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MAPPING RECHARGE (INFILTRATION/LEAKAGE) THROUGHOUT THE SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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MAPPING RECHARGE (INFILTRATION/LEAKAGE) THROUGHOUT THE SOUTH FLORIDA WATER MANAGEMENT DISTRICT

by

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ABSTRACT

Protection of ground-water recharge areas against continued intrusion from urban expansion is becoming a primary concern among local governments within south Florida; a region whose population depends almost exclusively on ground water to meet its potable water demands. The Florida Legislature, by enacting various statutes, requires the water management districts to provide recharge area information to local governments in an effort to assist these agencies with the development and subsequent implementation of appropriate water resource policies. As a result, the South Florida Water Management District undertook a project to map recharge (as a consequence of infiltration and leakage) for all of the primary public water supply aquifer systems within its four planning regions.

Recharge maps, at a scale of 1:300,000, were compiled for the unconfined Biscayne aquifer (Lower East Coast Planning Region), the unconfined Surficial aquifer system (Lower East Coast, Upper East Coast, and Lower West Coast Planning Regions), the semi-confined lower Tamiami and Sandstone aquifers (Lower West Coast Planning Region), and the semi-confined to confined upper Floridan aquifer (Kissimmee Basin Planning Region). The maps delineate average yearly rates of precipitation recharge or leakage, depending on the type of aquifer system(s) portrayed, as well as excess precipitation estimates (i.e., rainfall minus actual evapotranspiration losses) for each planning region. Recharge rates were determined from data sets extracted from existing regional numerical ground-water flow models representing a ten-year period of record (1980 through 1990), and standardized to long-term average or "normal" precipitation trends. A geographic information system (GIS) was employed to integrate the various data necessary in producing the final maps.

Because of the large-scale nature and numerous assumptions inherent within the data bases employed for completion of this project, the resulting map products are intended to be used as regional ground-water resource management planning aids only, and are not considered applicable for site-specific assessments.

ACKNOWLEDGMENTS

Several agency personnel provided valuable contributions which led to the completion of this project. Joe Chapa provided assistance during data manipulation and production of the various GIS map coverages. Jason Yan and Jose Valdes provided numerous technical comments and direction regarding the methodology employed. Diane Bello, Janet Wise, and Hedy Marshall provided assistance in developing the various illustrations and compiling this report. The authors extend their gratitude to these individuals for their support.

EXECUTIVE SUMMARY

As south Florida's population continues to expand, management of the area's ground-water resources is necessary to assure that both current and future water demands can be met District-wide. Because ground-water recharge is an essential process in replenishing the region's aquifer systems, maps delineating recharge areas can serve as planning tools for drafting and implementing effective ground-water management strategies. Sections 373.0391, 373.0395, and 373.0397, Florida Statutes, require the water management districts to provide recharge area information to local governmental agencies and to assist them in developing appropriate local water resource policies. As a result, the South Florida Water Management District has mapped ground-water recharge (as a consequence of infiltration and leakage) for all of the primary public water supply aquifer systems within its four planning regions.

Recharge maps, as illustrated on Plates I through VI, were compiled at a scale of 1:300,000 for the unconfined Biscayne aquifer (Lower East Coast Planning Region), the unconfined Surficial aquifer system (Lower East Coast, Upper East Coast, and Lower West Coast Planning Regions), the semi-confined lower Tamiami and Sandstone aquifers (Lower West Coast Planning Region), and the semi-confined to confined upper Floridan aquifer (Kissimmee Basin Planning Region) using the District's geographic information system (GIS). The maps depict two types of information within each planning region which include: 1) rates of precipitation recharge or leakage, depending on the type of aquifer system(s) portrayed, and 2) excess precipitation estimates. Precipitation recharge is defined herein as the amount of water derived from rainfall that infiltrates the ground surface and moves through the soil to the water table, thereby increasing ground-water storage. Leakage is defined as the amount of ground water which moves into or out of a confined aquifer through adjacent semi-permeable confining media, thus resulting in the recharge (gain) or discharge (loss) of water to or from the aquifer system. Average yearly precipitation recharge and leakage rates were determined from data sets extracted from existing regional numerical ground-water flow models representing a ten-year period of record (1980 through 1990), and standardized to long-term average or "normal" precipitation trends. Excess precipitation reflects the difference between long-term average annual rainfall and actual evapotranspiration data assembled from previous existing studies. Mapped overlays of excess precipitation estimates provide an indication of the amount of residual water potentially available (assuming runoff as an available component) for urban and/or rural utilization.

As expected, precipitation recharge to both the Biscayne aquifer and Surficial aquifer systems occurs throughout their entire areal extents and contributes, on average, approximately 40 in/yr. However, the amount of residual water (i.e., excess precipitation) potentially available for utilization within these regions varies spatially, reflecting regional precipitation trends. The potential for surplus is greatest along the coastlines and diminishes inland, with estimates ranging from approximately 12 in/yr along the west coast to 18 in/yr along the east coast.

Leakage to the lower Tamiami and Sandstone aquifers indicates both recharging and discharging conditions, accounting for 90 percent and 10 percent of the total aquifer areas, respectively. Areas of highest recharge within the lower Tamiami aquifer, displaying rates in excess of 21

in/yr, occur along the northern urban coastline of Collier County and the southwestern segment of Lee County, extending into the northeastern portion of Hendry County surrounding the Caloosahatchee river. Areas of highest recharge within the Sandstone aquifer, displaying rates in excess of 9 in/yr, extend throughout the west-central portions of Lee County and project southeastward into both Hendry and Collier counties along the county borders. Areas of discharge within the lower Tamiami and Sandstone aquifers reflect both natural processes (e.g., the Big Cypress National Preserve) and man induced stresses (e.g., agricultural and public water supply). The mapping of leakage to the upper Floridan aquifer also indicates areas undergoing recharge and discharge, with these areas equally apportioned throughout the region. Areas of highest recharge, displaying rates in excess of 8 in/yr, lie along the western border of the Kissimmee Basin within the Lake Wales Ridge, extending from Highlands County northward into Orange County. Areas of discharge are interspersed throughout the basin interior of the Osceola and Okeechobee Plains and the corresponding lowlands to the south. Unlike the lower Tamiami and Sandstone aquifers to the southwest, the natural flow regime within the upper Floridan (i.e., the natural "pre-development" vertical upward hydraulic gradient indicating discharge conditions) has been reversed with time due to increased pumpage, which has subsequently reduced the total amount of discharge area and expanded the area available for recharge.

This project represents an initial attempt to map precipitation recharge (infiltration) and leakage, for south Florida's principal aquifer systems, at a regional level. However, because of the large-scale nature and numerous assumptions inherent within the data bases employed during map compilation, the resulting maps are intended to be used as regional ground-water resource management planning aids only, and are not considered applicable for site-specific assessments. In addition, recharge conditions continue to change with time due to both urban development and natural causes. As a result, any maps depicting recharge estimates are constantly subject to revision.

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I. INTRODUCTION

As south Florida's population continues to escalate, followed by a marked increase in dependency on ground water as the principal source of water supplies, management of the area's ground-water resources is necessary to assure that both current as well as future water demands can be met. Present withdrawal of fresh water for consumptive use within this region exceeds 900 million gallons of water per day (SFWMD, 1994). Urban development continues to expand over areas of ground-water recharge, raising concerns regarding its effect(s) on the quality and quantity of recharge water. The varying human activities accompanying the urbanization process, along with the vast amount of impervious area created as a result, potentially adds to the degradation of water quality and the reduction of available recharge per unit area within an aquifer system. Hence, the preservation of "high-rate" recharge areas, in a natural or quasi-natural state, is a logical consequence of effective management strategy in maintaining ground-water resources.

As a result of this perspective, in order to assist local governments in the managing of these resources through development and implementation of policy initiatives, Florida has adopted legislation focusing on the identification, delineation, and protection of ground-water recharge areas (those areas hydrologically connected to an aquifer in which a contribution to storage within the aquifer is made). Section 373.0395 of the Florida Statues (FS) requires the water management districts (WMD's) to inventory "prime" recharge areas, while Section 373.0397, FS, requires the mapping of the boundaries of these areas for both the Biscayne aquifer and Floridan aquifer systems. In addition, Section 373.0391, FS, requires the WMD's to provide technical assistance (including recharge area delineation) to local governments in their efforts to comply with Chapter 163, FS, and Chapter 9J-5, Florida Administrative Code (FAC). This legislation requires the identification of "prime" and "natural" recharge areas as well as development of proposed policy(s) pertaining to the protection of these areas. As currently defined, a "natural" recharge area refers to an area which contributes a volume of water to the storage and flow of an aquifer through vertical movement from land surface; while a "prime" recharge area refers to an area generally within, but not limited to, "high" (i.e., contributes significant volumes of water) recharge areas that are afforded a higher level of protection due to their contribution to present and future ground-water uses, including protection and maintenance of natural systems and public water supply (GWRTAC, 1992).

Purpose and Scope

The information contained in this report is considered a necessary basic step in the overall procedure of satisfying the state's statutory requirements, but is not intended to completely fulfill these requirements, as application to local governments, from a local and regional planning perspective, is an ongoing process. As such, this project focused on the compilation and mapping of regional precipitation recharge and leakage rates (depending on the type of aquifer system) for all the primary public water supply aquifers utilized throughout the south Florida region. These include the unconfined Biscayne and Surficial aquifers bordering the east coast; the unconfined Surficial, and semi-confined Lower Tamiami and Sandstone aquifers of the west coast; and the semi-confined to confined upper Floridan aquifer located throughout south-central Florida. Extensive geographic information system (GIS) analysis was employed in producing the recharge maps for these aquifer systems for each of the South Florida Water Management District's (SFWMD) planning regions.

The recharge maps included in this report (Plates 1 through 6) provide a regional assessment of average annual recharge rates resulting from standardized "normal" year precipitation and leakance data. Depending on the range of values encountered within a given planning region, recharge rates are generally categorized into three broad classes corresponding in a relative sense to areas exhibiting low, medium, and high precipitation recharge or leakage. Maps displaying leakage estimates, for those aquifer systems exhibiting a confining nature, incorporate areas of recharge as well as areas of discharge. All procedures used to determine recharge rates and delineate the various areas on maps are outlined and discussed herein. In addition, conclusions are drawn regarding the feasibility and reliability of the mapping process and product output.

Area Coverage

Recharge maps, prepared at a scale of 1:300,000, are presented for each SFWMD planning region. As displayed in Figure 1, the SFWMD has been divided into four distinct areas: the Lower East Coast (LEC), the Upper East Coast (UEC), the Lower West Coast (LWC), and the Kissimmee Basin (KB). These areas represent regions displaying similarities in development patterns, degree of urbanization, and common water management issues and concerns.

All or portions of 16 counties are located within these four planning regions (refer to Figure 1). These counties include: Orange, Osceola, Polk, St. Lucie, Okeechobee, Highlands, Martin, Glades, Charlotte, Palm Beach, Hendry, Lee, Broward, Collier, Dade, and Monroe. Because of the general lack of municipal ground-water supply within Monroe County, this area has not been included in this report. The recharge map boundaries generally conform to the regional planning boundaries; however, because data compilation proceeded from county-wide ground-water assessments (exclusive of the Floridan aquifer system), complete rather than partial county coverage is presented for each region. Table 1 reveals the planning region and county cross-reference scheme as devised for this report.

TABLE 1. Counties Included within the SFWMD's Planning Regions

Planning Regions	Counties
Lower East Coast	Palm Beach, Broward, and Dade
Lower West Coast	Hendry, Lee, and Collier
Upper East Coast	Martin and St. Lucie
Kissimmee Basin	Orange, Osceola, Polk, Okeechobee, Highlands, Glades, and Charlotte

