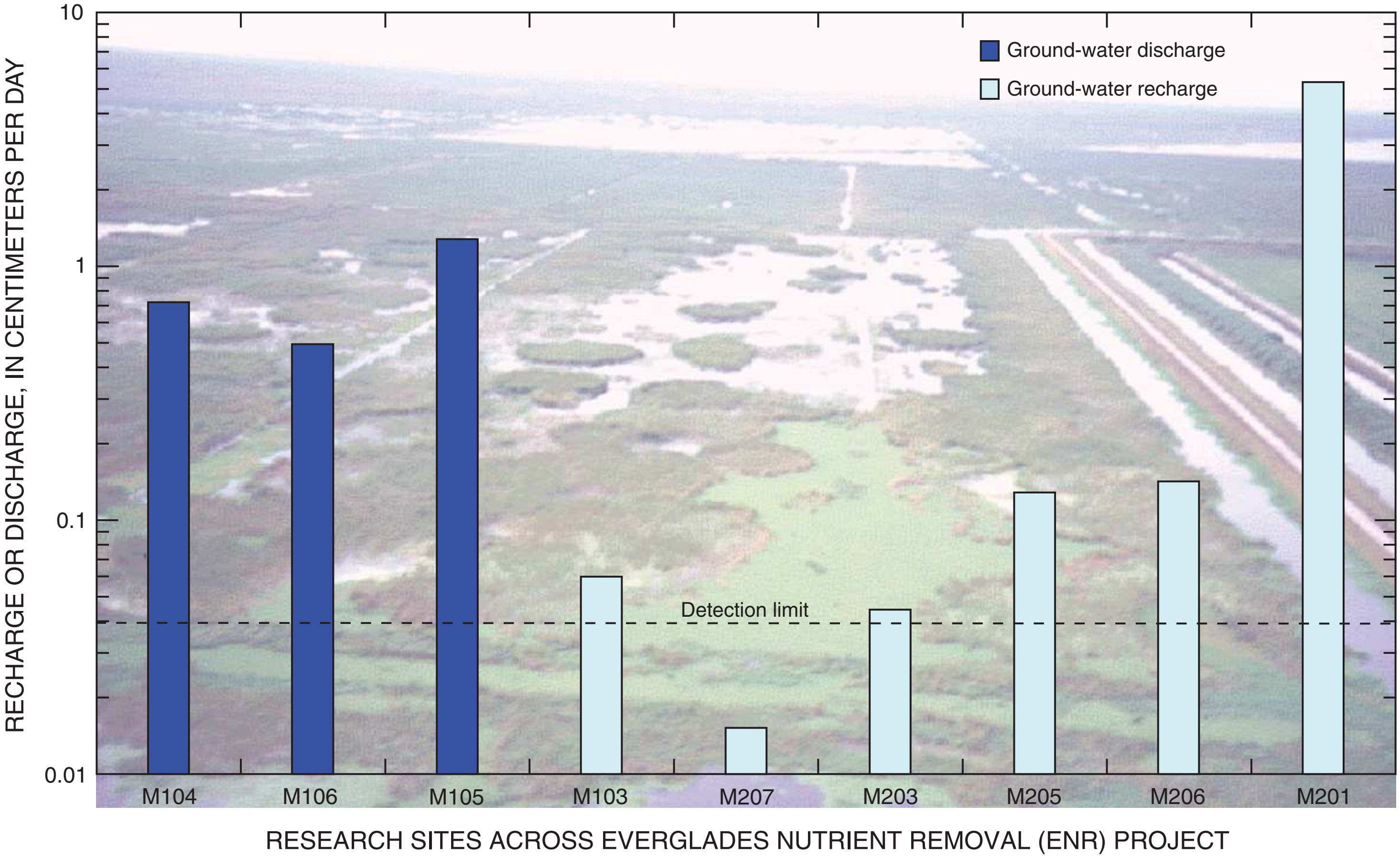
U.S. Department of the Interior
U.S. Geological Survey

In cooperation with

South Florida Water Management District

Interactions between Surface Water and Ground Water and Effects on Mercury Transport in the North-central Everglades

Water-Resources Investigations Report 02-4050



Prepared as part of the

U.S. Geological Survey Place-Based Studies Program

Front Cover: Ground-water discharge and recharge estimates are plotted on top of an aerial photo of the Everglades Nutrient Removal (ENR) project. The view is to the south and shows various plant communities, open water, and remnant canals from the time when this area of the Everglades was farmed. Beyond the canals on the far right is land that still is being farmed.

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

Interactions between Surface Water and Ground Water and Effects on Mercury Transport in the North-central Everglades

By Judson W. Harvey[1], Steven L. Krupa[2], Cynthia Gefvert[1, 2], Robert H. Mooney[3], Jungyill Choi[1], Susan A. King[4], and Jefferson B. Giddings[2]

[1]U.S. Geological Survey, Reston, Virginia
[2]South Florida Water Management District, West Palm Beach, Florida
[3]U.S. Geological Survey, Miami, Florida
[4]U.S. Geological Survey, Middleton, Wisconsin

Water-Resources Investigations Report 02-4050

In cooperation with

South Florida Water Management District

Reston, Virginia
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, *Secretary*

U.S. GEOLOGICAL SURVEY
Charles G. Groat, *Director*

For additional information write to:

Judson Harvey
U.S. Geological Survey
430 National Center
Reston, VA 20192
jwharvey@usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Federal Center
Denver, CO 80225-0286

Harvey and others—Interactions between Surface Water and Ground Water and Effects on Mercury Transport in the North-central Everglades—WRIR 02-4050

CONTENTS

FIGURES

24-25. Diagrams showing:

26-33. Graphs showing:

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
foot (ft)	30.48	centimeter (cm)
mile (mi)	1.609	kilometer (km)
	Area	
acre (ac)	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
foot per day (ft/d)	30.48	centimeter per day (cm/d)
	Hydraulic conductivity	
foot per day (ft/d)	30.48	centimeter per day (cm/d)

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

Hydraulic Conductivity: The standard unit for hydraulic conductivity is volume per time per unit cross-sectional area of sediment, such as $ft^3/(ft^2d)$. In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

Abbreviated water-quality units used in this report: Constituent concentrations, water temperature, and other water-quality measures are given in metric units. Constituent concentrations are given in milligrams per liter (mg/L), or nanograms per liter (ng/L).

Specific conductance (SC) of water is given in microsiemens per centimeter at 25 degrees Celsius (mS/cm at 25°C). The unit is equivalent to micromhos per centimeter at 25 degrees Celsius (mmho/cm), a unit formerly used by the U.S. Geological Survey.

