 2010. Simulation 4a provides a 22.5-mgd recharge rate, of which 16.2 mgd, or about 72%, contributes to direct spring flow. Like Simulation 2, Simulation 4a indicates that artificial recharge using RIBs appears to be an effective method for springflow augmentation.

Springflow Recoveries

Projected springflow decreases caused by increased water supply withdrawal may be offset, in part, by implementation of the feasible artificial recharge alternatives (Simulations 2 and 4a) identified in this investigation. Simulations 2 and 4a appear to recharge 7.5 and 22.5 mgd of reclaimed wastewater, respectively. The effects of these technically feasible recharge alternatives on springflow recoveries, including and excluding Apopka Spring, are summarized in Tables 11 and 12, respectively.

Table 11. *Effect of technically feasible artificial recharge alternatives on springflow recoveries, including Apopka Spring*

Simulated Condition	Spring Flow, cfs (mgd)
Baseline 2010 springflow reduction	105.8 (68.4)
2010 springflow recovery for Simulation 2 (7.5 mgd artificial recharge rate)	8.2 (5.3)
2010 springflow recovery for Simulation 4a (22.5 mgd artificial recharge rate)	25.0 (16.2)
	Springflow Recovery (percent)
2010 springflow recovery for Simulation 2 (7.5 mgd artificial recharge rate)	7.8
2010 springflow recovery for Simulation 4a (22.5 mgd artificial recharge rate)	23.6

Note: cfs = cubic feet per day
mgd = million gallons per day

Table 12. Effect of technically feasible artificial recharge alternatives on springflow recoveries, excluding Apopka Spring

Simulated Condition	Spring Flow, cfs (mgd)
Baseline 2010 springflow reduction	91.1 (58.9)
2010 springflow recovery for Simulation 2 (7.5 mgd artificial recharge rate, excluding Apopka Spring)	4.3 (2.8)
2010 springflow recovery for Simulation 4a (22.5 mgd artificial recharge rate, excluding Apopka Spring)	16.1 (10.4)
	Springflow Recovery (percent)
2010 springflow recovery for Simulation 2 (7.5 mgd artificial recharge rate)	4.7
2010 springflow recovery for Simulation 4a (22.5 mgd artificial recharge rate)	17.7

Note: cfs = cubic feet per day
mgd = million gallons per day

The total projected decrease in spring flow between 1994 and 2010 is 105.8 cfs. Implementation of the seven RIBs of Simulation 2 appears to reduce this projected decrease by 8.2 cfs, or 7.8%. Implementation of the 21 RIBs of Simulation 4a appears to increase spring flows by 25 cfs, or about 23.6%, of the anticipated 2010 springflow reduction. Therefore, a significant portion (25%) of the adverse effects of additional water supply withdrawals on spring flows could be offset by additional artificial recharge using RIBs. However, if Apopka Spring is excluded from consideration, an 18% recovery may be possible (Table 12).

Minimum Spring Flows

The minimum flows (Vergara 1994) required for various springs in the study area are shown in Table 9. The minimum spring flows are those that are required to maintain the environmental integrity of the receiving water body. The minimum stream flows and levels define the minimum range within which the streams must fluctuate to maintain the current ecological nature of the system (Hupalo et al. 1994). At this stage, the minimum flows are not available for all the springs (Vergara 1994). In Table 10, the required minimum flows are defined for seven of the 24 springs in the study area. As shown in the table, only two springs of the seven are flowing above the required minimums. Despite a 25% improvement of the projected adverse impact, none of the artificial recharge scenarios tested in this study appear to be adequate alone in increasing spring flows above required minimum flows.

Discussion and Conclusions

Results of Simulations

As much as 24.6 mgd of reclaimed wastewater have been identified as potentially available for artificial recharge. Five RIB configurations were investigated to accommodate the potential recharge. Of these, Simulations 2 and 4a appeared to be technically feasible. The remaining simulations were not technically feasible because of excessive groundwater mounding at one or more of the potential RIB sites. Simulation 2 is a 7-RIB configuration providing a recharge of 7.5 mgd. Simulation 4a is a 21-RIB configuration providing a recharge of 22.5 mgd. Together, these feasible alternatives define the upper and approximate lower limits of practical application of additional RIBs within the study area.

The steady-state groundwater simulations conducted as part of this investigation quantified the effects of the feasible artificial recharge scenarios on regional aquifer potentiometric surface elevations and on spring flows within the study area in the Wekiva River Basin. These evaluations were conducted for both 1994 and year 2010 groundwater withdrawal conditions.

Regional potentiometric surface elevations are expected to decline in the surficial, Upper Floridan, and Lower Floridan aquifers because of increased groundwater withdrawals. Artificial recharge using RIBs appears to be most effective in offsetting the effects of groundwater withdrawals within the surficial aquifer (Table 8). The decline of up to 44% of the projected regional water table in the surficial aquifer could be offset by the 21 RIB configurations defined in Simulation 4a. RIBs are much less effective in offsetting potentiometric head declines in the Floridan aquifer. The maximum potential drawdown recovery is estimated to be 15.9 and 12.1% in the Upper Floridan and Lower Floridan aquifers, respectively.

RIBs can also reduce the magnitude of projected springflow declines. Spring flow within the study area could decline by about 106 cfs (68.4 mgd) by the year 2010 because of increased water supply withdrawals. The maximum feasible use of RIBs (Simulation 4a) could enhance spring flows by about 25 cfs (16.2 mgd), nearly 25% of the projected reduction. The simulations indicate that about 70% of the artificial recharge will become direct springflow augmentation.

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

- The feasibility of the RIB method for the artificial recharge of reclaimed water is highly dependent on site-specific geologic, hydrologic, and geomorphic conditions.

- Using the GIS siting criteria developed and reported in this investigation, up to 21 potential new RIB sites were identified within the study area.

- Up to 22.5 mgd of additional reclaimed water may be recharged within the study using all 21 identified potential new RIB sites.

- Artificial recharge using RIBs can reduce the adverse effects of increased water supply withdrawal. RIBs are most effective for increasing potentiometric surface elevations in the surficial aquifer, and least effective for increasing potentiometric surface elevations in the Lower Floridan aquifer.

- RIBs can also augment spring flow. For the RIB configurations investigated in this study, approximately 70% of the recharged water contributes to direct increase in spring flow, including Apopka Spring, which alone receives about 25% of the total contribution.

- In the short term, strategically located RIB projects may enhance spring discharge without affecting additional groundwater withdrawal for water supply. However, in the long term, it appears that many of the springs are likely to flow below their required minimum discharge level.

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