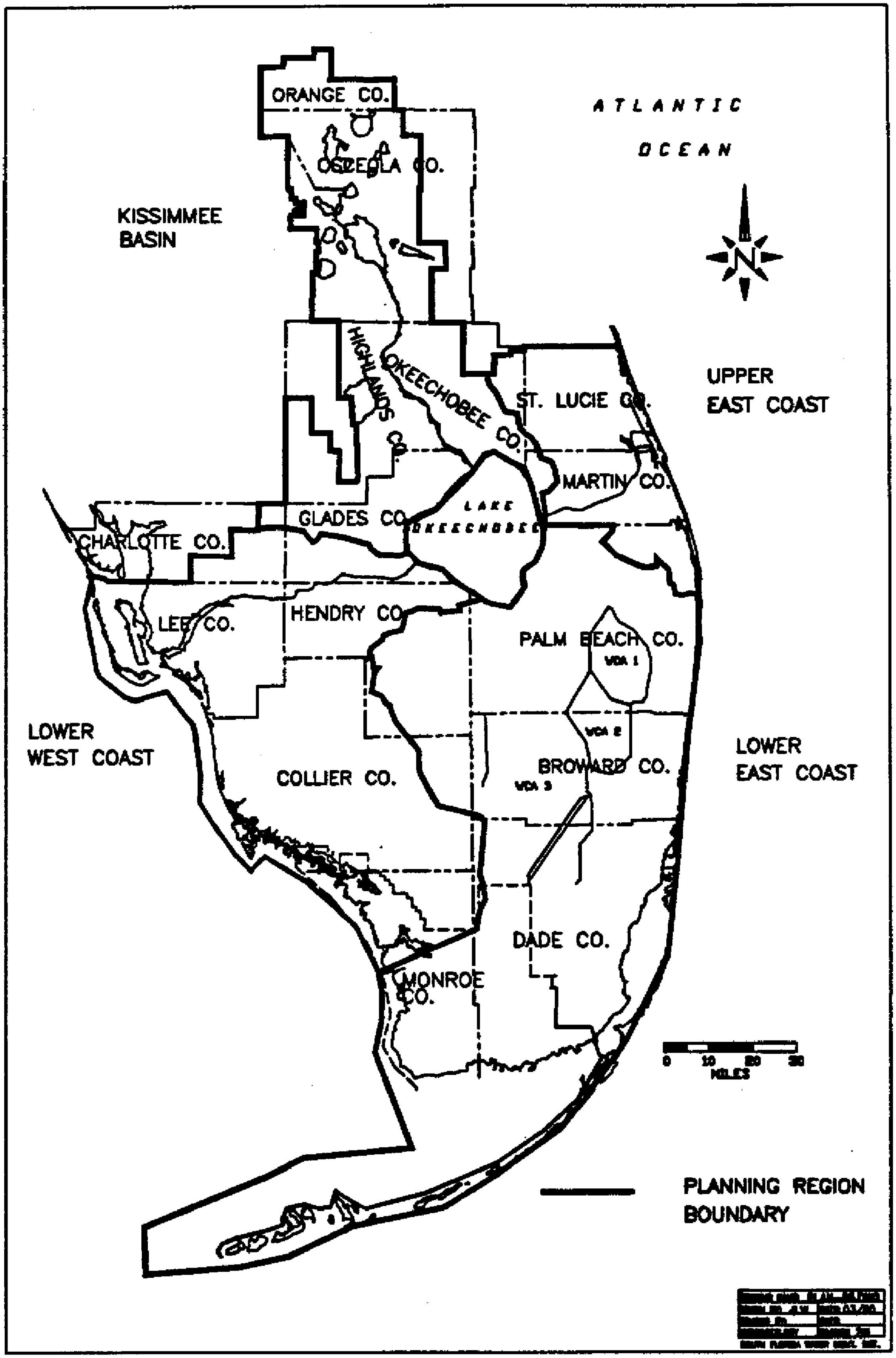


FIGURE 1 Planning Regions
South Florida Water Management District

Previous Investigations

Apart from this project, published maps displaying regional spatial variability of ground-water recharge rates within south Florida are currently available only for the Floridan aquifer system (refer to Stewart (1980), Bush and Johnston (1988), and Aucott (1989)). However, a multitude of previous reports exist which address recharge for a variety of aquifer systems throughout the SFWMD's planning regions; either implicitly through water resource investigations and numerical model analysis or explicitly as an outcome of special projects conducted on a local level.

Various water resource investigations contain limited reference to natural ground-water recharge processes and/or rates, both past and present. Examples include work by numerous authors.

1. Matson and Sanford (1913), Thompson and Stringfield (1931), Parker (1943, 1960), Cooper and Stringfield (1950), Conover (1973), and Fernald and Patton (1984) provide a general regional overview of ground-water resource information.
2. Vorhis (1948), Parker (1948, 1955), Schroeder, Milliken, and Love (1954), Schroeder, Klein, and Hoy (1958), Sherwood (1959, 1973), Tarver (1964), Klein (1970), McCoy and Hardee (1970), Land, Rodis, and Schneider (1973), Sherwood, McCoy and Galliher (1973), Rodis and Land (1976), Land (1977), Klein and Hull (1978), Hanson (1980), Causaras (1982), and Fish (1988, 1991) contribute water resource investigations conducted predominantly on the Biscayne aquifer within the LEC planning region.
3. Lichtler (1957, 1960), Bearden (1972), Miller (1978, 1988), and the SFWMD-RPD (1987) focus on water resource evaluation of the shallow surficial aquifer system within the UEC planning region.
4. Klein (1954), Sherwood and Klein (1961), McCoy (1962, 1967, 1972), Klein, Schroeder, and Lichtler (1964), Sutcliffe (1975), Wolansky (1978, 1983), Klein (1980), Wedderburn, Knapp, Waltz, and Burns (1982), Knapp, Burns, Sharp, and Shih (1984), Boggess and Watkins (1986), Knapp, Burns, and Sharp (1986), Burns and Bower (1988), Duerr, Hunn, Lewelling, and Trommer (1988), Smith and Adams (1988), and Smith, Sharp, and Shih (1988) describe water supply potential within the surficial and intermediate aquifer systems of the LWC planning region.
5. Sellards (1908), Bishop (1956), Klein, Schroeder, and Lichtler (1964), Lichtler and Joyner (1966), Stewart (1966), Lichtler, Anderson, and Joyner (1968), Sutcliffe (1975), Wolansky (1978, 1983), Frazee (1980), Shaw and Trost (1984), and Planert and Aucott (1985) report primarily on the water resource potential within the shallow surficial and Floridan aquifers of central Florida representing the KB planning region.

Recently, the application of numerical modeling has provided a more refined quantitative assessment of the spatial distribution of recharge rates. MacVicar, VanLent, and Castro (1984) document the development of a coupled surface-water/ground-water model currently employed for water management within the LEC region. In addition, studies conducted by Higer, Cordes, and Coker (1976), Shine, Padgett, and Barfknecht (1989), Restrepo, Bevier, and Butler (1992), Yan, Bevier, and Smith (1995), and Yan (in preparation) reflect regional modeling results for predominantly urbanized sections of Dade, Broward, and Palm Beach counties, as well as the Everglades. Regional modeling studies undertaken within the UEC area of Martin and St. Lucie counties include reports by Hopkins (1991), Adams (1992), Lukasiewiez (1992), and Butler and Padgett (in preparation). Bower, Adams, Restrepo (1990), Smith (1990), Bennett (1992), and Shih, Burns, Bower (1992), report modeling results for water supply aquifers within Lee, Hendry and Collier counties (LWC); while Planert and Aucott (1985), Bush and Johnston (1988), CH2M HILL (1991, 1993) and Nguyen (1993) report modeling results focused on the utilization of the Floridan aquifer as a principal water source within the KB area.

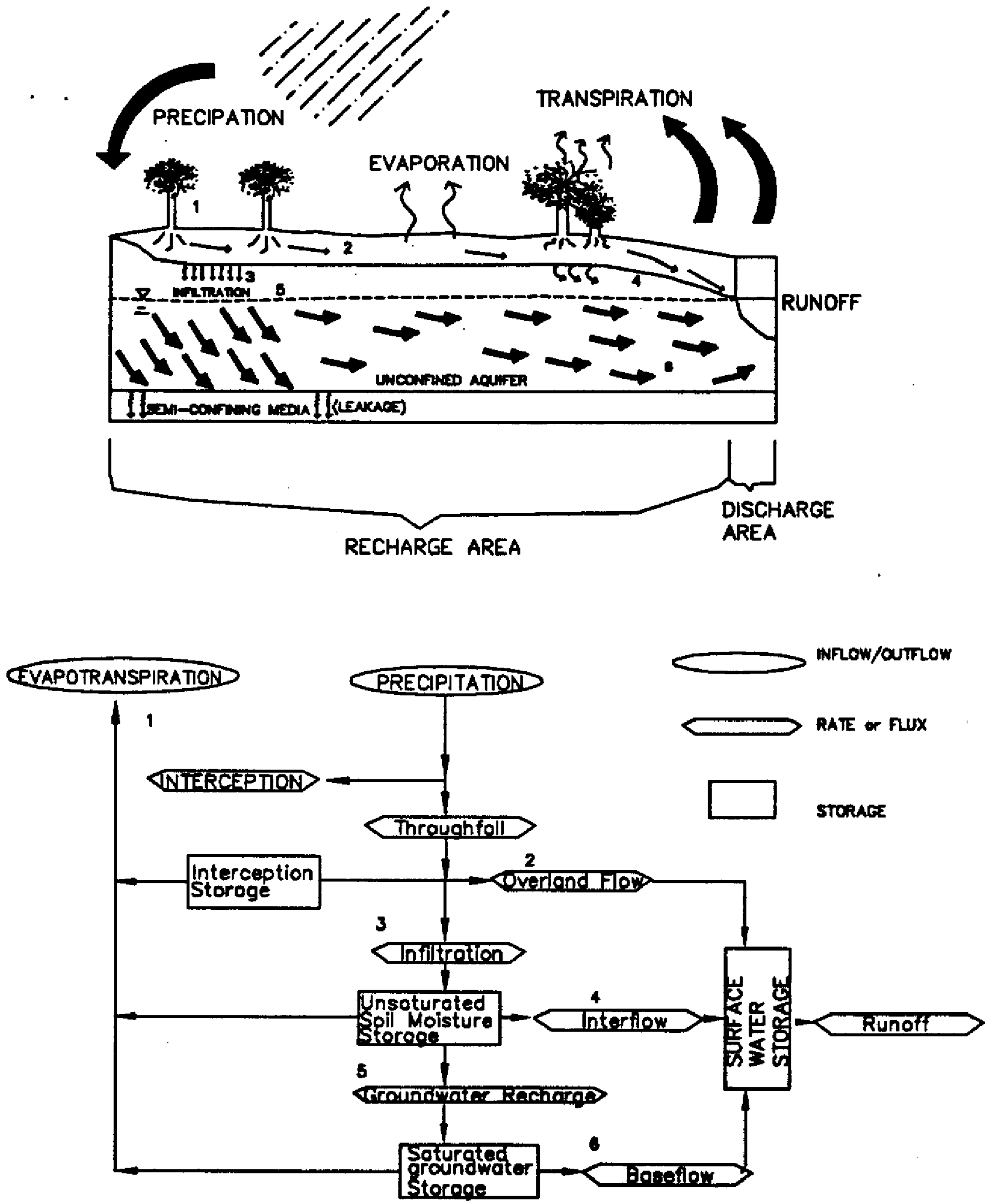
Numerous research efforts conducted locally within south Florida have resulted in a variety of special projects specifically addressing recharge, either directly or indirectly through related topics such as artificial recharge (including ASR, exfiltration systems, and drainage wells), lake and canal seepage, aquifer yield and leakance rates, and water budget analyses. Examples detailing these efforts include studies authored by Unklesbay and Cooper (1946), Parker (1951), Klein, Howard, and Sherwood (1961), Sherwood and Leach (1962, 1963), Schneider (1966), Kohout and Klein (1967), Meyer and Hull (1969), Meyer (1971, 1974, 1989), Robertson (1973), Knochenmus (1975), Putnam (1975), Allman and Winter (1976), Lichtler, Hughes, and Pfischner (1976), Sinclair (1977), Watkins (1977), Grubb (1978), Miller (1978), Tibbals (1978), Bush (1979), Merritt, Meyer, Sonntag, and Fitzpatrick (1983), Schiner and German (1983), Kimrey and Fayard (1984), Merritt (1985, 1989), German (1986), Branscome and Tomasello (1987), Lin and Gregg (1988), CH2M HILL (1989), German (1989), and Chin (1990).

II. GROUND-WATER RECHARGE

Ground-water recharge is essential in order to continue to replenish the water withdrawn from the multi-aquifer systems throughout south Florida. Recharge, in a general sense, is the result of a physical process whereby the downward flow of water accumulates or is "added" to the water table surface (within a given aquifer), thereby increasing the amount of ground water in storage (Lerner et.al., 1990). This process may occur naturally from precipitation, rivers, canals, and lakes or as man-induced activities such as irrigation and underground injection. Although ground-water recharge is typically initiated at the ground surface, those aquifer systems exhibiting an artesian or confining nature may receive recharge indirectly as the gain of water through adjacent semi-permeable confining media (i.e., leakage). Thus, the amount of recharge received by an aquifer is a function of both the available water present and the ability of the aquifer materials to transmit (through infiltration or leakage) that water, thereby making recharge rates somewhat aquifer specific.

Recharge is a major component of the hydrologic cycle. Inflow within the hydrologic cycle begins with precipitation in the form of rainfall. Rainfall occurring over the south Florida landscape is normally subjected to a variety of processes initiated upon impact with the ground surface. These processes include: interception by vegetative cover (if present); overland flow to various lowland water bodies including lakes, streams, canals, and wetlands; surface-water evaporation; infiltration into the unsaturated soils with some lateral migration (interflow); and evapotranspiration or water uptake by the vegetation itself. The remaining water permeates downward below the root zone, eventually intercepting the water table. That part of the precipitation, as well as any other source of water, which reaches the water table is defined as precipitation recharge, and those areas where the recharge process occurs are referred to as recharge areas. Outflow within the hydrologic cycle takes place as runoff or discharge of surface water, and as evapotranspiration: a combination of evaporation from open water bodies, evaporation from soil surfaces, and transpiration from the soil by plants. Runoff occurs principally in the form of overland flow and by subsurface flow (interflow and baseflow) following infiltration into the soil. Figure 2 conceptually illustrates this "flow-system" concept of the hydrologic cycle.

Water that infiltrates to the water table tends to migrate away from recharge areas toward discharge areas; these areas normally correspond to topographic high and low regions, respectively. Under natural conditions, this flux within the ground-water system is considered to be in equilibrium if the amount of water recharged balances or equals the amount of water discharged. However, this idealized state is rarely achieved for any appreciable length of time, especially in the rapidly expanding populous coastal areas of south Florida. In areas such as these, direct recharge from precipitation is augmented (and at times superseded) by other sources including: lake/river/canal infiltration, excess infiltration of irrigation water, effluent from septic tank drainfields, and leakage from utility water and sewer conduits. In addition, continued diversion of surface-water drainage combined with the induced stresses imparted to an aquifer(s) by expanding ground-water withdrawals from municipal wellfields alters the system's natural recharge-discharge patterns.



FLOW SYSTEM CONCEPTUALIZATION and SCHEMATIC
(after Freeze and Cherry, 1979)

FIGURE 2 Flow System Conceptualization And Schematic Representation Of The Hydrologic Cycle

Factors that Influence the Rate of Recharge

Many factors, both natural and man-induced, influence the ability of water to infiltrate the ground surface and ultimately contribute to ground-water recharge. These include: 1) frequency, intensity, and volume of rainfall; 2) ability of soil(s) to absorb and transmit water; 3) topography; 4) water uptake by vegetation; 5) evapotranspiration; and 6) urban and agricultural development (American Society of Civil Engineers, 1949).