Additional abbreviations:
inches (in)
millimeter (mm)
micron (µ)
milliliter (ml)
grams per year (g/yr)
inches per mile (in/mi)
ohm-meters (ohm-m)

Interactions between Surface Water and Ground Water and Effects on Mercury Transport in the North-central Everglades

By Judson W. Harvey, Steven L. Krupa, Cynthia Gefvert, Robert M. Mooney, Jungyill Choi, Susan A. King, and Jefferson B. Giddings

ABSTRACT

The hydrology of the north-central Everglades was altered substantially in the past century by canal dredging, land subsidence, ground-water pumping, and levee construction. Vast areas of seasonal and perennial wetlands were converted to uses for agriculture, light industry, and suburban development. As the catchment area for the Everglades decreased, so did the sources of water from local precipitation and runoff from surrounding uplands. Partly in response to those alterations, water-resources managers compartmentalized the remaining wetlands in the north-central Everglades into large retention basins, called Water Conservation Areas (WCAs). In spite of efforts to improve how water resources are managed, the result has been frequent periods of excessive drying out or flooding of the WCAs because the managed system does not have the same water-storage capacity as the pre-drainage Everglades. Linked to the hydrological modifications are ecological changes including large-scale invasions of cattail, loss of tree islands, and diminishing bird populations in the Everglades. Complex interactions among numerous physical, chemical, and biological factors are responsible for the long-term degradation of the ecological character of the Everglades.

Over the past 15 years, a new set of smaller wetland basins, called Stormwater Treatment Areas (STAs), have been designed and constructed by water-resources engineers on the former wetlands adjacent to WCAs. The purpose of STAs is to remove excess nutrients from agricultural drainage water prior to its input to WCAs. STAs tend to be about one-tenth the size of a WCA, and they are located on former wetlands on the northwestern side of WCAs on sites that were managed as farmland for much of the twentieth century in an area referred to as the Everglades Agricultural Area, or EAA.

The objective of the present investigation was to quantify interactions between surface water and ground water in the Everglades Nutrient Removal Project (ENR), a prototype project for the STAs that began operation in 1994. Determining the effect of ground water on the mercury balance of the ENR treatment wetland was an important additional objective. In order to broaden the relevance of conclusions to all parts of the north-central Everglades, interactions between surface water and ground water and mercury also were investigated in Water Conservation Area 2A (WCA-2A) and, to a lesser extent, in two other WCA basins, WCA-2B and WCA-3A.

An important conclusion of this study is that creation of the WCA basins, and accompanying water-resources management, have appreciably increased both recharge and discharge in the north-central Everglades compared with pre-drainage conditions. Recharge and discharge are highest near the northern and northwestern edges of the Everglades, in the relatively small basins such as ENR and the STAs that share borders with both WCA-1 and the EAA. All basins experienced greater increases in recharge relative to discharge, because of the effects that land subsidence and ground-water pumping outside the Everglades had on hydraulic gradients. The highest basin-wide estimate of recharge was measured in ENR, where recharge averaged 0.9 centimeter per day (cm/d) over a 4-year study period. For perspective, that estimate of recharge is the equivalent of 30 percent of pumped

surface-water inflows and 230 percent of average daily precipitation in ENR. Ground-water discharge was 10 times smaller than recharge at ENR. The present study estimated a basin-averaged recharge for WCA-2A (0.2 cm/d) that was a factor of 4 smaller than ENR. Although preliminary, that estimate of recharge is 5 times higher than previous estimates (approximately 0.04 cm/d), probably because the newer measurements were able to quantify recharge and discharge at finer spatial and temporal scales. Recharge at WCA-2A is smaller than ENR because WCA-2A has a smaller topographic gradient (3×10^{-5} and 2×10^{-4} in WCA-2A and ENR, respectively), as well as a smaller ratio of perimeter length to total wetland surface area (6×10^{-5} and 4×10^{-4} in WCA-2A and ENR, respectively), which decreases the importance of processes outside the wetlands such as land subsidence or ground-water pumping. At the present time, recharge and discharge are thought to be higher in the WCAs compared to the pre-drainage Everglades (perhaps by a factor of 4 or 5), although that comparison is uncertain because of the difficulty of estimating pre-drainage hydrologic fluxes. The reason that recharge and discharge are thought to be higher now compared to pre-drainage conditions is that water-resources management has increased fluctuations in surface-water levels. The present study showed that the magnitude of recharge and discharge, as well as temporary reversals between recharge and discharge, are related to increased surface-water fluctuations caused by large water releases from WCA-1 into WCA-2A.

The most important geologic factor affecting interactions between surface water and ground water in the north-central Everglades is the hydraulic conductivity (*K*) of the Surficial aquifer. Estimates of *K* in the top 40 feet (ft) of the aquifer at both ENR and WCA-2A are higher (by more than an order of magnitude) than previously published estimates of *K* for the northern Everglades (typically, reported as 5 ft/day). Finding higher than anticipated hydraulic conductivities in the upper sand and limestone layers of the Surficial aquifer has important implications. In particular, it was found that the upper sand and limestone layers with high permeability are the main parts of the aquifer with appreciable freshwater. Sampling of major-ion chemistry in ground water showed that freshwater was usually located only at shallow depths, approximately the top 40 ft of the 200-ft deep Surficial aquifer. Hydraulic and chemical results, therefore, indicate that in many areas of the north-central Everglades, interactions between surface water and ground water primarily involve the top layers (layers 2 and 3) of the Surficial aquifer, causing appreciable recharge and discharge to a depth of approximately 40 ft.

Geochemical measurements provided further information about the source of the thin layer of fresh ground water beneath the north-central Everglades. Water-stable isotopic ratios of hydrogen and oxygen showed that the source of fresh ground water was recharge of Everglades surface waters, specifically, recharge of surface waters from wetland sloughs that had been present long enough in the surface flow system to be substantially evaporated. An exception was the portion of the aquifer beneath the interior of ENR, where stable isotopes indicated that recharge occurred quickly and without appreciable evaporation. This result, along with the distinct ionic signature of the water, is consistent with an interpretation that the source of recharging water beneath ENR was precipitation onto ENR during the time period it was managed for agricultural purposes. The "light" stable isotopic composition of that water indicates that precipitation infiltrated quickly through the unsaturated zone without appreciable evaporation. Another exception is apparent in ground water near levees. The amount and type of salts in ground water in the vicinity of levees indicate that ground-water seepage beneath the levee causes deep mixing in the Surficial aquifer that results in upward movement of relict seawater from the bottom two-thirds of the aquifer (below 60 ft) to shallow ground water and to wetland surface water.

Part of the motivation for the present study was a concern that arose among the water-resources managers that designed the ENR treatment wetland. The concern was whether mercury methylation, and, thus, mercury bioavailability, might increase when agricultural soils were re-flooded and managed once again as wetlands. The present study complements the work of many other mercury investigators in the Everglades by specifically addressing the effect of interactions between surface water and ground water on mercury cycling.

Total dissolved mercury (Hg_T) was detectable in all monitoring wells in ENR and WCA-2A at an average concentration of 0.7 nanogram per liter (ng/L), which is slightly below the average concentration in surface water (1 ng/L). An important exception was shallow wells on the western side of ENR, where the average concentration was 40 percent higher (1.4 ng/L) than surface water. Higher concentrations of Hg_T in ground water on the western side of ENR was the result of recharge from ENR surface water combined with release of Hg_T from solid phases in peat to recharging water. Dissolved methylmercury (MeHg) in ground water was undetectable in all deep wells (greater than 40 ft deep) and most shallow wells (less than 0.02 ng/L compared with 0.1 ng/L in ENR surface water). Shallow wells beneath the interior of ENR were the exception, with detectable MeHg concentrations as high as 0.2 ng/L. Wells with detectable MeHg are of interest because they are the same wells classified by water-stable isotopes and major ion chemistry as "agricultural recharge water." In general, Hg_T and MeHg concentrations were not positively correlated with sulfate concentrations at either ENR or WCA-2A.

A budget was developed for ground-water fluxes of mercury at ENR, which made possible a comparison with the surface and atmospheric components of the mercury budget for ENR developed by other researchers. Recharge of Hg_T from surface water to ground water was a major pathway for transport of total dissolved mercury but not MeHg. Recharge of Hg_T accounted for a loss from ENR surface water equivalent to 10 percent of the total inputs of Hg_T to surface water. In comparison, recharge of MeHg was not detectable and accounted, therefore, for none of the losses of MeHg from surface water in ENR.

Chemical data and water-stable isotopic ratios indicate that most surface water recharged in ENR is discharged to a seepage canal on the western and northern side of ENR. Transport of recharged water through the Surficial aquifer to the seepage canal appears to take place in a matter of weeks to months, with only relatively minor mixing with deeper ground water. Measurements of Hg_T in the seepage canal suggested that Hg_T had not yet discharged to the canal at the end of the 4-year study period. Because the flow path between points of recharge in ENR and discharge in the seepage canal was short, it was concluded that mercury was retained or delayed in its transport through the aquifer by interaction with aquifer sand or limestone or fine organic sediments at the base of the seepage canal.

INTRODUCTION

Surface-water resources in the Florida Everglades are managed to accommodate a rapidly growing urban area to the east and an agricultural industry operating in former wetlands to the northwest. Management of the north-central Everglades for flood control and water supply has changed the character of flow in the wetlands. Since the 1960s, the wetlands have been divided into large artificial basins called Water Conservation Areas (WCAs) that are fed by drainage from Lake Okeechobee, runoff from the Everglades Agricultural Area (EAA), rainfall, and ground-water discharge directly into wetlands or canals that overflow into the wetlands. Surface water flows from one conservation area to the next, moving southward through the wetlands, canals, culverts, and spillways, eventually into Florida Bay or the Gulf of Mexico (fig. 1). Along the way, surface flow may be depleted by evapotranspiration or by recharge to ground water. A portion of the surface water in the Everglades replenishes ground water that will be withdrawn later for domestic use from well fields to the east of the Everglades. In other areas, recharge contributes to high water tables and seepage problems for housing developments located just east of the Everglades. During wet periods in south

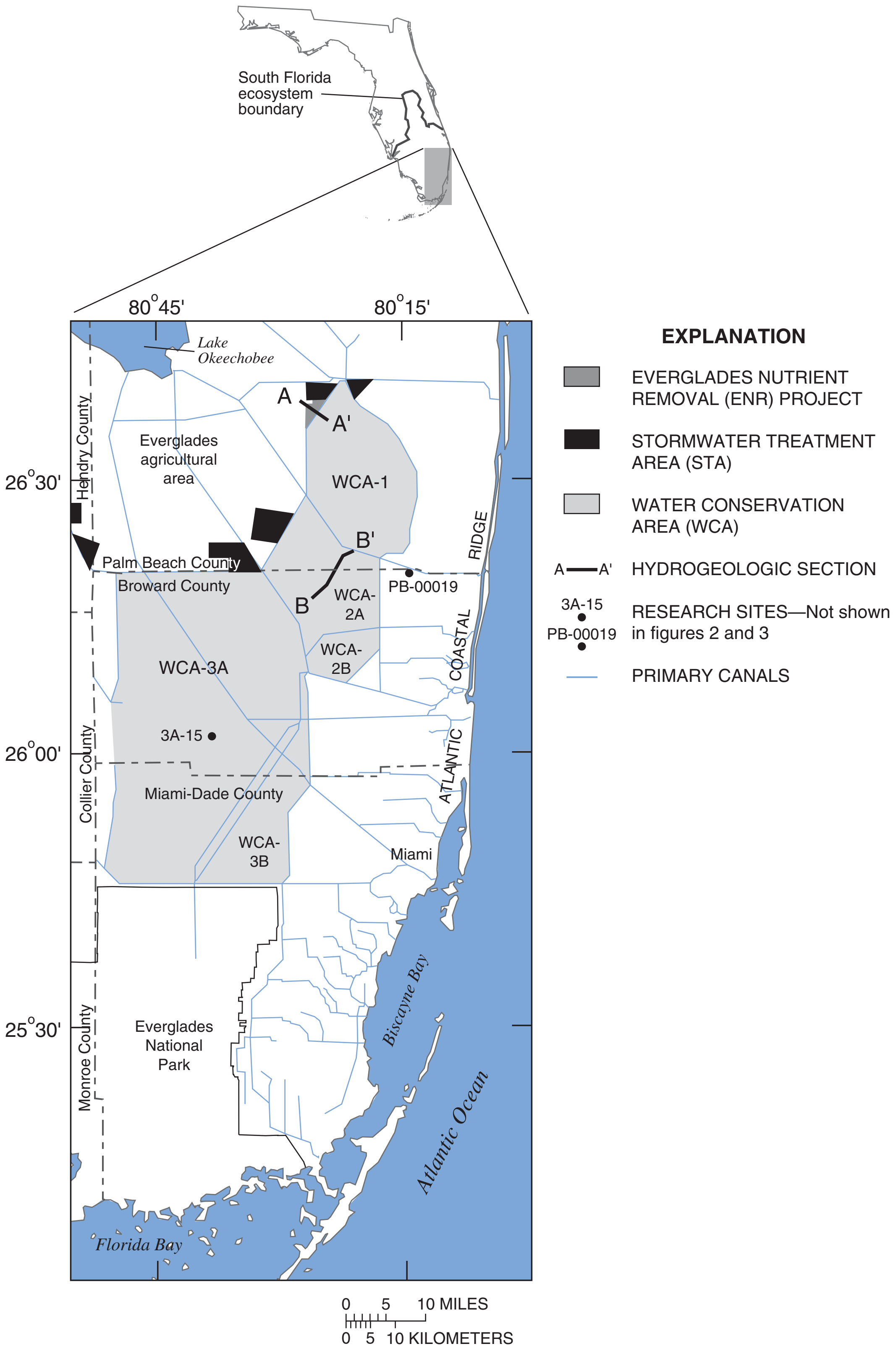


Figure 1. Central Everglades and adjoining areas, south Florida, showing locations of Water Conservation Areas (WCA), Everglades Nutrient Removal (ENR) project, and Stormwater Treatment Areas (STA). Southwestern coastal areas of Everglades in Monroe County are not shown.

Florida, a large amount of surface water moves eastward through canals and discharges directly to the Atlantic Ocean.