Rainfall

In south Florida, particularly in the summer months, rain events are often localized products of convective thunderstorms. Routinely, these storms are very intense and of short duration. In winter months, however, frontal systems and occasional tropical depressions (hurricanes) provide more evenly distributed rainfall. Heaviest rainfall, by volume, occurs during the wet season (June-September). Recent average wet season rainfall, tabulated over a 10-year period of record (1983-1993) District-wide, approaches 30 inches or approximately 60 percent of the average annual amount of 52 inches (unpublished data SFWMD, 1994). In general, the greater the precipitation over the recharge area, the greater the amount of precipitation recharge occurring to the ground-water system. Frequent rains during the wet season months enable the soils to remain moist and maintain a relatively "high" conductivity or permeability (i.e., approaching maximum infiltration capacity). As a result, with other variables being equal, moderate rainfall intensities that do not exceed soil infiltration capacities produce maximum recharge rates. If, however, infiltration capacity is exceeded during periods of intense rainfall, depression storage and overland flow (runoff of excess water) will occur, although some of this runoff may infiltrate during transit across the land surface or from lake/river/canal percolation at a later time. Annual runoff within the south Florida region varies from 10 to 20 inches throughout the highlands of the Kissimmee Basin, decreasing to below 10 inches for remaining areas south of Lake Okeechobee (Kenner, 1966).

Soils

Differences in soil types influence the amount of infiltration and downward percolation of rainwater to the ground-water table. As illustrated in the Water Resource Atlas of Florida (1984), five principal soil types are found within the south Florida region, each differing in their ability to transmit water vertically due to contrasting conductivities based principally on composition (i.e., particle size). Assuming the soil profile has reached its moisture holding capacity, well-drained sandy soils, such as those found along the southeastern portion of the coastal ridge and scattered throughout the interior highlands within the Kissimmee Basin, readily transmit water downward to the saturated zone. As a result, these areas (representing various upland vegetative communities) experience little flooding. In contrast, those soils underlying much of the Everglades region inhibit or retard the vertical migration of surface water because of their increased "fine-grained" clay and silt composition, leading to long term inundation of water as displayed within wetland areas.

Topography

Topography is another factor which influences the length of time that rainfall is retained in a given area and subsequently allowed to infiltrate. Excluding a few scattered highland areas lying within the Lake Wales Ridge of the Kissimmee Basin, all land elevations within the SFWMD are below 175 feet National Geodetic Vertical Datum (NGVD) (Fernald and Patton (1984). Regionally, the land surface gradually slopes to the southeast under an extremely low gradient. The coastal regions and most of the peninsula south of Lake Okeechobee are essentially flat (lying below 25 feet NGVD), except near Immokalee and parts of the Atlantic Coastal Ridge. The generally shallow gradient displayed within these areas favors recharge by allowing rainfall to accumulate in many shallow depressions, thereby maximizing the time available for infiltration to occur. Even if the amount of precipitation during a storm event exceeds the infiltration capacity of the soil(s), thereby increasing runoff potential, the additional retention of rainwater on the land surface (due to depressional storage) will prolong the infiltration period, resulting in more rainfall becoming recharge than that which is absorbed by the soil(s) during the actual storm event itself. Steeper slopes, such as those found north of Lake Okeechobee within the Lake Wales Ridge and bordering Osceola Plain to the east, where land surface elevations generally exceed 50 feet NGVD, tend to diminish this effect.

Vegetation

Vegetation within south Florida affects the amount of infiltration reaching the ground-water table in several ways. Different types of upland and wetland vegetation, as well as agricultural crops, vary in their water consumption and transpiration rates. Depending on the type and density of vegetation, the immediate soil characteristics, depth to ground water, and time of year, root systems will absorb water in varying quantities. The majority of this water is transmitted throughout the plant and escapes through pores in the leaf system, thus allowing for the process of transpiration or evaporation from plant surfaces. Quantities of water consumed in this manner can be quite large, especially if the root zone extends into or below the water table as typically evidenced by plants known as phreatophytes (Viessman et.al., 1977). The type and density of vegetation not only effects the quantity of transpiration, but also serves to impede infiltration by intercepting some of the available precipitation and subsequently returning it to the atmosphere through the process of evaporation.

Evapotranspiration

Evaporation is the mechanism whereby water is changed or transferred from a liquid state into a gaseous state, potentially occurring from every "free" or exposed water surface. Evaporation and transpiration combined (evapotranspiration or ET) account for the majority of natural losses within the hydrologic cycle, thereby reducing the amount of water available for recharge. In most cases, actual ET rates are determined from estimates of potential ET and soil moisture conditions existing within a given area. Potential ET is defined as the water loss which will occur if there is an adequate (i.e., ideal) water supply available for the use of vegetation. If the water supply available to plants is less than the idealized potential ET rate calculated, the deficit will be drawn from existing soil moisture storage. Ultimately, with increasing soil moisture stress, actual ET rates will decrease below potential ET rates until the wilting point is reached (at which time the ET process ceases).

The primary factors which govern the rate of ET loss are solar radiation, temperature, wind velocity, and vapor pressure gradients (Viessman et.al., 1977). As a result of the interaction of these factors producing high ET rates within south Florida (i.e., subtropical climatic conditions coupled with the vast amount of wet-vegetated surface area within this region), ET losses consume up to 87 percent of the average annual precipitation (Bush and Johnston, 1988). In general, the potential for ET is greater south of Lake Okeechobee, with estimated losses on the order of 45 inches per year (Bush and Johnston, 1988).

Urbanization

Urban and agricultural development within south Florida can have a considerable impact upon ground-water recharge to an area. Some of the primary changes caused by man's activities include: 1) reduction in recharge area resulting from land surface modifications; 2) leakage from water and sewage conduits; 3) induced recharge resulting from wellfield withdrawal and augmented recharge resulting from wellfield injection; 4) seepage to and from canals and surface-water impoundments; and 5) percolation of applied irrigation water.

In general, urbanization produces impervious ground surfaces (i.e., reduction in recharge area), thereby increasing the amount of runoff per unit area and subsequently decreasing the amount of water available for recharge. Some of this runoff, however, especially in areas lacking regional storm drain or sewer systems, may eventually be returned to the subsurface. Even where these systems are installed, leakage can contribute to recharge. Urban metropolitan areas, such as Miami, typically experience utility losses from water and sewer mains, resulting from underground pipe leaks which may run as high as 14 percent (Florida Rural Water Association unpublished data, 1992).

The withdrawal or pumping of ground water from wells to meet residential, commercial/industrial, and agricultural demands enhances the potential for induced recharge within the aquifer system being utilized. This induced recharge may partially or fully compensate the total amount of withdrawal or discharge occurring within the aquifer, assuming demand does not exceed supply. Wells may also be used to augment natural recharge by injecting water underground for temporary storage and later recovery. This process, known as aquifer storage and recovery (ASR), is being applied on a limited basis to assist in expanding potable water supplies within the south Florida region.

A vast surface-water conveyance network comprised of more than 1,400 miles of canals and levees exists throughout southeast Florida to effectively and efficiently transport large quantities of water. Although this network was constructed primarily to drain broad interior areas within the District, many of the canals (as well as surface-water impoundments) often provide additional recharge (via seepage) to the ground-water table. This canal seepage ranges, at times, in excess of 50 percent of the total amount of transported water (SFWMD unpublished data, 1994).

Finally, approximately 62 percent of the current water demand within south Florida is accounted for as irrigated agricultural acreage (SFWMD, 1994). Depending on the type of irrigation system employed (e.g., flood, drip, micro-jet, overhead, etc.), the time of year or season, and the duration of application period(s), farming practices within the region can contribute considerable amounts of water available for infiltration and subsequent recharge.

III. METHODOLOGY

In any ground-water system, there can exist a multitude of recharge sources. Some of these sources include: 1) precipitation or direct recharge; 2) river, canal, and/or lake seepage; 3) interaquifer flows or leakage; 4) percolation of irrigation water; and 5) urban recharge (e.g., leaky utility/sewer lines, drainage wells, drainfields, etc.) (Lerner et.al., 1990). Various methods have been used to determine rates of recharge attributable to these sources which include: 1) direct measurement(s) of the quantity of infiltration through the use of lysimeters and seepage meters; 2) water budget (i.e., mass balance) calculations which commonly employ basin area analysis; 3) Darcian approaches (based on the concept of Darcy's law) which incorporate analytic solutions and numerical modeling; 4) tracer techniques which involve the introduction of various chemical constituents into the ground water; and 5) empirical methods in which recharge is correlated with other variables (e.g., precipitation, elevation, canal flow, etc.) (Lerner et.al., 1990).

In order to quantify total recharge received by an aquifer, all of the sources mentioned above would need to be taken into account by employing one or more of the methods discussed. Although this project focuses specifically on the mapping of precipitation recharge and/or leakage for various aquifer systems within the SFWMD, all major recharge sources for these aquifer systems have been previously addressed through the application of various numerical ground-water flow models. Thus, the initial recharge data employed in this effort are the result of recently "numerically" adjusted, or calibrated, water budgets computed for various modeled regions within south Florida over a ten-year period (1980 through 1990).

Estimating Precipitation Recharge and Leakage

Generally, precipitation recharge may be defined in a process format as:

recharge = precipitation - runoff - ET $\pm$ unsaturated storage change (Lerner et.al., 1990)

As discussed previously, this recharge is a by-product of the hydrologic cycle initiated at the land surface from precipitation. Some of the precipitation returns to the atmosphere by various evaporation processes and some runs off laterally as discharge, while the remainder becomes available for recharge. Initial recharge and leakance estimates for all aquifer systems mapped in this report were obtained, directly or indirectly, from ground-water flow model data sets which attempted to account for these processes as discussed below.

Ground-water model utilization

A. Unconfined aquifer systems

Initial estimates of recharge, for all unconfined or water table aquifer systems mapped for this project, were obtained from calibrated ground-water flow model data sets. The models, which incorporate eight counties (i.e., Dade, Broward, Palm Beach, Martin, St. Lucie, Collier, Hendry, and Lee) within the LEC, UEC, and LWC Planning Regions, were developed using the U.S. Geological Survey (USGS) modular three-dimensional finite-difference code commonly known as MODFLOW. MODFLOW simulates water levels and flow, in three-dimensions, for geographic areas (model cells) overlying an aquifer system(s) using data describing aquifer characteristics (e.g., transmissivity, storativity, and leakance) and aquifer stresses (e.g., recharge, evapotranspiration, well withdrawals, etc.). For a detailed description of MODFLOW documentation, the reader is referred to the USGS publication by McDonald and Harbaugh (1988).

The recharge term used in MODFLOW represents water that is potentially available to reach the water table. For all model data sets, average recharge per model cell (R_p) was calculated as a function of precipitation, surface-water runoff, and ET loss, and is described mathematically as:

$$R_p = P_n - Q_d - ET_u$$

where

P_n is the average net precipitation depth not lost to interception or depressional storage,
Q_d is the average depth of water lost to surface drainage (not otherwise simulated using a MODFLOW package), and
ET_u is the average actual evapotranspiration depth from the unsaturated zone.

Precipitation. The average monthly net precipitation depth for a model cell (P_n) was approximated from the total monthly precipitation depth over the cell (P_t) as:

$$P_n = MAX\{K_i \text{ x } P_t - (Sum[K_d(n), n=1,N]),0\}$$

where

K_i is the interception coefficient,
$K_d(n)$ is the depth of daily maximum depression storage loss, and
n is the number of days in the month.

Interception is that portion of gross precipitation which wets and adheres to foliage until such time as it returns to the atmosphere through evaporation. The quantity of water intercepted depends upon the storm character, the season of the year, and the species, age, and density of the prevailing plants and trees within a particular area. Approximations for interception were based on land use (refer to SFWMD Land Use and Land Cover Classification Code, Level III). For non-urban land uses, extreme values of K_i were defined as (Viessman, et al., 1977):

$$K_i = \begin{cases} 1.00 & \text{for clear bare ground surface (0\% interception)} \\ 0.75 & \text{for dense closed forest (25\% interception).} \end{cases}$$

Values for K_i in urban areas ranged from 1.00 to 0.50, depending upon the land use type present. The value of K_i assigned to an individual model cell represented the weighted average of the K_i values for all land use types existing within the cell.

Precipitation that reaches the ground surface may infiltrate, flow over the surface, or become trapped in numerous small depressions contributing to depression-storage loss. Because of the relatively shallow slopes encountered throughout south Florida, an upper limit of 0.11 inch was assumed for each precipitation event. The model depression storage loss (K_d) was calculated as:

$$K_d = K_d^{max} \text{ x } MAX\{[1 - SQR(K/K_m)], 0\}$$

where

K_d^{max} is the sum of maximum daily depression storage losses, in inches, for the stress period computed on a daily basis (an upper limit of 0.11 inches was assumed for each day),
K is the vertical hydraulic conductivity of the soil layer, and
K_m is a calibration factor defined as the value of hydraulic conductivity at which infiltration is assumed to be nearly instantaneous, thus precluding evaporative losses from storage in depression.

A value of $(K/K_m) = 0$, signifying an impervious drainage area, implies a value of $K_d = 0.11$ inch per single precipitation event, while a value of $(K/K_m) = 1$, a highly pervious area, implies a value of $K_d = 0$. Rainfall of less than the critical daily precipitation depth ($K_d = 0.11$") is assumed to evaporate and create neither infiltration nor runoff drainage.

The value of soil hydraulic conductivity (K) in a model cell was estimated by examination of the tables of saturated vertical permeability for applicable soil types found in Soil Conservation Service soil survey books.

Runoff. Then average net depth of water lost to runoff or surface drainage (Q_d) was estimated by the following equation:

$$Q_d = K_s \text{ x } K_a \text{ x } P_n$$

where

K_s is a coefficient relating the potential for runoff to surface-water bodies,
K_a is a coefficient relating the potential for aquifer recharge from surface drainage, and
P_n is the average net precipitation depth not lost to interception or depressional storage, as previously defined.

In theory, coefficient K_s may vary between limits of 0 and 1, depending on the potential of the land use type(s) within a model cell, to provide overland flow into a surface-water body(s) (i.e., canal or lake). However, actual model values for K_s ranged between 0.1 and 0.3 (mostly 0.1). For uniformity between model data sets, each land use within south Florida (refer to SFWMD Land Use and Land Cover Classification Code, Level III) was assigned a particular value for K_s.

Coefficient K_a takes into account the effect of delayed recharge from surface drainage. The value of K_a is a function of the average hydraulic conductivity and the average slope of the land surface within a particular model cell. It is assigned a value of 1 if there is no infiltration into the unsaturated zone and, conversely, a value of 0 when runoff becomes negligible and rainfall is completely diverted to potential recharge. The value for K_a was defined as:

$$K_a = K_a^{max} \times (1 - K/K_{max})$$

where

K_a^{max} is the maximum value that K_a may take (less than or equal to 1),
K is the vertical hydraulic conductivity of the soil layer, and
K_{max} is the maximum soil hydraulic conductivity determined in the model area.

Evapotranspiration. Evapotranspiration from the unsaturated zone (ET_u) was not accounted for in the current model data sets. Because of the relatively shallow depth to ground water, it is generally assumed that the majority of annual ET loss within south Florida occurs from the saturated zone below the water table, thus minimizing the effect of ET_u on recharge. In modeled areas (cells) where there is a significant unsaturated zone above the water table, however, the recharge calculations may become inaccurate without considering this loss. It is anticipated that future revisions of the model data sets will address this limitation by incorporating ET_u. Technically, by ignoring the effect of ET_u, the resultant recharge estimates more closely define infiltration rates (i.e., rates potentially higher than actual recharge rates).

Preprocessing. The following generic outline summarizes the preprocessing steps, incorporating the methodology discussed above, taken to create the model recharge arrays.

1) Daily rainfall totals were assembled from numerous stations throughout the modeled area(s) (references include federal, state, and private sources).
2) Assuming one precipitation event per rainy day, 0.11 inch of rainfall from that event was removed and summed for each month as depression storage loss.
3) Monthly depression storage losses were subtracted from monthly rainfall totals, and the remaining recharge estimates were contoured throughout the entire modeled area(s) to determine individual cell values.
4) The resulting arrays further compensated for additional losses by removing estimates of interception and runoff, thereby producing final recharge estimates.
5) In some cases, final recharge arrays were adjusted (i.e., increased) to account for flood irrigation in modeled areas where appropriate.

For specific details regarding the preprocessing procedures utilized for a particular model data set, the reader is directed to the various model reports referenced herein.

Precipitation recharge estimation for all models was an iterative procedure. Initial estimates were revised and refined by comparing them to the results of other methods and to other data. Final estimates resulted from "trial and error" calibration of the ground-water flow models when ground-water responses, in space and time, were subjectively matched to previous existing conditions.

B. Leaky confined aquifer systems

Leakage is defined as indirect recharge (or discharge) or the gain (or loss) of water received (or supplied) by a confined aquifer through adjacent (bounding) semi-permeable confining media. As with the unconfined systems, initial estimates of leakage (recharge/discharge) for all confined aquifer systems mapped for this project were derived from calibrated ground-water flow model data sets. However, unlike the unconfined aquifer system data sets which represented one model code, two different models were utilized. The models, which included a three-dimensional hybrid of Trescott, Pinder, and Larson's two-dimensional finite-difference aquifer simulation model (Trescott, 1975; Trescott and Larson, 1976) as well as the MODFLOW model previously discussed, incorporate a total of 11 counties (Orange, Osceola, Polk, Okeechobee, Highlands, Charlotte, Glades, Charlotte, Hendry, Lee, and Collier) within the KB and LWC Planning Regions.

The data utilized in the construction of the recharge/discharge map for the upper Floridan aquifer system within the KB Planning Area were taken directly from previously mapped outputs contained in the Regional Aquifer System Analysis (RASA) work undertaken by Bush and Johnston (1988). These data were the product of leakage coefficient estimates used in the modeling process. The original data utilized in the construction of the recharge/discharge maps for the lower Tamiami and Sandstone aquifers within the LWC Planning Area, however, were extracted from three separate models each covering a county-wide region. In this case, leakage estimates were derived from leakance values previously applied in the various model data sets.

The leakage term is a function of the leakance, which is defined as the ratio of the vertical hydraulic conductivity (K_v) of the aquifer confining bed (i.e., the unit overlying the aquifer of interest) to the thickness of the confining bed (T):

$$\text{Leakance} = K_v/T$$

Initial leakance values applied in the models were calculated from assumed and/or determined vertical conductivity values (K_v) and thicknesses (T) specific to the modeled areas. For specific information regarding the derivation of leakance values utilized for a particular model data set, the reader is once again directed to the various model reports referenced herein. As with precipitation recharge estimation, previous model calibration led to the final leakance estimates applied in this project.

Standardization

A. Unconfined aquifer systems - precipitation recharge

Initial precipitation recharge data, representing the Biscayne aquifer and Surficial aquifer system, was compiled from model data sets reflecting 1986 through 1990 hydrologic conditions. Because all of the existing model estimates for recharge utilized in this project vary temporally, as a result of relatively short calibration periods, a method was sought in order to standardize these estimates to long-term precipitation trends. Many attempts have been made to empirically define a simple relationship between precipitation and recharge (Lerner et.al., 1990). One such approach assumes recharge as a linear function of precipitation stated as:

$$R = C \times P$$

where

R represents precipitation recharge
C is a constant of proportion, and
P represents precipitation or rainfall.

The constant of proportion, C, is defined as the ratio of recharge to precipitation for any given year or (R/P). Therefore, the above equation can be re-written as:

$$R_y/P_y = R_{norm}/P_{norm}$$

where

R_y/P_y represents the recharge-precipitation ratio for a particular period of record, and
R_{norm}/P_{norm} represents the recharge-precipitation ratio for a long-term precipitation record.

Solving for the variable, R_{norm}, yields:

$$R_{norm} = P_{norm} \times R_y/P_y$$

where

R_{norm} represents the average long-term or "normal" recharge within the modeled area,
P_{norm} represents the average long-term or "normal" precipitation within the modeled area,
R_y represents the averaged model recharge for a given period of record, and
P_y represents the averaged available precipitation occurring during the model period of record.

This solution was applied to all model recharge data sets representing the unconfined aquifer systems within appropriate planning regions (i.e., LEC, UEC, and LWC). The following outline summarizes the processing steps used to create the final recharge arrays prior to mapping.

1) Model data sets were organized by corresponding planning regions as discussed previously (e.g., Martin and St. Lucie County models within the UEC, etc.).
2) Monthly recharge estimates for each model within a planning region were then grouped

by season (assuming a six-month dry, two-month transitional, and four-month wet season scheme as referenced in Sculley (1986)).

3) Weighted averages were tabulated based upon this scheme in order to compensate for the difference in calibration periods of record between model data sets (refer to Table 2).

4) In order to standardize model recharge estimates and thus reflect "normal" precipitation trends, the ratio (P_{norm}/P_y) was calculated for each model data set based on long term precipitation information tabulated by basin (refer to Table 2). (Sources of precipitation data include Sculley (1986), which reports a 71-year period of record prior to 1985, and unpublished SFWMD records from 1983 through 1993.)

5) Final long term estimates of potential average precipitation recharge were then produced from each model data set by multiplying all the adjusted array or model cell values by the appropriate P_{norm}/P_y ratio, and subsequently converting them to appropriate rate-units (i.e., inches per year). These estimates represent potential average annual precipitation recharge rates, assuming current (1986 through 1990) aquifer stresses and "normal" rainfall.

TABLE 2. Model Calibration Periods of Record and Associated P_{norm}/P_y Ratios

Model	Planning Area	Calibration Period of Record	P_{norm}/P_y Ratio
Dade Co.	LEC	1/86 - 12/89	1.18
Broward Co.	LEC	1/89 - 12/89	1.52
Palm Beach Co.	LEC	1/89 - 6/90	1.40
Martin Co.	UEC	1/89 - 12/89	1.13
St. Lucie Co.	UEC	7/89 - 6/90	1.18
Collier Co.	LWC	2/86 - 12/88	1.14
Hendry Co.	LWC	1/86 - 12/88	1.15
Lee Co.	LWC	4/85 - 9/86	1.13

B. Leaky confined aquifer systems - leakage

Leakage (recharge/discharge) to the lower Tamiami and Sandstone aquifers was calculated from: 1) the regional hydraulic pressure or head differences existing between the aquifers and the overlying water table, and 2) the leakance rates associated with the upper confining units separating the aquifers. Leakance rates were derived from models reflecting 1985 through 1988 hydrologic conditions, while the difference in head elevations were tabulated and subsequently averaged from monthly data collected in 1992. A base year of 1992 was selected because of the close comparison between long-term average basin precipitation and total precipitation for that year. Leakage to the upper Floridan aquifer, however, was determined from analysis of two published maps after Bush and Johnston (1988), detailing estimated predevelopment (circa 1930's) recharge/discharge from the upper Floridan aquifer and estimated changes in recharge/discharge due to recent (1980) pumpage.

Lower Tamiami and Sandstone Aquifers

Calculation of leakage to the lower Tamiami and Sandstone aquifers is based on the following equation:

$$R_l = H \times L_k$$

where

R_l represents leakage into or out of the aquifer,
H represents the hydraulic pressure difference existing between the water-bearing unit directly above the aquifer and the aquifer itself, and
L_k represents the leakance as previously defined.

Average head elevations for the 1992 season (January through December) were compiled for every USGS well actively monitored within the Surficial, lower Tamiami, and Sandstone aquifers for Collier, Hendry, and Lee counties (refer to the USGS Water-Data Reports FL-92-2B and FL-93-2B). Acceptable sample size ranged from 9 to 15 measurements per well, with the majority constituting 12 measurements (1 per month) made over the entire year. These elevations, in combination with leakance data extracted from the three county models, were input into a GIS database for spatial interpolation and ensuing calculations. The resultant leakage estimates, for both the lower Tamiami and Sandstone aquifers, represent potential average recharge/discharge rates (in inches per year), assuming current (1992) aquifer stresses and "normal" rainfall.

Floridan Aquifer

As briefly mentioned above, leakage to or from the upper Floridan aquifer was determined from previous regional modeling work undertaken by Bush and Johnston (1988). Two maps displaying pre-development recharge/discharge rates and associated post-development changes to these rates existing throughout the entire KB planning region were digitized to a GIS format for subsequent use. By superimposing these maps, a final composite map was produced reflecting the potential leakage conditions (average recharge/discharge rates, in inches per year) existing within the upper Floridan aquifer, assuming relatively current (1980) aquifer stresses and "normal" rainfall.

Estimating Excess Precipitation

Excess precipitation, as herein defined, is the difference between the long-term average annual rainfall and actual ET occurring within a specified area. It may be represented as:

$$P_e = P - AET$$

where

P_e represents excess precipitation,
P represents average annual rainfall, and
AET represents average annual actual evapotranspiration losses.

This parameter accounts for the amount of precipitation potentially available as recharge (ignoring surface-water drainage) once the principle natural loss to an aquifer system (i.e., ET) has occured. Thus, within a particular planning region, the excess precipitation provides an indication of the amount of residual water potentially available for urban and/or rural utilization, assuming runoff as an available component.

The ET data used in producing the excess precipitation estimates was taken from previous work compiled by Bush and Johnston (1988). These authors employed a method developed by Dohrenwend (1977) to estimate actual ET loss from existing long-term temperature and precipitation data (incorporating a 30-year period of record). This, in turn, was used to determine and subsequently map the spatial distribution of average annual ET rates throughout the state of Florida. Although this method gives only a first order approximation of the true distribution of ET, as evidenced in the mapped polygon projection, it is useful when working at the regional scales undertaken in this project.

Like the ET data, the precipitation data used in producing the excess precipitation estimates was taken from a previous study conducted by MacVicar (1981). His efforts produced long-term estimates of average annual rainfall statewide from original data spanning a sixty-year period. This information is displayed spatially throughout the SFWMD in the form of a contour map.

The ET and precipitation data were both digitized to a GIS format for later manipulation and incorporation as excess precipitation overlays when producing the final recharge maps. These overlays were generated for each of the four planning regions within the SFWMD (refer to recharge maps; Plates I - III, VI).

GIS Integration

A geographic information system, or GIS, was used to integrate the various data bases necessary to map precipitation recharge and leakage for the principal public water supply aquifer systems within the SFWMD. Environmental Systems Research Institute's (ESRI) ARC/INFO system was the GIS software chosen by the SFWMD to automate the compilation of map coverages, each coverage consisting of map features or attributes (e.g., ET and precipitation for excess precipitation estimates, infiltration rates, leakance and head elevations for leakage rates, latitudelongitude, etc.). The following outline provides a generic overview of the steps employed in producing the various coverages utilized in compiling the final maps.