Concern has been growing for many years in south Florida over the long-term decreases in surface water flowing through the Everglades, and the effects of these decreased flows on wildlife within Everglades National Park (ENP). Simultaneous to the decreasing surface flow, there has been increasing awareness of the deteriorating surface-water quality in WCAs and accompanying changes in the ecology of the wetlands. Ecological changes include disappearance of tree islands, proliferation of cattails, and loss of wading bird populations. In the past 20 years, these concerns have fueled wide-ranging discussions on how to improve water management in the Everglades in a way that would restore proper ecosystem function. In 2000, Congress approved a plan for restoration of the Everglades, referred to as the Comprehensive Everglades Restoration Plan or CERP. The overall goal of CERP is to restore some of the pre-drainage conditions, including the overall volume of surface flow, and characteristics of the depth, duration, and flow patterns of surface water. Restoration objectives also include reducing excessive inputs of dissolved nutrients and other constituents that could have deleterious effects on biogeochemical processes and ecological characteristics in the Everglades (McPherson and Halley, 1996; South Florida Water Management District, 1995; Stober and others, 1996; Gerould and Higer, 1995).

Evaluating the success of ongoing management and restoration efforts depends on reliable hydrologic information, including a better understanding of interactions between surface and ground water. One of the major initiatives already underway is the extensive rerouting of surface-water inflows to WCAs so that water first passes through Stormwater Treatment Areas (STAs) to remove excess nutrients before water enters the WCAs. A concern regarding the function of STAs is their potential effect in mobilizing toxic forms of mercury. Addressing that concern required considerable effort on the part of the South Florida Water Management District and cooperating agencies (Florida Department of Environmental Protection, U.S. Geological Survey, and others). One difficulty in developing a reliable mercury mass balance for STAs is uncertainty about how mercury is affected by interactions between surface water and ground water.

In an effort to learn more about interactions between ground water and surface water in the Everglades, the U.S. Geological Survey (USGS) and the South Florida Water Management District (SFWMD) developed an agreement to undertake a detailed study of interactions between surface water and ground water in selected areas of the north-central Everglades. The study would provide insight about the effect of interactions between ground water and surface water and chemical balances of STAs and WCAs. Investigations of surface and ground-water interactions were focused in two principal areas. The first area was the 3,815-acre Everglades Nutrient Removal Project (ENR), a prototype STA. The second area was Water Conservation Area 2A (WCA-2A), a 105,000-acre basin with a long history of ecological research on the changing character of the Everglades.

Purpose, Scope, and Source of Funding

The purpose of this report is to interpret results and develop final conclusions of an investigation of surface-water and ground-water interactions and their effect on the mercury budget in the north-central Everglades. The overall goals of the project were to:

1.) quantify ground-water recharge and discharge in the ENR and WCA-2A,
2.) determine relative importance of geologic, climatic, and water-resources management in affecting ground-water recharge and discharge, and
3.) use improved estimates of ground-water recharge and discharge to develop accurate hydrologic budgets and chemical mass balances for mercury in the two areas.

A previous report (Harvey and others, 2000) contains detailed study methods and complete data sets covering all topics, including borehole drilling, geophysical measurements, sampling of ground-water geochemistry, and design and operation of shallow piezometers and seepage meters. The present report and the report by Harvey and others (2000) constitute the final deliverables for Cooperative agreement C-6661 between USGS and the South Florida Water Management District. Funding for the investigation also came from the USGS Place-Based Studies Program.

Hydrologic Setting: Characteristics of Pre- and Post-drainage Everglades

A thorough investigation of Everglades hydrology requires an understanding of the pre-drainage hydrologic system. The pre-drainage Everglades received water primarily from direct rainfall, periodic overflow from Lake Okeechobee, and runoff from surrounding pine flatwoods and other upland systems (Gleason and Stone, 1994). In addition, the slough systems of the Everglades probably received ground-water discharge and shallow subsurface runoff from the adjacent low-lying pinelands.

The driving force for water flow in the Everglades is the water-surface slope, which is controlled by the regional topographic gradient. In the pre-drainage Everglades, the topographic gradient was a relatively consistent 2 inches per mile (in/mi), with only minor undulations of the natural landscape affecting water flow. Topography varied across the full (pre-drainage) width of the north-central Everglades (approximately 50 mi). On the western side of the Everglades, a major slough system was present that graded into a broad sawgrass plain in the central area, back into another major slough system on the east side. Microtopography in the sloughs consisted of alternating ridge and slough systems with typical spacing of approximately 0.5 mi.

Changes in topography (for example, because of subsidence or construction of levees) or water levels (because of canal drainage) easily perturb the direction of water flow in the Everglades. Canal construction and drainage began to modify water levels and topography substantially in the northern and north-central parts of the Everglades beginning about 1912. The initial effort was to construct four major north-south canals to drain water to the Atlantic Ocean. Early canal drainage in the Everglades Agricultural Area (EAA) led to excessive oxidation of the peat in the vast sawgrass plain and swamp forest directly south of Lake Okeechobee. Drainage and oxidation eventually caused between 3 and 10 ft of subsidence in the agricultural area over the past century. Subsidence and continual pumping in the EAA to keep agricultural fields dry have had the effect of reversing the horizontal direction of ground-water flow in some areas of the Everglades. Where ground water once flowed toward the southeast, it presently flows toward the northwest (Miller, 1988).

Drainage canals continue to be the primary water-management effort in the north-central Everglades. During excessively wet conditions, the major drainage canals shunt excess water from Lake Okeechobee or the EAA to the Atlantic Ocean (fig. 1). Under more typical wet-season conditions, drainage canals deliver and store water in the WCAs. East of the Everglades the canals have various functions, including drainage of the low-lying pinelands and aquifer recharge to balance losses by ground-water pumping. Interactions between surface flow in canals and ground water have been frequently investigated in south Florida (Miller, 1978: Chin, 1990; Genereux and Slater, 1999; Nemeth and others, 2000, Bolster and others, 2001).

The conversion of wetlands to agriculture compressed the northern part of the Everglades to approximately one-third its pre-drainage width. By the 1950s, it was apparent that the canals were too effective in draining wetlands that were becoming increasingly important for sustaining water supply to the newly formed Everglades National Park, and to the growing population along the Florida Atlantic Coast. Construction of levees during the 1950s and early 1960s began to enclose the large basins now known as the WCAs. These areas are large levee-enclosed basins that encompass only the easternmost part of the pre-drainage system. WCAs were designed for multiple purposes, including storage for later delivery to Everglades National Park, and protection from flooding for the drained areas just outside the wetlands. The WCAs are all that remain of the north-central Everglades and their construction and management have had substantial effects on surface- and ground-water flow in Palm Beach and Broward Counties (fig. 1).