1) All of the data sets (ASCII standard) were reformatted, as necessary, for input into the GIS.
2) A Triangulated Irregular Network (TIN) of all appropriate data was then made in order to produce point coverages. TIN is the ESRI procedure typically used to create 3-dimensional surfaces. However, for this project the TIN served only as an intermediate step for the creation of 2-dimensional point coverages (i.e., digital analogs of single map sheets containing specific values attributable to discrete points in space). Individual point coverages were constructed for each aquifer system within each planning region.
3) Point coverages were subsequently edited and appended on a case-by-case basis, depending on the particular planning region being represented and the type(s) of aquifer systems present.
4) In order to uniformly distribute the point data throughout a particular planning region, point coverages were subjected to ESRI's ordinary kriging (linear model) procedure transforming them to grid coverages. Kriging is a local weighted-average interpolation technique which provides data estimates, in a regular grid format, from a set of randomly or non-randomly distributed sample points. A grid consists of a uniform framework (i.e., rows and columns of equal size) of multiple cells superimposed over a select geographic region, with each cell addressed by an x,y-coordinate and containing interpolated data or z-values derived from original data points. Regular grids were constructed for each of the four planning regions. Although the areal extent of each grid varies with respect to the geographic boundaries of the planning region encompassing it, the size of each individual grid cell is constant and represents a uniform spacing of 500 feet on the earth's surface or 2,500 square feet in area. This grid cell spacing was selected in order to create "smooth" polygon boundaries on the final maps. The combined planning region grids incorporate a total land area in excess of 17,000 square miles District-wide.
5) Descriptive statistics (e.g., mean, standard deviation, range, etc.) were tabulated from the individual grid coverages, as grouped by aquifer system and planning region, to aid in determining the various map classes. Classes were arbitrarily selected to reflect low, medium, and high recharge/discharge rates, with data exceeding a 1.5 standard deviation cutoff as characterizing a fourth class of anomalous values. Statistical information, as well as the appropriate class intervals, are displayed on the final maps (refer to recharge maps; Plates I - VI).
6) Lastly, after completing all mathematical operations, the grid coverages were converted to polygon coverages in preparation to output the final maps. These polygon coverages were subsequently mapped at a scale of 1:300,000 using ESRI's mapping procedure ARCPLOT (refer to recharge maps; Plates I - VI).

IV. RESULTS

The maps contained in this report focus principally on the amount of water available as recharge to the District's major water-supply aquifers as a result of rainfall. As such, they do not delineate recharge attributable to other important sources such as river and canal seepage, although leakage estimates within the confined aquifer systems implicitly include these fluxes. Whether or not this fact becomes significant, can only be addressed contingent upon the user's objectives when employing these maps. The reader is cautioned regarding data interpretation. Because these maps portray recharge estimates derived from regional model(s) calibration, emphasis should be given to regional data trends rather than to local anomalies (i.e., high and low values displayed within a small area); as these areas may represent artifacts of the modeling process rather than actual conditions. All results, as summarized below, are tabulated based on the percentage of "active" modeled area within each District planning region and the corresponding class intervals selected to portray the map data.

Lower East Coast Region

Biscayne Aquifer and Surficial Aquifer System

In general, precipitation recharge to the unconfined Biscayne aquifer and Surficial aquifer system occurs throughout the entire region, with the highest rates dominating the non-urban or rural areas. However, the amount of residual water potentially available for urban and/or rural utilization, as reflected in the excess precipitation estimates, varies spatially as a result of south Florida's rainfall patterns. Thus, the greatest potential for surplus (assuming the availability of runoff through surface-water retention or infiltration) tends to border the coastline and gradually diminishes inland. Excess precipitation estimates range from approximately 18 in/yr along the coast to 14 in/yr within the interior.

Recharge rates range from 1 to 60 in/yr, with the long-term average approaching 39 in/yr ($\pm$ 8) which constitutes approximately 66 percent of the LEC's normal rainfall. Recharge areas displaying infiltration rates greater than or equal to 42 in/yr encompass approximately 683 sq mi, or 34 percent of the total modeled recharge area. Areas displaying recharge rates ranging from 21 to 42 in/yr encompass approximately 1,294 sq mi, or 64 percent of the recharge area. Areas displaying recharge rates of less than 21 in/yr encompass approximately 32 sq mi, or 2 percent of the recharge area. Total recharge area encompasses 2,009 sq mi.

Excess precipitation estimates range from 7 in/yr to 20 in/yr, with the long-term average approaching 16 in/yr ($\pm$ 3). Recharge areas displaying excess precipitation greater than or equal to 17 in/yr encompass approximately 1,024 sq mi, or 51 percent of the modeled recharge area. Areas displaying excess precipitation ranging from 11 to 17 in/yr encompass approximately 895 sq mi, or 45 percent of the recharge area. Areas displaying excess precipitation of less than 11 in/yr encompass approximately 89 sq mi, or 4 percent of the recharge area.

Upper East Coast Region

Surficial Aquifer System

As with the neighboring Biscayne aquifer and Surficial aquifer system to the south, precipitation recharge to the northern extention of the unconfined Surficial aquifer system occurs throughout this entire region also, with moderate rates dominating the vast rural areas. Similarly, as evidenced in the LEC region, excess precipitation estimates vary spatially as a result of precipitation trends. Thus, the greatest potential for surplus throughout this region also flanks the coastline, and gradually diminishes inland. Excess precipitation estimates range from approximately 17 in/yr along the coast to 14 in/yr within the interior.

Recharge rates range from 14 to 58 in/yr, with the long-term average approaching 33 in/yr (± 5) which constitutes approximately 63 percent of the UEC's normal rainfall. Recharge areas displaying infiltration rates greater than or equal to 44 in/yr encompass approximately 21 sq mi, or 2 percent of the total modeled recharge area. Areas displaying recharge rates ranging from 28 to 44 in/yr encompass approximately 920 sq mi, or 83 percent of the recharge area. Areas displaying recharge rates of less than 28 in/yr encompass approximately 170 sq mi, or 15 percent of the recharge area. Total recharge area encompasses 1,111 sq mi.

Excess precipitation estimates range from 0 in/yr to 19 in/yr, with the long-term average approaching 14 in/yr (± 2). Recharge areas displaying excess precipitation greater than or equal to 14 in/yr encompass approximately 659 sq mi, or 59 percent of the modeled recharge area. Areas displaying excess precipitation ranging from 7 to 14 in/yr encompass approximately 445 sq mi, or 40 percent of the recharge area. Areas displaying excess precipitation of less than 7 in/yr encompass approximately 8 sq mi, or 1 percent of the recharge area.

Lower West Coast Region

Surficial Aquifer System

Like its eastern counterparts, precipitation recharge to the unconfined Surficial aquifer system occurs throughout the entire region, with the highest rates confined to rural areas within and bordering the western edge of the Immokalee Rise. These locations project southward from the tri-county boundary intersection and extend into the Corkscrew Swamp/Golden Gate Estates area. However, the greatest potential for water surplus, as reflected in the excess precipitation estimates, tends to border the coastline mimicking precipitation trends. Excess precipitation estimates, in general, are lower than those occurring within the eastern planning regions, ranging from approximately 10 in/yr along the coast to 5 in/yr within the interior.

Recharge rates range from 31 to 67 in/yr, with the long-term average approaching 47 in/yr (± 5) which constitutes approximately 85 percent of the LWC's normal rainfall. Recharge areas displaying infiltration rates greater than or equal to 56 in/yr encompass approximately 181 sq mi, or 6 percent of the total modeled recharge area. Areas displaying recharge rates ranging from 43 to 56 in/yr encompass approximately 2,349 sq mi, or 78 percent of the recharge area. Areas displaying recharge rates of less than 43 in/yr encompass approximately 482 sq mi, or 16 percent of the recharge area. Total recharge area encompasses 3,012 sq mi.

Excess precipitation estimates range from 3 in/yr to 14 in/yr, with the long-term average approaching 7 in/yr (± 3). Recharge areas displaying excess precipitation greater than or equal to 10 in/yr encompass approximately 844 sq mi, or 28 percent of the modeled recharge area. Areas displaying excess precipitation ranging from 6 to 10 in/yr encompass approximately 922 sq mi, or 31 percent of the recharge area. Areas displaying excess precipitation of less than 6 in/yr encompass approximately 1,246 sq mi, or 41 percent of the recharge area.

Lower Tamiami Aquifer

Diffuse leakage to the semi-confined lower Tamiami aquifer indicates both recharging and discharging conditions, accounting for 78 percent and 22 percent of the mapped aquifer area, respectively. Areas of highest recharge, displaying rates in excess of 21 in/yr, occur along the upper urban coastline of Collier County and proceed through the southwestern segment of Lee County, extending into the northeastern portions of Hendry County surrounding the Caloosahatchee river. Anomalously high recharge rates (on the order of 100 in/yr) are associated with the Coastal Ridge, suggesting the existence of a thin and/or highly permeable lower Tamiami confining unit within this area. The two principal areas of discharge reflect both natural processes (e.g., the Big Cypress National Preserve to the east) and man-induced stresses (e.g., agricultural and public water supply pumpage along the southeastern coast). Areas of anomalous high discharge (reflecting rates on the order of 160 in/yr) are associated with wellfield withdrawals for the Naples community.

Recharge rates range from 0 to 102 in/yr, with the long-term average approaching 8 in/yr (± 12). Recharge areas displaying downward leakage rates greater than or equal to 21 in/yr encompass approximately 163 sq mi, or 10 percent of the total modeled recharge area. Areas displaying recharge rates ranging from 14 to 21 in/yr encompass approximately 111 sq mi, or 7 percent of the recharge area. Areas displaying recharge rates ranging from 7 to 14 in/yr encompass approximately 275 sq mi, or 16 percent of the recharge area. Areas displaying recharge rates of less than 7 in/yr encompass approximately 1,112 sq mi, or 67 percent of the recharge area. Total recharge area encompasses 1,661 sq mi.

Discharge rates range from 0 to 168 in/yr, with the long-term average approaching 11 in/yr (± 24). Discharge areas displaying upward leakage rates less than or equal to 16 in/yr encompass approximately 393 sq mi, or 86 percent of the total modeled discharge area. Areas displaying discharge rates ranging from 16 to 32 in/yr encompass approximately 24 sq mi, or 5 percent of the discharge area. Areas displaying discharge rates ranging from 32 to 48 in/yr encompass approximately 14 sq mi, or 3 percent of the discharge area. Areas displaying discharge rates greater than 48 in/yr encompass approximately 28 sq mi, or 6 percent of the discharge area. Total discharge area encompasses 459 sq mi.

Sandstone Aquifer

Similar to the overlying lower Tamiami aquifer, diffuse leakage to the semi-confined Sandstone aquifer indicates both recharging and discharging conditions, accounting for 78 percent and 22 percent of the mapped aquifer area, respectively. Areas of highest recharge, displaying rates in excess of 9 in/yr, extend throughout the west-central portions of Lee County and project southeastward into both Hendry and Collier counties along the county borders. Here, anomalously high recharge rates (on the order of 25 in/yr) are attributable to the combined effects of both high leakance associated with the thinning upper Hawthorn confining zone and the large head contrast existing between the Sandstone aquifer and overlying aquifer. As displayed by the lower Tamiami aquifer, areas of discharge reflect both natural processes (e.g., the upward migration of water to the overlying unconfined surficial aquifer system in the northwestern region encompassing the Caloosahatchee River) and man-induced stresses (e.g., agricultural and public water supply pumpage from within the aquifer and/or directly above it). Anomalous high discharge rates (on the order of 40 in/yr) are associated with wellfield withdrawals for the Bonita Springs community.

Recharge rates range from 0 to 25 in/yr, with the long-term average approaching 4 in/yr (± 5). Recharge areas displaying downward leakage rates greater than or equal to 9 in/yr encompass approximately 106 sq mi, or 12 percent of the total modeled recharge area. Areas displaying recharge rates ranging from 6 to 9 in/yr encompass approximately 75 sq mi, or 8 percent of the recharge area. Areas displaying recharge rates ranging from 3 to 6 in/yr encompass approximately 157 sq mi, or 18 percent of the recharge area. Areas displaying recharge rates of less than 3 in/yr encompass approximately 560 sq mi, or 62 percent of the recharge area. Total recharge area encompasses 898 sq mi.

Discharge rates range from 0 to 42 in/yr, with the long-term average approaching 3 in/yr (± 6). Discharge areas displaying upward leakage rates less than or equal to 5 in/yr encompass approximately 200 sq mi, or 79 percent of the total modeled discharge area. Areas displaying discharge rates ranging from 5 to 10 in/yr encompass approximately 31 sq mi, or 13 percent of the discharge area. Areas displaying discharge rates ranging from 10 to 15 in/yr encompass approximately 9 sq mi, or 3 percent of the discharge area. Areas displaying discharge rates greater than 15 in/yr encompass approximately 13 sq mi, or 5 percent of the discharge area. Total discharge area encompasses 253 sq mi.

Kissimmee Basin Region

Upper Floridan Aquifer

Diffuse leakage to the semi-confined/confined upper Floridan aquifer also indicates areas undergoing recharge and discharge, with these areas apportioned throughout the region at 55 and 45 percent, respectively. Areas of highest recharge, displaying rates in excess of 8 in/yr, lie along the western border of the Kissimmee Basin within the Lake Wales Ridge; from Highlands County and extending north into Orange County. Here, excess precipitation equals or exceeds

10 in/yr as potential available precipitation recharge. Areas of discharge are interspersed throughout the basin interior of the Osceola and Okeechobee Plains, and the corresponding lowlands to the south. Unlike the lower Tamiami and Sandstone aquifers to the southwest, natural discharge conditions within the upper Floridan have been altered with time due to increased pumpage, which has subsequently reduced the total amount of discharge area and expanded the area available for recharge.

Recharge rates range from 0 to 12 in/yr, with the long-term average approaching 3 in/yr ($\pm$ 3). Recharge areas displaying downward leakage rates greater than or equal to 8 in/yr encompass approximately 63 sq mi, or 3 percent of the total modeled recharge area. Areas displaying recharge rates ranging from 4 to 8 in/yr encompass approximately 705 sq mi, or 31 percent of the recharge area. Areas displaying recharge rates of less than 4 in/yr encompass approximately 1,495 sq mi, or 66 percent of the recharge area. Total recharge area encompasses 2,263 sq mi.

Discharge rates range from 0.25 to 1.25 in/yr, with the long-term average approaching 0.8 in/yr ($\pm$ 0.5). Discharge areas displaying upward leakage rates less than or equal to 0.75 in/yr encompass approximately 849 sq mi, or 45 percent of the total modeled discharge area. Areas displaying discharge rates greater than 0.75 in/yr encompass approximately 1,020 sq mi, or 55 percent of the discharge area. Total discharge area encompasses 1,869 sq mi.

Excess precipitation estimates range from 0 in/yr to 15 in/yr, with the long-term average approaching 10 in/yr ($\pm$ 2). Leakage areas, both recharge and discharge, superimposed by excess precipitation greater than or equal to 10 in/yr encompass approximately 2,848 sq mi, or 69 percent of the total modeled area. Areas displaying excess precipitation ranging from 5 to 10 in/yr encompass approximately 1,062 sq mi, or 26 percent of the recharge/discharge area. Areas displaying excess precipitation of less than 5 in/yr encompass approximately 223 sq mi, or 5 percent of the recharge/discharge area. Total recharge/discharge area encompasses 4,132 sq mi.

V. CONCLUSIONS

This project represents an initial attempt to map precipitation recharge (infiltration) and leakage, for south Florida's principal aquifer systems, at a regional level. The principal data utilized includes recent (predominately 1988) District-wide land-use coverages, infiltration and leakance rates from numerical models, long-term average precipitation records (in excess of 30 years), and monthly ground-water elevations (tabulated yearly by the USGS). However, because these maps were compiled from "large-scale" data sets, they provide regional assessments of recharge-discharge rates only and, therefore, are not intended for site-specific evaluations.

Mapping recharge on a quantitative basis is particularly difficult in areas having extensive wetlands and/or highly controlled surface-water drainage, such as is exhibited within the SFWMD. Methods for estimating direct recharge in areas such as this are limited, making techniques such as base flow analysis impractical, while others, such as tracer profiling or lysimeter installation, are either very data intensive or costly or both. This project incorporated three methods which include: 1) soil moisture budgeting which attempts to account for variables such as precipitation, runoff, and evapotranspiration; 2) numerical modeling of the saturated zone which yields calibrated estimates of recharge (infiltration) and leakance; and 3) an empirical linear relationship assumed between precipitation and recharge which approximates average long-term rates. The combination of these methods serves to establish spatial estimates of potential recharge rather than actual distribution trends. While these estimates may prove useful in analyzing water resources on a regional scale, they do not replace the merit of actual data. Actual spatial and temporal interpretation must come from the analysis of actual field data, not hypothetical estimates.

As a result of the methods employed, the recharge estimates are prone to various errors. Two principal types are identified: 1) an incorrect conceptual model and/or variable estimates regarding the model, and 2) the neglecting (through averaging techniques) of spatial and temporal variability. Conceptual model errors occur when the recharge process is not fully understood, leading to simplifying assumptions regarding the process. In addition, errors regarding variable estimates associated with the conceptual model (such as interception and runoff coefficients) exist. Lack of accuracy in accounting for spatial and temporal variability within the recharge process produces recharge estimates biased by the averaging scheme employed. For this project, mapped outputs represent average recharge rates calculated for relatively large areas (not less than 1 square mile) and standardized to "normal" precipitation trends, ignoring short-term and local variation. The use of recharge data originating from calibrated ground-water flow models attempts to minimize the uncertainty in recharge estimates; since this data results from application of the water budget (balance) process which, in theory, accounts for all water fluxes within the hydrogeologic system. However, because of this approach, the recharge estimates on the final maps are constrained to the scale of the regional models themselves.

Finally, it should be noted that recharge conditions change over time (due to both man-made and natural causes), especially in areas where ground-water levels are very near the land surface.

As ground-water levels fluctuate within an area, the potential for recharge is modified. Under certain conditions, current areas undergoing recharge may be altered to discharge and conversely areas undergoing discharge may become recharge receptive. Thus, any maps depicting recharge estimates are constantly subject to revision.

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Biscayne Aquifer and Surficial Aquifer System

Potential Precipitation Recharge and Excess Precipitation for the Lower East Coast Planning Region: Palm Beach, Broward and Dade Counties

Average Precipitation Recharge

(Rainfall - Runoff - *$ET_{unsaturated}$)

*Considered negligible

- < 21
- 21 - 42
- >= 42

Inches per Year

Range 1 - 60
Mean: 39
Stnd Dev: 8

Average Excess Precipitation

(Rainfall - ET_{actual})

I	< 7
II	7 - 14
III	>= 14

Inches per Year

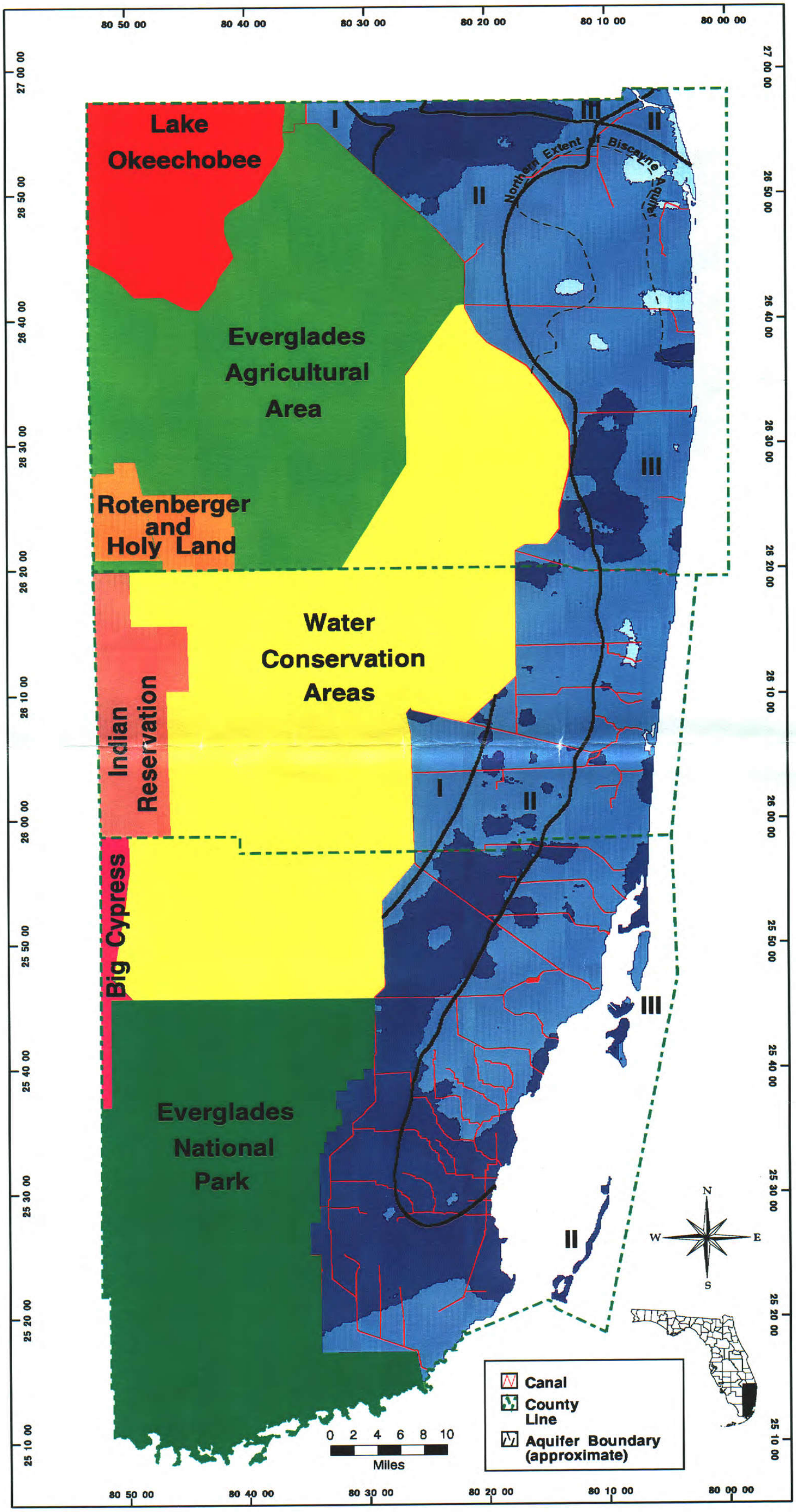
Range: 7 - 20
Mean: 16
Stnd Dev: 3

This recharge map was developed using the District's ARC/INFO geographic information system (GIS) software. Recharge rates were determined principly from data sets extracted from existing numerical ground-water flow models and standardized to reflect long-term average annual precipitation trends. Map coverages portray regional assessments of precipitation recharge and excess precipitation within the shallow unconfined Biscayne aquifer and Surficial aquifer system of the Lower East Coast (LEC) region. As such, the map is intended for use as a regional planning aid for ground-water resource management. It is not intended for site-specific assessments.

Precipitation recharge is defined as the amount of water derived from rainfall that infiltrates the ground surface, moving through the soil to the water table, thereby increasing ground-water storage. Rates are typically calculated as the result of rainfall minus runoff minus unsaturated evapotranspiration (ET) losses; although unsaturated ET loss, considered negligible as compared to saturated ET loss within south Florida, was not accounted for in the compilation of this map.

Precipitation recharge to the Biscayne aquifer and Surficial aquifer system occurs throughout their entire areal extent. However, excess precipitation varies spacially reflecting precipitation trends. Excess precipitation, defined as the difference between long-term average annual rainfall and actual evapotranspiration estimates, represents the amount of residual water potentially available for urban and/or rural supply; assuming runoff as an available component.

This map is Plate I of Technical Publication 95 - 02, (DRE 327), *Mapping Recharge (Infiltration/Leakage) throughout the South Florida Water Management District* (SFWMD).



Surficial Aquifer System

Potential Precipitation Recharge and Excess Precipitation for the Upper East Coast Planning Region: St. Lucie and Martin Counties

This recharge map was developed using the District's ARC/INFO geographic information system (GIS) software. Recharge rates were determined principly from data sets extracted from existing numerical ground-water flow models and standardized to reflect long-term average annual precipitation trends. Map coverages portray regional assessments of precipitation recharge and excess precipitation within the shallow unconfined Surficial aquifer system of the Upper East Coast (UEC) region. As such, the map is intended for use as a regional planning aid for ground-water resource management. It is not intended for site-specific assessments.

Precipitation recharge is defined as the amount of water derived from rainfall that infiltrates the ground surface, moving through the soil to the water table, thereby increasing ground-water storage. Rates are typically calculated as the result of rainfall minus runoff minus unsaturated evapotranspiration (ET) losses; although unsaturated ET loss, considered negligible as compared to saturated ET loss within south Florida, was not accounted for in the compilation of this map.

Precipitation recharge to the Surficial aquifer system occurs throughout its entire areal extent. However, excess precipitation varies spacially reflecting precipitation trends. Excess precipitation, defined as the difference between long-term average annual rainfall and actual evapotranspiration estimates, represents the amount of residual water potentially available for urban and/or rural supply; assuming runoff as an available component.

This map is Plate II of Technical Publication 95 - 02, (DRE 327), *Mapping Recharge (Infiltration/Leakage) throughout the South Florida Water Management District* (SFWMD).

Average Precipitation Recharge

(Rainfall - Runoff - *$ET_{unsaturated}$)

*Considered negligible

- < 28
- 28 - 44
- >= 44

Inches per Year

Range: 14 - 58

Mean: 33

Stnd Dev: 5

Average Excess Precipitation

(Rainfall - ET_{actual})