Under pre-drainage conditions, surface flow in the Everglades was augmented by substantial shallow runoff from the surrounding uplands. Under water management, the water levels outside the WCAs normally are maintained at lower levels than inside the WCAs, which causes net recharge from surface water to ground water in the WCAs (Miller, 1988). Seepage losses resulting from flow of recharged water beneath levees represent an important component of water loss from the WCAs. Seepage appears to be greatest along the eastern and northwestern borders of the WCAs, where land is now being managed for a variety of uses, including agriculture, light industry, or suburban development (Miller, 1988). Water losses from the Everglades by seepage were large enough that they became obvious almost as soon as the levee-construction method was tested in the 1950s (U.S. Army Corps of

Engineers, 1952). Seepage at many of the Everglades levees began to be widely investigated beginning in the 1960s (Klein and Sherwood, 1961; Swayze, 1988; Genereux and Guardiario, 1998; Nemeth and others, 2000, Sonenshein, 2001). Although often less studied, seepage flow also occurs beneath the levees that separate WCAs (Harvey, 1996; Harvey and others, 2000). Because recharge now occurs at locations where formerly the Everglades gained water from shallow runoff and ground-water discharge, seepage losses have become one of the most important unintended side effects of water management in the north-central Everglades.

Another factor associated with water management that may have affected surface-water and ground-water interactions is the increasing fluctuations of surface-water-levels in the WCAs compared with pre-drainage conditions. From the 30-year comparative simulations of the South Florida Water Management Model (SFWMM) and Natural System Model (NSM), surface-water-level fluctuations under pre-drainage conditions appear to be from 50 to 75 percent of present day fluctuations. As shown in the present study, the increased water-level fluctuations in WCAs drive recharge and discharge in interior areas of the wetlands far from levees.

Site Information

The study described within this report was conducted in the following area: Everglades Nutrient Removal Project (ENR), Water Conservation Area 2A or 2B (WCA-2A or 2B), or in Water Conservation Area 3A (WCA-3A). Measurements were made at 17 sites in ENR, 7 sites in WCA-2A, and 1 site each in WCA-2B and WCA-3A (figs. 1, 2, and 3). Specific locations for study were chosen both to satisfy the need for broad spatial coverage, as well as to co-locate study activities with previous or ongoing ecological investigations. The most comprehensive sets of measurements were conducted in the ENR and in WCA-2A. Two or more seepage meters were used to measure vertical water fluxes across the sediment surface at all the interior wetland sites. Most of the sites (10 sites at the ENR and 7 sites at WCA-2A) also had one or more research wells emplaced in the Surficial aquifer underlying the Everglades, and a surface-water recorder.

Everglades Nutrient Removal Project

Although the ENR is a large, constructed wetland (3,815 acres), it is relatively small compared to the WCAs that generally are more than 100,000 acres. The land encompassed by the ENR was formerly part of the historical Everglades. It was drained and farmed beginning in the mid-1900s up until construction of the ENR beginning in 1989. The purpose of the ENR was to test the capacity of a constructed wetland (with controlled hydrology, and managed aquatic and emergent wetland plants) to remove nutrients from agricultural drainage waters (fig. 2). The ENR project area is located on the western border of WCA-1, where water levels are maintained at high elevations. Located to the west of the ENR is the Everglades Agricultural Area (EAA), where land is drained to maintain a low water table for agriculture. Drainage is accomplished by a system of canals that transports the water southward into the WCAs. Guardo and Tomasello (1995) and Guardo (1999) modeled surface-water hydrodynamics and calculated water-balance fluxes and hydrologic residence times for the ENR project. Preliminary work showed that both ground-water recharge and discharge are important components of ground-water interactions at ENR (Harvey, 1996). This is important because of the overall steep gradient and step-changes in hydraulic head over a distance of 5–10 mi from WCA-1 (where water levels are approximately 14 ft above sea level) to the EAA (where water levels are approximately 8 ft above sea level) (fig. 2). Abtew and Mullen (1997) developed initial estimates of net seepage in ENR as part of determining a project-wide water balance. Hydrogeologic investigations within the ENR project included geotechnical investigations for levee and pump station footings (Burns and McDonnell, 1991; Hutcheon Engineers, 1996) and two studies of seepage under the levees (Hutcheon Engineers, 1996; Rohrer, 1999).

Water Conservation Area 2A

WCA-2A is located to the south-southeast of ENR (fig. 1). Similar to ENR, WCA-2A shares a boundary with WCA-1 and is affected by the high water levels that are maintained in WCA-1. WCA-2A is 25 times larger in area (105,000 acres) than ENR, and therefore, is less likely to be affected by ground-water interactions that result from levee underflow. The construction of levees that eventually surrounded WCA-2A began in about 1920. By about