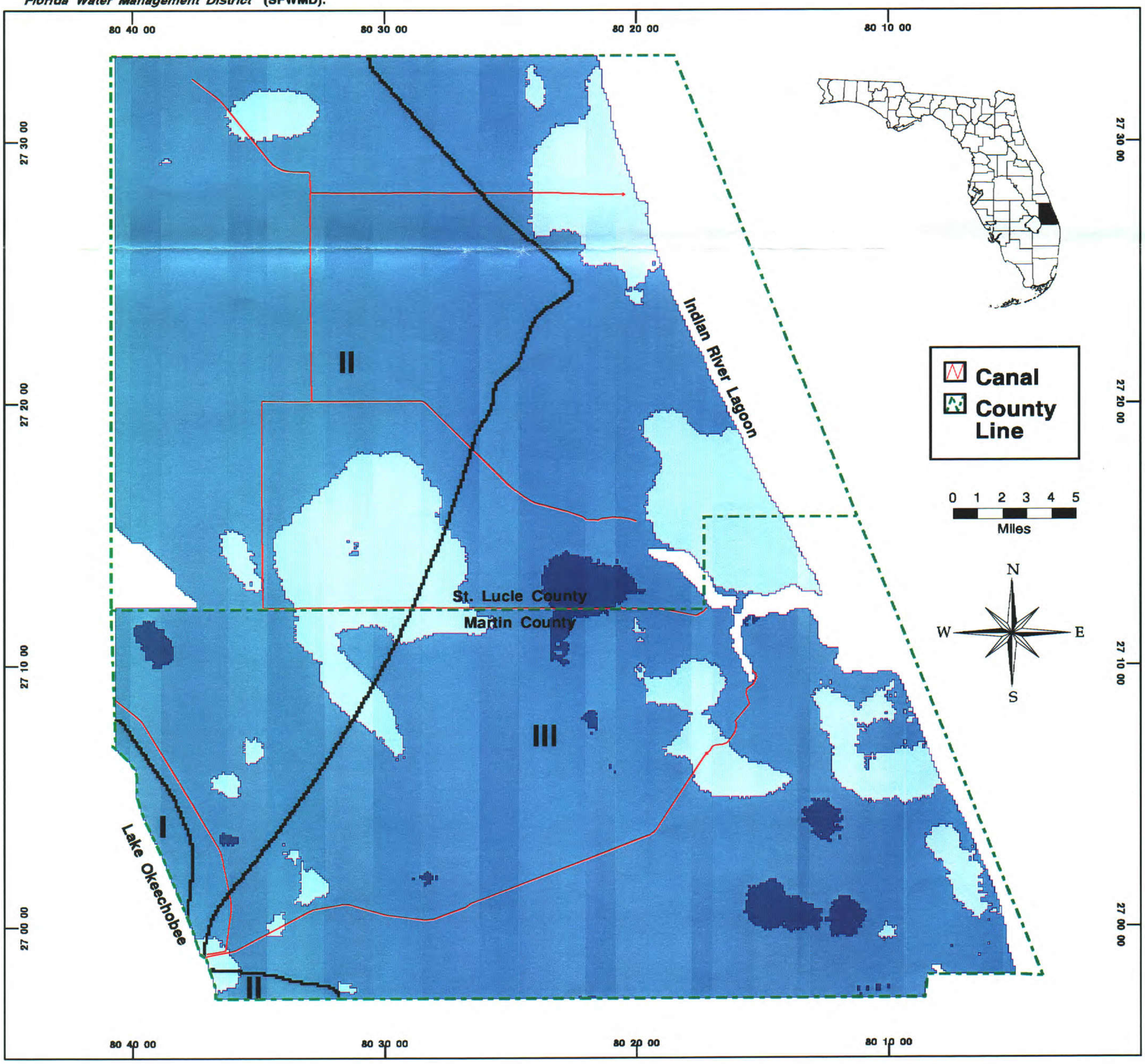
I	< 7
II	7 - 14
III	>= 14

Inches per Year

Range: 0 - 19

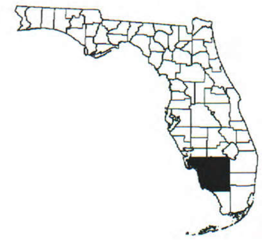
Mean: 14

Stnd Dev: 2



Surficial Aquifer System

Potential Precipitation Recharge and Excess Precipitation for the Lower West Coast Planning Region: Collier, Hendry and Lee Counties



This recharge map was developed using the District's ARC/INFO geographic information system (GIS) software. Recharge rates were determined principly from data sets extracted from existing numerical ground-water flow models and standardized to reflect long-term average annual precipitation trends. Map coverages portray regional assessments of precipitation recharge and excess precipitation within the shallow unconfined Surficial aquifer system of the Lower West Coast (LWC) region. As such, the map is intended for use as a regional planning aid for ground-water resource management. It is not intended for site-specific assessments.

Precipitation recharge is defined as the amount of water derived from rainfall that infiltrates the ground surface, moving through the soil to the water table, thereby increasing ground-water storage. Rates are typically calculated as the result of rainfall minus runoff minus unsaturated evapotranspiration (ET) losses; although unsaturated ET loss, considered negligible as compared to saturated ET loss within south Florida, was not accounted for in the compilation of this map.

Precipitation recharge to the Surficial aquifer system occurs throughout its entire areal extent. However, excess precipitation varies spacially reflecting precipitation trends. Excess precipitation, defined as the difference between long-term average annual rainfall and actual evapotranspiration estimates, represents the amount of residual water potentially available for urban and/or rural supply; assuming runoff as an available component.

This map is Plate III of Technical Publication 95 - 02, (DRE 327), *Mapping Recharge (Infiltration/Leakage) throughout the South Florida Water Management District* (SFWMD).

Average Precipitation Recharge

(Rainfall - Runoff - *$ET_{unsaturated}$)

*Considered negligible

- < 43
- 43 - 56
- >= 56

Inches per Year

Range: 31 - 67

Mean: 47

Stnd Dev: 5

Average Excess Precipitation

(Rainfall - ET_{actual})

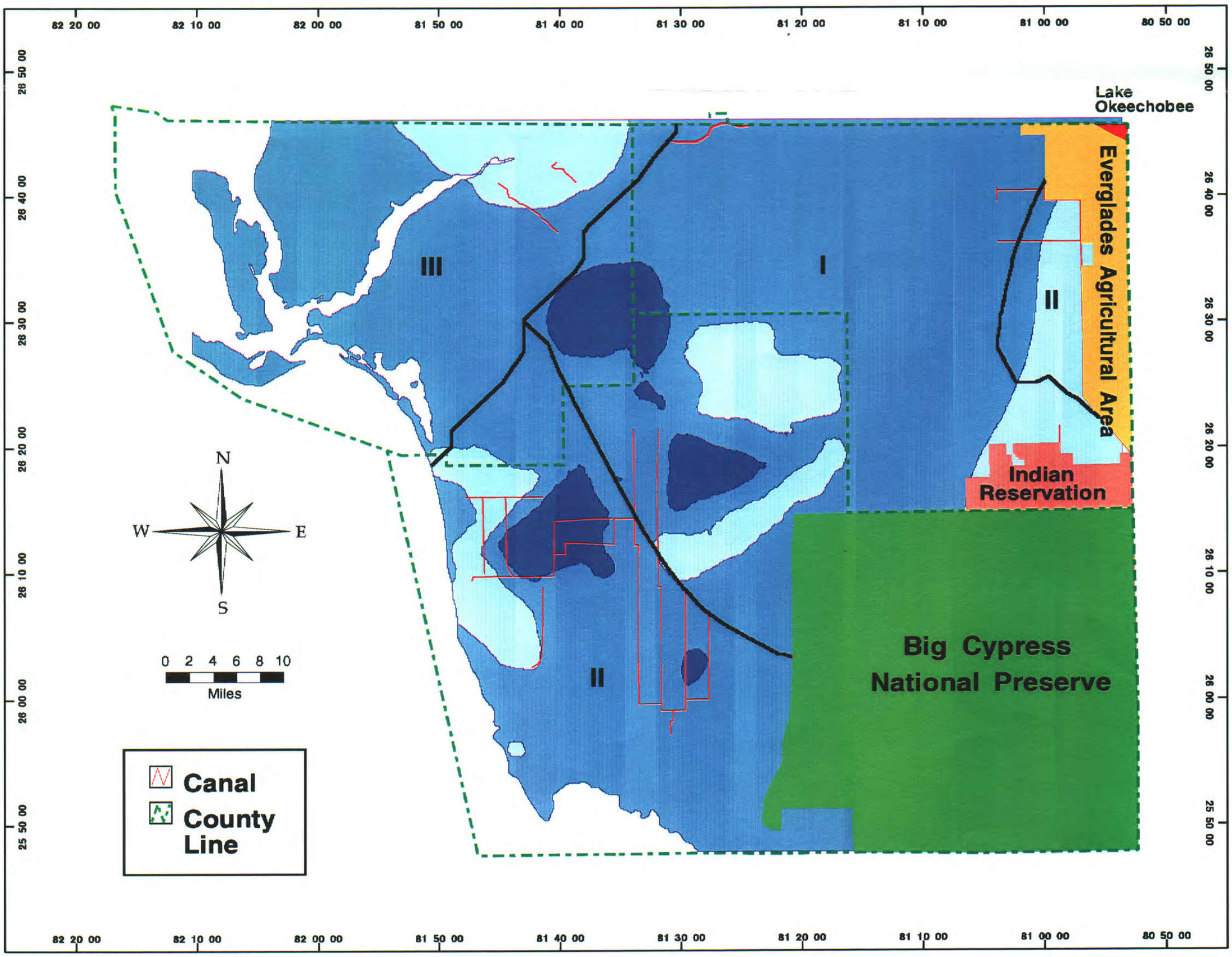
I	< 6
II	6 - 10
III	>= 10

Inches per Year

Range: 3 - 14

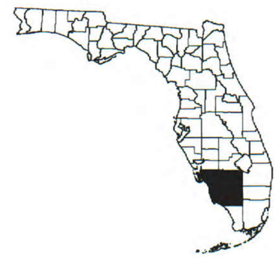
Mean: 7

Stnd Dev: 3



Lower Tamiami Aquifer

Potential Recharge/Discharge for the Lower West Coast Planning Region: Collier, Hendry and Lee Counties



This recharge map was developed using the District's ARC/INFO geographic information system (GIS) software. Leakage rates were determined based on the regional hydraulic pressure differences (averaged over 1992) existing between the lower Tamiami aquifer and the overlying water table, and modeled leakance estimates from the upper confining media separating these aquifer systems. A base year of 1992 was selected because of the close comparison between long-term average basin precipitation and total precipitation for that year. Map coverages portray regional assessments of leakage (recharge/discharge) within the semi-confined lower Tamiami aquifer of the Lower West Coast (LWC) planning region. As such, the map is intended for use as a regional planning aid for ground-water resource management. It is not intended for site-specific assessments.

Leakage is defined as the amount of ground water moving into or out of a confined aquifer through adjacent semi-permeable confining media, thus resulting in the recharge (gain) or discharge (loss) of water to the aquifer system. Rates are typically calculated as the product of hydraulic pressure (head) differences existing between the water bearing unit directly above the aquifer and the aquifer itself, and the leakance of the confining media.

Recharge to the lower Tamiami aquifer occurs in areas where the elevation of the water table within the Surficial aquifer is higher than the elevation of the potentiometric surface displayed within the lower Tamiami aquifer. In these areas, water moves from the Surficial aquifer in a downward direction to the lower Tamiami aquifer, moving through the upper confining media which separates the two.

In contrast, discharge from the lower Tamiami aquifer occurs in areas where the elevation of the potentiometric surface within the aquifer is higher than the elevation of the water table above. In these areas, water moves from the lower Tamiami aquifer in an upward direction, passing through the upper confining media to the overlying unconfined Surficial aquifer system.

This map is Plate IV of Technical Publication 95 - 02, (DRE 327), *Mapping Recharge (Infiltration/Leakage) throughout the South Florida Water Management District* (SFWMD).

Average Recharge
as Diffuse Downward Leakage
(Head Difference x Leakance)

- < 7
- 7 - 14
- 14 - 21
- >= 21

Inches per Year
Range: 0 - 349
Mean: 7
Stnd Dev: 13

Average Discharge
as Diffuse Upward Leakage
(Head Difference x Leakance)

- >= -16
- -32 - -16
- -48 - -32
- < -48

Inches per Year
Range: -167 - -1
Mean: -16
Stnd Dev: 28

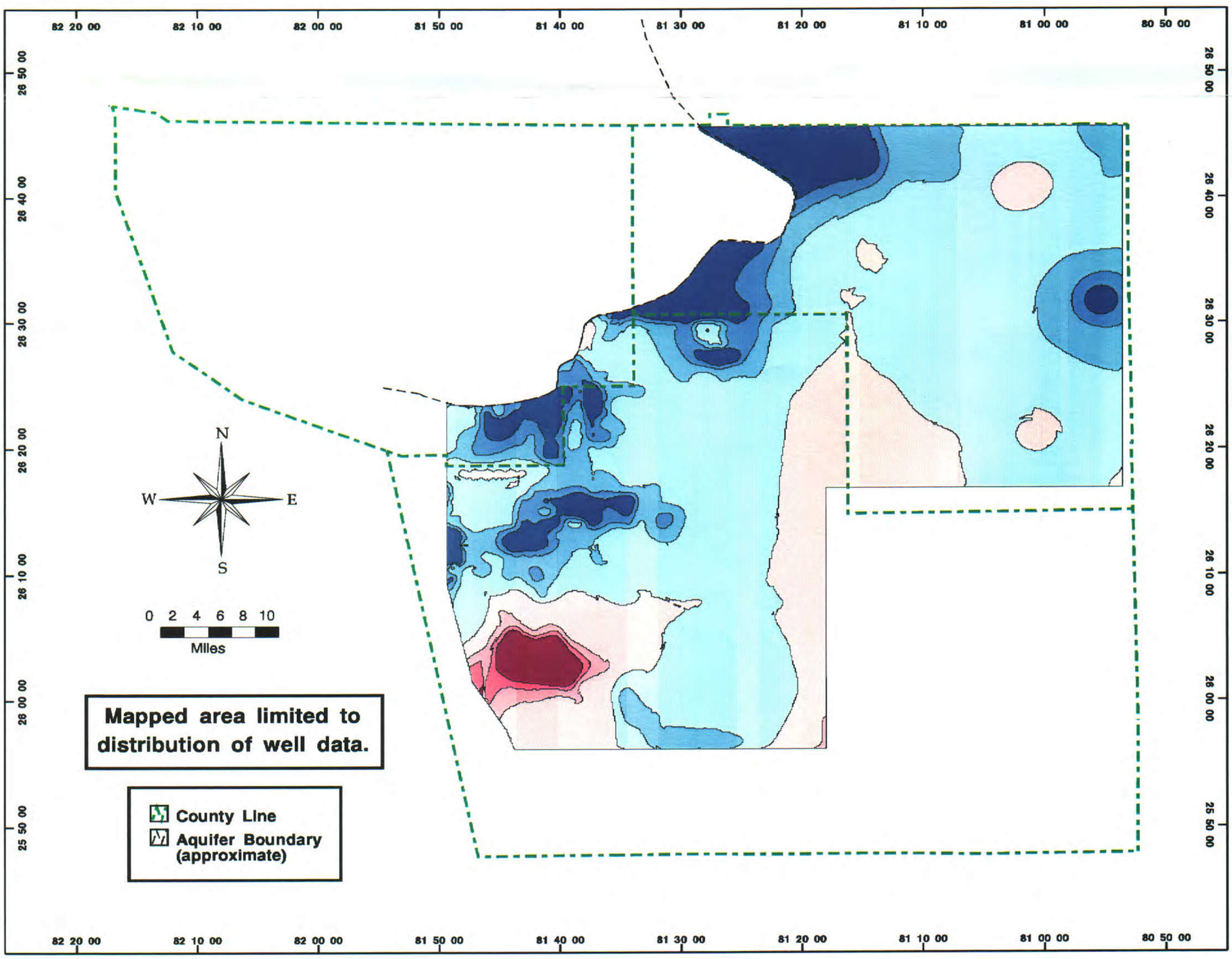


Plate IV

Sandstone Aquifer

Potential Recharge/Discharge for the Lower West Coast Planning Region: Collier, Hendry and Lee Counties

This recharge map was developed using the District's ARC/INFO geographic information system (GIS) software. Leakage rates were determined based on the regional hydraulic pressure differences (averaged over 1992) existing between the Sandstone aquifer and the overlying aquifer (lower Tamiami or unconfined Surficial), and modeled leakance estimates from the upper confining media separating these aquifer systems. A base year of 1992 was selected because of the close comparison between long-term average basin precipitation and total precipitation for that year. Map coverages portray regional assessments of leakage (recharge/discharge) within the semi-confined Sandstone aquifer of the Lower West Coast (LWC) planning region. As such, the map is intended for use as a regional planning aid for ground-water resource management. It is not intended for site-specific assessments.