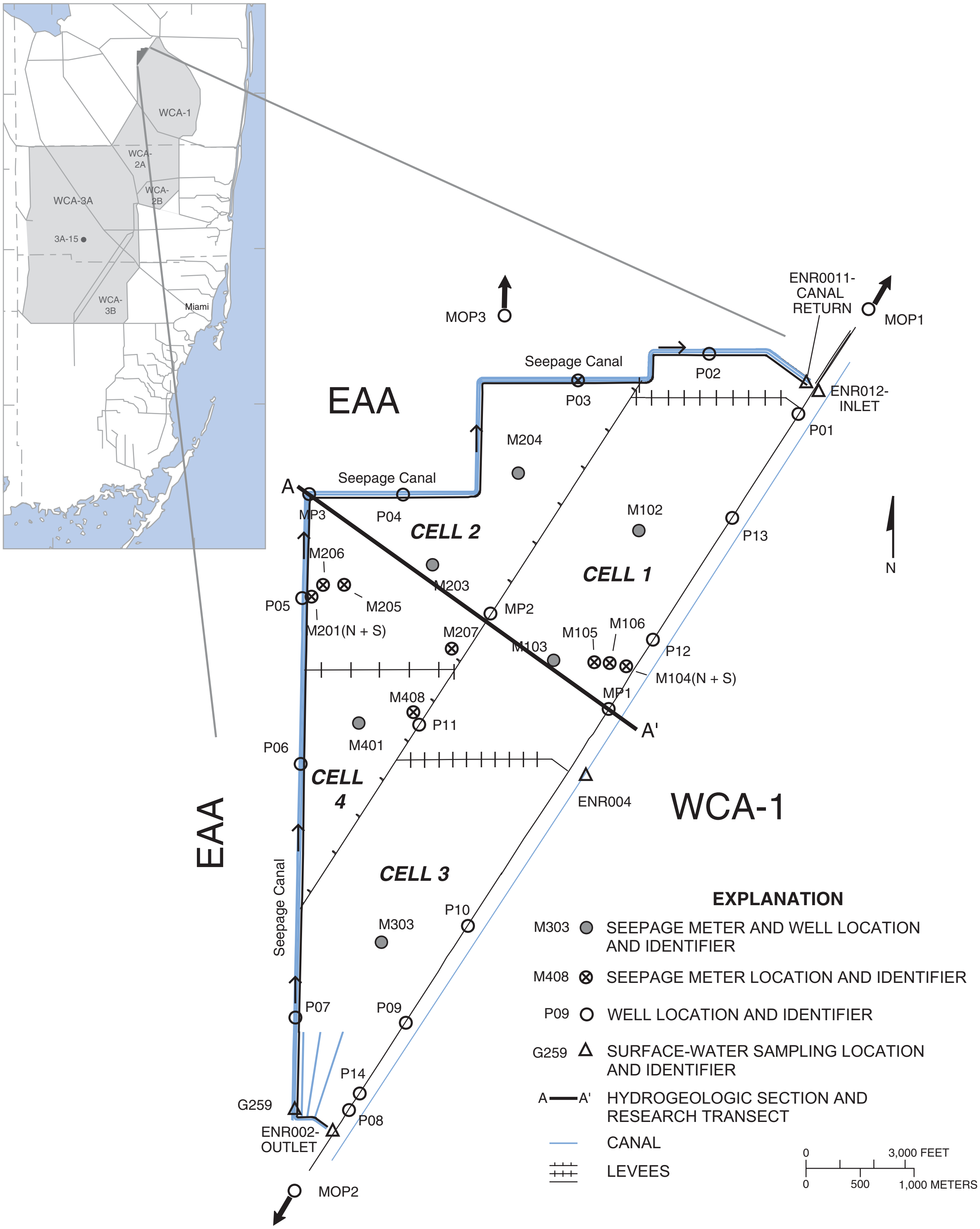


Figure 2. Location of study sites in Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida. ENR is bordered by Water Conservation Area 1 (WCA-1) to the east and the Everglades Agricultural Area (EAA) to the west and north. A seepage canal that collects ground-water discharge separates ENR from the EAA (thin arrows show direction of flow). Note that true locations for sites MOP1, MOP2, and MOP3 are further from ENR than indicated, as shown by thick arrows.

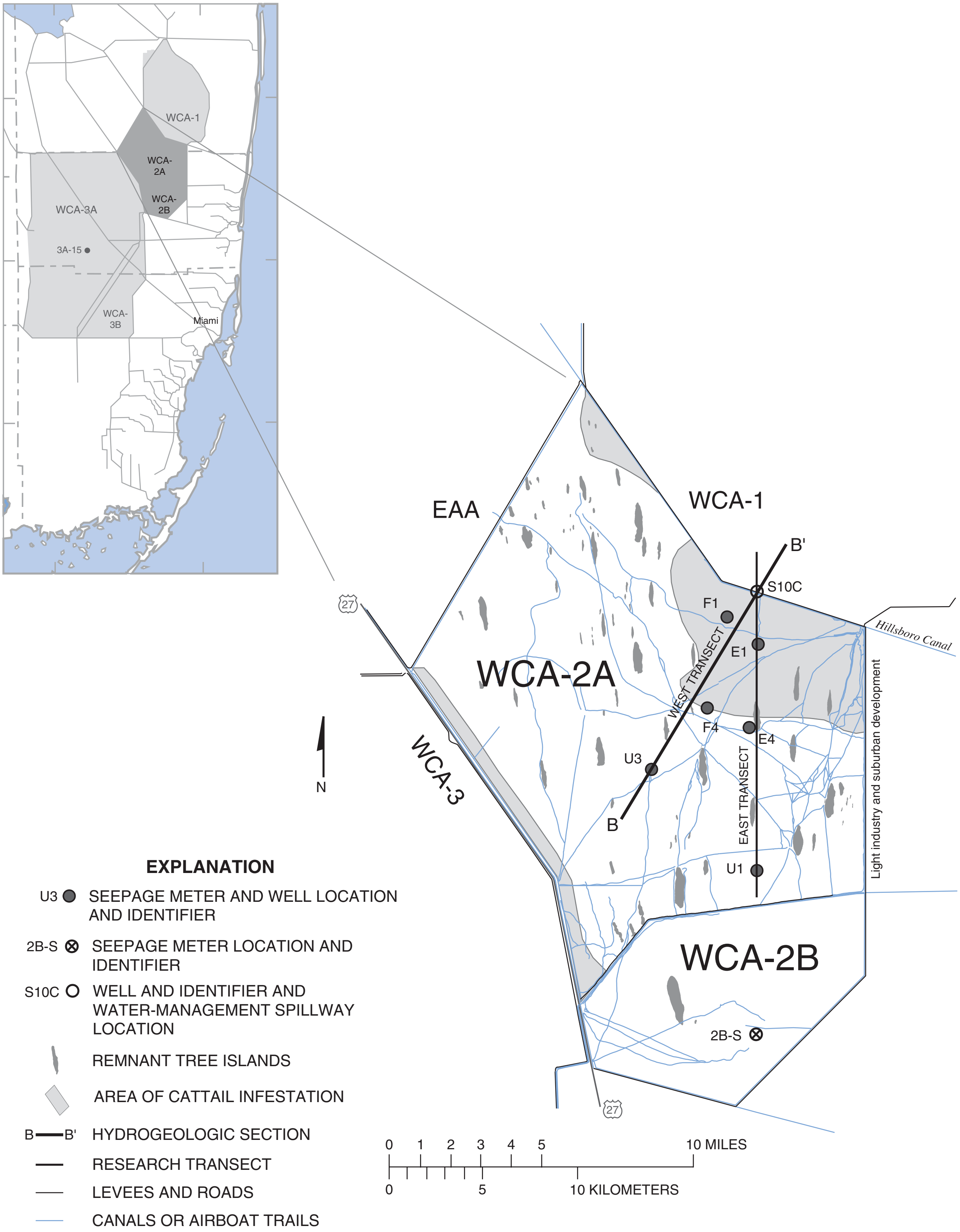


Figure 3. Location of study sites in Water Conservation Area 2 (WCA-2), north-central Everglades, south Florida. WCA-2 shares borders with Water Conservation Area 1 (WCA-1) to the northeast, the Everglades Agricultural Area (EAA) to the northwest, WCA-3A to the southwest, and areas of light industry and suburban development to the east. Approximate locations of airboat trails are shown.

1963, WCA-2A was completely compartmentalized by levees and canals, including the split between WCA-2A and 2B. Since about 1975, researchers have investigated the ecology of WCA-2A, documenting, for example, the loss of tree islands and a transition from a sawgrass wetland to one affected by extensive cattail growth in some areas. Excess nutrients from agricultural runoff, and multi-year droughts and flooding have been investigated previously to better understand those ecological changes. The effect of interactions between ground water and surface water has not been investigated in WCA-2A. Therefore, studying the hydrology of WCA-2A is an excellent complement to similar studies in ENR, because of the much larger area and much longer history at WCA-2A of nutrient pollution (Urban and others, 1993; Jensen and others, 1995).

The wetlands in the vicinity of ENR were converted to agriculture early in the 1900s, and then reconstructed as a wetland in 1993. In contrast, WCA-2A remained more in a natural state, without the direct effects of drainage, ditching, grading, or farming. WCA-2A also has not been affected by blasting and excavation of extensive irrigation canals, nor by extensive peat shrinkage and oxidation, as is the case at ENR. The engineered land slope of ENR is approximately three times as steep in the direction of flow compared with the natural slope in WCA-2A (1×10^{-4} at ENR compared with 3×10^{-5} at WCA-2A). Average water-level differences when compared with WCA-1 were similar at the two study areas, 2.4 and 2.8 ft at ENR and WCA-2A, respectively. However, variability in water-level differences was greater at WCA-2A compared with ENR. Expressed as a coefficient of variation, the temporal variability of water-level differences about the mean was 50 percent at WCA-2A and 18 percent at ENR.

Unlike ENR, where an attempt is made to maintain relatively stable operating water levels, WCA-2A has large (up to 4 ft) fluctuations in water levels lasting from weeks to months. These water-level fluctuations result, in part, from the operation of control structures that release water from WCA-1, and partly from natural processes such as rainfall and evapotranspiration. Another important feature affecting water flow at WCA-2A is a berm on the tailwater side of the Hillsboro canal (fig. 3). Water in the canal flows to the east at times of low water before water enters the wetland. However, when large releases from the S10C spillway occur, the high water in the tailwater canal overtops the berm and moves directly into the wetland in a southwestern direction.

Acknowledgments

The authors are indebted especially to the following individuals whose help was critical to project success: Gene Shinn, Chris Reich, Don Hickey, David Krabbenhoft, Bill Orem, Jonah Jackson, Eric Nemeth, Jessica Thomas, Brent Banks and Aaron Higer of the USGS; and Larry Fink, Carl Miles, Pete Rawlik, Darren Rumbold, Wossenu Abtew, Kevin Rohrer, Jim Vincent, Doug Ellington, Pete Dauenhauer, Bruce Webb, Stan Jones, Paul McGinnes, Mark Hummel, Ben Harkenson, Sharon Niemczyk, Anne Shoffner, Jennifer Cornwell, Emily Hopkins, Heidi Bazell, Angela Chong and John Lukasiewicz of SFWMD.

HYDROGEOLOGY OF THE NORTH-CENTRAL EVERGLADES

The Surficial aquifer is a principal source of fresh drinking water in south Florida. Sediments within the aquifer were deposited during the middle Pleistocene epoch and range in age from 1.8 million years before present (BP) to 13,000 years BP (Perkins, 1977). These Surficial aquifer sediments are composed mainly of shallow water marine facies, including coral limestones, beach and offshore sandbar complexes, lagoonal limestones, and an oolitic ridge along the coast of Miami (Perkins, 1977; Hoffmeister, 1974). The Surficial aquifer includes the highly transmissive Biscayne aquifer, which underlies Miami-Dade, Broward and eastern Palm Beach Counties. The Biscayne aquifer is thickest beneath the Atlantic coastal ridge to the east of the Everglades, and it thins from east to west, disappearing beneath the north-central Everglades. Aquifers to the west of the Biscayne and beneath the Everglades generally have been ignored as potential sources of ground water, both because of the lower transmissivities (Fish, 1988) and because of the higher total dissolved solids in ground water beneath the Everglades (Howie, 1987; Miller, 1988).

Except for a few studies mentioned above, there is little comprehensive information available about the hydrogeology beneath the north-central Everglades. Previous site-specific investigations included various studies at ENR. A study by Hutcheon Engineers at ENR was associated closely with engineering design projects for STAs, but provided relatively little in the way of lithologic or hydrogeologic data. Rohrer (1999) broadly characterized the hydrogeology of the ENR from boreholes placed on ENR levees and focused attention on the near-surface layer of the Surficial aquifer. A goal of the present investigation was to characterize in detail the geology and hydraulic properties of the Surficial aquifer at new drilling sites in ENR and WCA-2A. Of particular importance was identifying layers of relatively high or low hydraulic conductivity and their relation to physical properties and geologic classification of aquifer layers.

Geologic Setting of Study Areas

In Palm Beach County, the Surficial aquifer extends from near ground surface to depths in excess of 165 ft below land surface (bls). Deposition of the shallow water marine units in south Florida was regulated by eustatic sea-level fluctuations associated with glacial and interglacial stages of the Pleistocene (Perkins, 1977). Climatic instability, and glacial retreat and advance during the Pleistocene caused sea level to repeatedly recede and advance over large areas of south Florida. Many of the sediments appear lithologically similar but often represent different depositional events (Perkins, 1977). Sediment deposition during this period resulted from dune building, near-shore progradation of the coastline, and soil development.

The Quaternary and Tertiary deposits of south Florida are dominated by shallow water marine carbonates and siliciclastic materials deposited as part of reef systems, tidal flats, and coastal barrier/bar complexes. Interbedded within these units are indications of subaerial exposure, including paleosols and freshwater limestones (Perkins, 1977). The stratigraphy of these Quaternary sediments is described briefly below following from Parker and others (1955), Brooks (1968), and Perkins (1977).

Lake Flirt Marl Formation

The Lake Flirt Marl is Pleistocene in age. According to Schroeder and others (1958), it is up to 6 ft thick, relatively impermeable, and composed primarily of calcareous mud with some areas of dense limestone. The Lake Flirt Marl underlies the organic (peat) soils throughout much of the Everglades and coastal marshes (Parker and others, 1955). Reese and Cunningham (2000) found the Lake Flirt Marl in southwestern Palm Beach County to be composed of silty marl or quartz sand with a marl matrix. The areal distribution of the Lake Flirt Marl and lithographic textures are consistent with deposition in freshwater lakes (Reese and Cunningham, 2000).

Fort Thompson Formation

The Fort Thompson Formation consists of alternating beds of marine, brackish and freshwater limestones similar to those found at the type locale along the Caloosahatchee River. The formation overlies the Caloosahatchee Marl and is Pleistocene in age (Parker and Cooke, 1944; Mitterer, 1975). The thickness of the formation is about 40 ft in eastern Miami-Dade, Broward and Palm Beach Counties (fig. 1) where it makes up the highly productive zone of the Biscayne aquifer (Fish and Stewart, 1991). This formation covers the greatest geographical expanse of all Quaternary formations in southern Florida. The depositional environment of this formation can be linked to late Quaternary sea level fluctuations. The discontinuity surfaces of the Fort Thompson Formation can include dense, well-indurated laminated crusts (Giddings, 1999). Core samples collected during this study are primarily from the Fort Thompson Formation.

Anastasia Formation

The Anastasia Formation consists of alternating offshore bar, beach ridge, and dune system deposits and may be at least 39 ft thick along the coast (Perkins, 1977). The age of the formation is estimated to be late Pleistocene and is considered to be contemporaneous with the Fort Thompson Formation (Parker and others, 1955). This formation can be divided into two distinct facies: a coquina facies and a shell rock facies (Lovejoy, 1983). The coquina facies represents a high-energy environment typical of an offshore bar complex and generally is aligned with the present coastline. The shell rock facies is found behind the coquina facies, between the offshore bar complex and the shoreline. The shell rock facies is characterized by a diverse molluscan fauna with minimal damage to the fossils in a fine-grained quartz matrix, suggesting a shallow bay origin (Lovejoy, 1983). The Anastasia Formation is seen in areas east of the study sites.