Leakage is defined as the amount of ground water moving into or out of a confined aquifer through adjacent semi-permeable confining media, thus resulting in the recharge (gain) or discharge (loss) of water to the aquifer system. Rates are typically calculated as the product of hydraulic pressure (head) differences existing between the water bearing unit directly above the aquifer and the aquifer itself, and the leakance of the confining media.

Recharge to the Sandstone aquifer occurs in areas where the elevation of the overlying aquifer is higher than the elevation of the potentiometric surface displayed within the Sandstone aquifer. In these areas, water moves from the overlying aquifer in a downward direction to the Sandstone aquifer, moving through the upper confining media which separates the two.

In contrast, discharge from the Sandstone aquifer occurs in areas where the elevation of the potentiometric surface within the aquifer is higher than the elevation of the aquifer above. In these areas, water moves from the Sandstone aquifer in an upward direction, passing through the upper confining media to the overlying aquifer.

This map is Plate V of Technical Publication 95 - 02, (DRE 327), ***Mapping Recharge (Infiltration/Leakage) throughout the South Florida Water Management District*** (SFWMD).

Average Recharge
as Diffuse Downward Leakage
(Head Difference x Leakance)

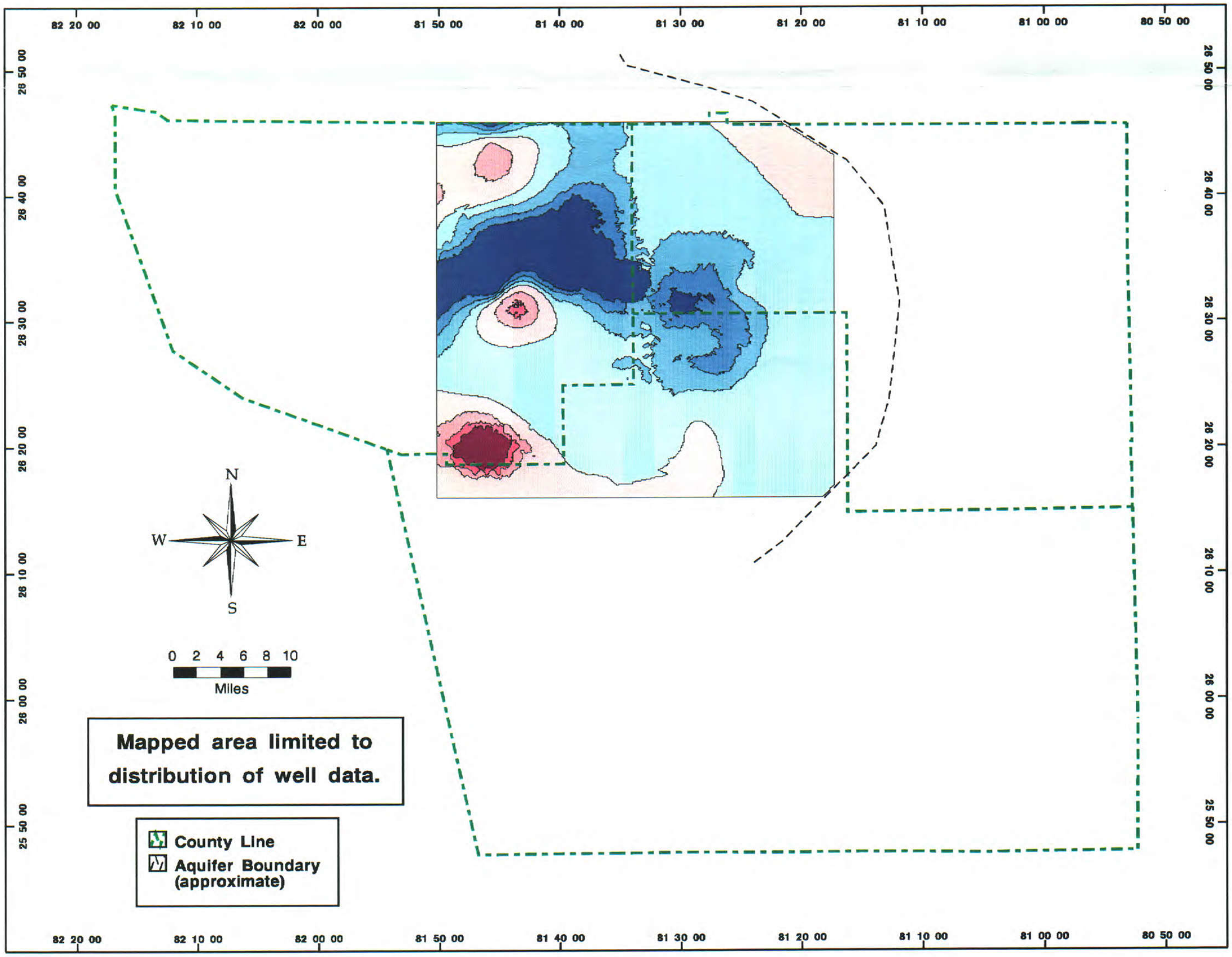
- < 3
- 3 - 6
- 6 - 9
- >= 9

Inches per Year
Range: 0 - 25
Mean: 3
Stnd Dev: 4

Average Discharge
as Diffuse Upward Leakage
(Head Difference x Leakance)

- >= -5
- -10 - -5
- -15 - -10
- < -15

Inches per Year
Range: -41 - -1
Mean: -6
Stnd Dev: 7



Upper Floridan Aquifer

Potential Recharge/Discharge and Excess Precipitation for the Kissimmee Basin Planning Region: Charlotte, Glades, Highlands, Okeechobee, Orange, Osceola and Polk Counties within SFWMD boundaries.

Average Recharge
as Diffuse Downward Leakage
- < 4
- 4 - 8
- >= 8

Inches per Year
Range: 0 - 12
Mean: 3
Stnd Dev: 3

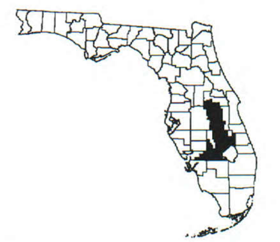
Average Discharge
as Diffuse Upward Leakage
- >= -0.75
- < -0.75

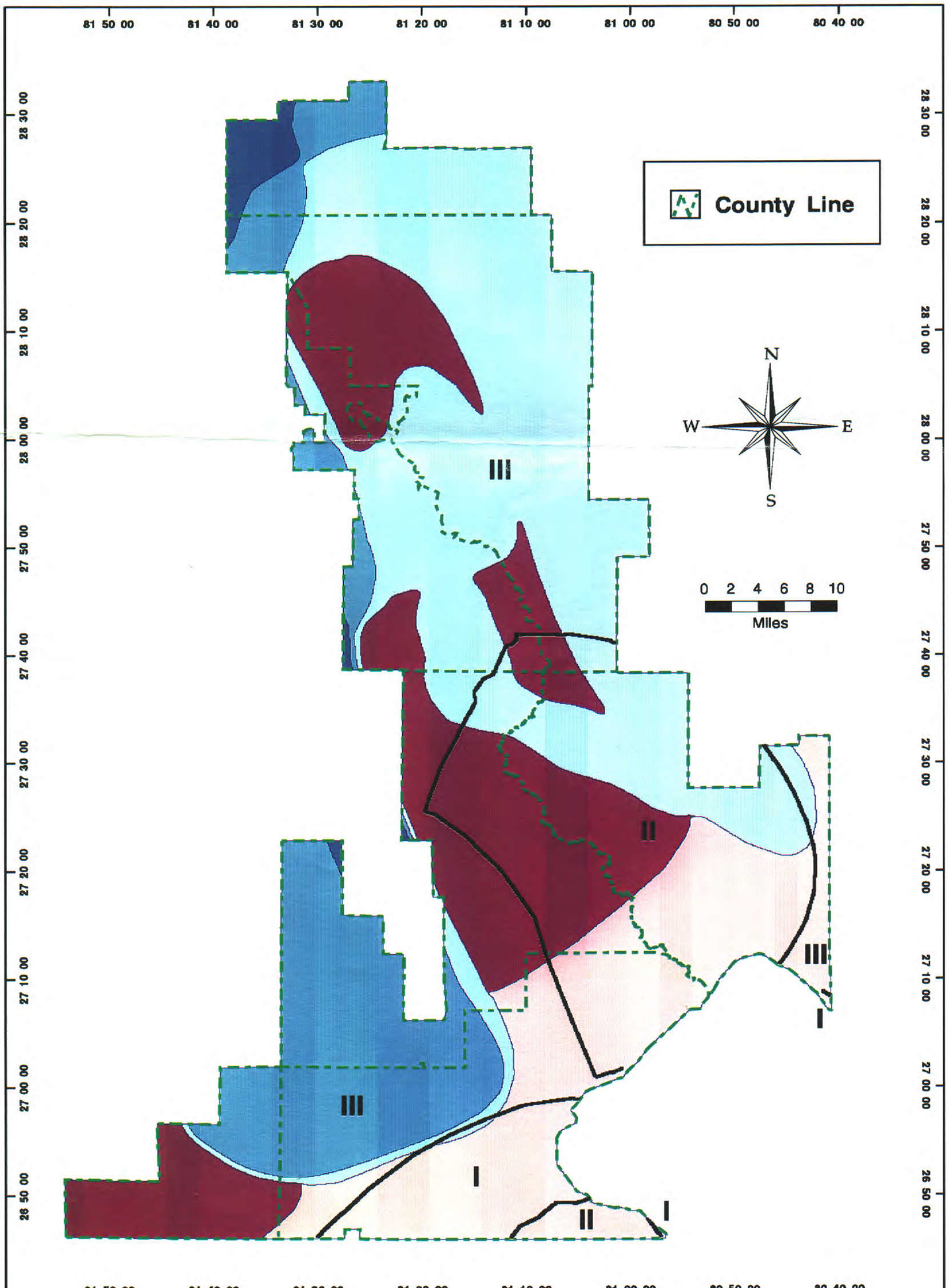
Inches per Year
Range: -1.25 - -0.25
Mean: -0.8
Stnd Dev: 0.5

Average Excess Precipitation
(Rainfall - ET_{actual})

I	< 5
II	5 - 10
III	>= 10

Inches per Year
Range: 0 - 15
Mean: 10
Stnd Dev: 2





This recharge map was developed using the District's ARC/INFO geographic information system (GIS) software. Leakage rates were determined from analysis of two published maps after Bush and Johnston (1988), detailing estimated predevelopment (circa 1930's) recharge/discharge from the upper Floridan aquifer and estimated changes in recharge/discharge due to recent (1980) pumpage. Map coverages portray regional assessments of leakage (recharge/discharge) and excess precipitation within the generally semi-confined to confined upper Floridan aquifer of the Kissimmee Basin (KB) planning region. As such, the map is intended for use as a regional planning aid for ground-water resource management. It is not intended for site-specific assessments.

Leakage is defined as the amount of ground water moving into or out of a confined aquifer through adjacent semi-permiable confining media, thus resulting in the recharge (gain) or discharge (loss) of water to the aquifer system. Rates are typically calculated as the product of hydraulic pressure (head) differences existing between the water bearing unit directly above the aquifer and the aquifer itself, and the leakance of the confining media.

Recharge to the Floridan aquifer occurs in areas where the elevation of the water table within the surficial aquifer is higher than the elevation of the potentiometric surface displayed within the Floridan aquifer. In these areas, water moves from the surficial aquifer in a downward direction to the Floridan aquifer, moving through the upper confining media which separates the two. Recharge also occurs directly from infiltrating rainfall, within small scattered areas to the west - northwest, where the top of the aquifer approaches land surface. The excess precipitation coverage, defined as the difference between long-term average annual rainfall and actual evapotranspiration estimates, provides information regarding the amount of precipitation potentially available for recharge (ignoring surface-water drainage) to the Floridan aquifer in areas such as these.

In contrast, discharge from the Floridan aquifer occurs in areas where the elevation of the potentiometric surface within the aquifer is higher than the elevation of the water table above. In these areas, water moves from the Floridan aquifer in an upward direction, passing through the upper confining media to the overlying surficial aquifer. Some of these discharge areas, especially those located to the south where the elevation of the potentiometric surface exceeds that of the land surface, contain free-flowing artesian wells.

This map is Plate VI of Technical Publication 95 - 02, (DRE 327), ***Mapping Recharge (Infiltration/Leakage) throughout the South Florida Water Management District*** (SFWMD).