Caloosahatchee (Marl) Formation

The transition between the Tertiary Pliocene and the Quaternary Pleistocene occurs in the upper members of the Caloosahatchee Formation (Enos, 1977). The Caloosahatchee Marl is composed of sandy marl, clay, and silt-size particles interbedded with shell beds (Land and others, 1973). Parker and others (1955) describe the Caloosahatchee Marl as sandy marl, clay, and silt with interbedded layers of sand and shell beds. Hydraulic conductivities range from 1 ft/d to 10 ft/d (Scott, 1977). Parker and others (1955) state that in many places the Caloosahatchee Marl is thinner because of erosion and solutioning, whereas in some places it is absent or appears only in isolated patches.

Tamiami Formation

The Tamiami Formation underlies the Caloosahatchee Formation and generally is described as cream, white, and greenish-gray clayey marl, silty and shelly sands, and shell marl that may be hardened locally into limestone (Schroeder and others, 1958). In Broward County, the formation grades from hard, sandy limestone interbedded with calcareous sandstone to green marly silt (Parker and others, 1955). Fish (1988) describes the Tamiami Formation in Broward County as greenish clay marl, silty and shelly marl with calcareous marl, locally hardened to impure limestone. The Tamiami Formation is estimated to be about 6 million years before present (Hoffmeister, 1974). Parts of the upper Tamiami are cavity-riddled and hydraulically similar to the Anastasia Formation (Russell and Wexler, 1993). In this study, the formation was found only at ENR site MP3-A.

Hawthorn Group

The Hawthorn Group underlies the Tamiami Formation and is described by Scott (1988) as highly complex. In south Florida, the upper layer of the Hawthorn Group consists of phosphatic siliciclastic sediments of fine- to coarse-grained quartz sand, quartz silt, and clay minerals (Scott, 1992). According to Miller (1987), impermeable and semi-permeable marls (calcareous clays) of the Hawthorn Group form the base of the Surficial aquifer. Because of the phosphatic sediments, the Hawthorn Group in south Florida generally has a higher gamma-ray signature than underlying or overlying layers (Scott, 1988). In this study, these sediments were seen only at the bottom of the borehole at site MP3-A.

A summary of the chronostratigraphy of the Surficial aquifer is shown in table 1. The age of each formation, its average thickness, primary lithology, and Q unit designations are shown in table 2.

Subaerial Exposure and Weathering Affecting Aquifer Hydraulic Properties

Subaerial exposure and weathering is one of the most important factors affecting the hydraulic properties of Surficial aquifer sediments (Perkins, 1977). Exposure to the atmosphere and chemical weathering of the exposed rock by dissolution resulted in formation of discontinuous bands of dense caliche-type crusts, paleosols, freshwater limestone, and laminated crusts (Perkins, 1977; Beach, 1982). Identifying subaerial exposure surfaces is an accepted means of identifying the boundaries between different stratigraphic subdivisions of the Quaternary units. In practice, these

Table 1. Chronostratigraphy of the Quaternary sediments underlying the north-central Everglades, south Florida

[–, not applicable]

Q Unit	Age (years before present) Mitterer, 1974	Giddings, 1999	Formations in Study Areas
Q5	125,000	115,000	Anastasia and Fort Thompson
Q4	180,000	200,000	Anastasia and Fort Thompson
Q3	236,000	350,000	Anastasia and Fort Thompson
Q2	324,000	Estimated 400,000	Anastasia and Fort Thompson
Q1	–	Estimated 800,000	Anastasia and Fort Thompson

subaerial exposure surfaces are difficult to identify because their thicknesses may be appreciably less than 3 ft (Perkins, 1977). Detailed continuous geologic logs are, therefore, the only reliable means to identify these surfaces.

Perkins (1977) differentiated the depositional framework of south Florida into five distinct marine units punctuated by episodes of subaerial exposure. The estimated age of the Q5 unit was assigned based upon radiometric dating of the Key Largo Limestone and Miami Limestone (Osmond and others, 1965; Broecker and Thurber, 1965). Dates for the remaining four Quaternary sediments were estimated from amino acid racemization results from the Fort Thompson Formation (Mitterer, 1974, 1975; Giddings, 1999). Drilling at ENR site MP3 fully penetrated this complete Quaternary sequence. The chronostratigraphic details of these units are shown in table 1.

Another potentially important type of weathering surface was described by Krupa (1999). Krupa (1999) established the presence of radioactive crusts in the sediments that he referred to as Secondary Depositional Crusts (SDC). These SDCs are less distinctive than the Q unit indicators and they usually are not visible. They typically are associated with increases in the natural gamma measurements at a depth just below a subaerial exposure surface. Evidence indicates the SDCs are a function of the paleo ground-water interface location (Krupa, 1999). Krupa proposed that the crusts are formed by residual leachate deposited at the ground-water interface as a result of downward percolation of rainfall through the vadose zone. The SDCs were found to exhibit levels of elements such as Ca, Mg, Al, Sr, Fe, U, Th, and K above the natural background level of the area. Krupa (1999) suggested those elements could be important in the hydraulic properties of the rock because of the effects of secondary cementation within the pore network.

Lithology of the Surficial Aquifer

To characterize the lithology, the deepest borehole at each levee site was sampled continuously from top to bottom. Split-spoon sampling was used for unconsolidated sediments, and conventional or wireline coring was used for consolidated sediments. Detailed sampling methods are described in Harvey and others (2000). Visual observations of split-spoon and core samples indicate that the aquifer generally is composed of sand overlying limestone with interbedded sand stringers in the top third. The bottom two-thirds of the aquifer is composed of sands of varying grain size. A detailed lithologic description of these core and sand samples and the grain-size analyses are given in Harvey and others (2000). Lithostratigraphic interpretations for two sections (locations shown in figure 1) are provided in figures 4 and 5.

The relative percentage of sampling by split spoon or coring provides an indication of site-to-site lithologic variation. Sites MP1, MP3, and MOP1 in the northern part of ENR (fig. 2) were sampled by coring for more than 80 percent of their lengths. The high percentage of coring indicates that sediments are mostly consolidated in the upper 100 ft at those sites. In contrast, two boreholes south of ENR, sites MOP2 and

Table 2. Summary of hydrogeologic, lithostratigraphic, and chronostratigraphic units in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[BP, before present; <, less than; >, greater than; –, not applicable]

Layer	Average thickness (ft)	Primary lithology	Common formation/group name	Geologic time scale (epochs)	Perkins Q1 – Q5 Series	Estimated age of formation (years BP)
1a	2.3	Peat	Recent	Holocene	–	<5000
1b	1.0	Marly sand/sand	Lake Flirt Marl	Transition to Pleistocene	–	20,000
2	2.0	Sand	Upper Fort Thompson	Pleistocene	Q5 – Q4	125,000 to 210,000
3	27.0	Limestone with sand stringers	Fort Thompson	Pleistocene	Q3 – Q2	270,000 to 500,000
4	91.0	Sand	Fort Thompson	Lower Pleistocene	Q1	500,000 to 1,600,000
			Caloosahatchee Marl		–	
			Tamiami	Upper Pliocene	–	1,600,00 to 2,800,000
5	>93.0	Fine sand	Tamiami/Hawthorn	Pliocene to Miocene	–	2,800,000 to 23,700,000

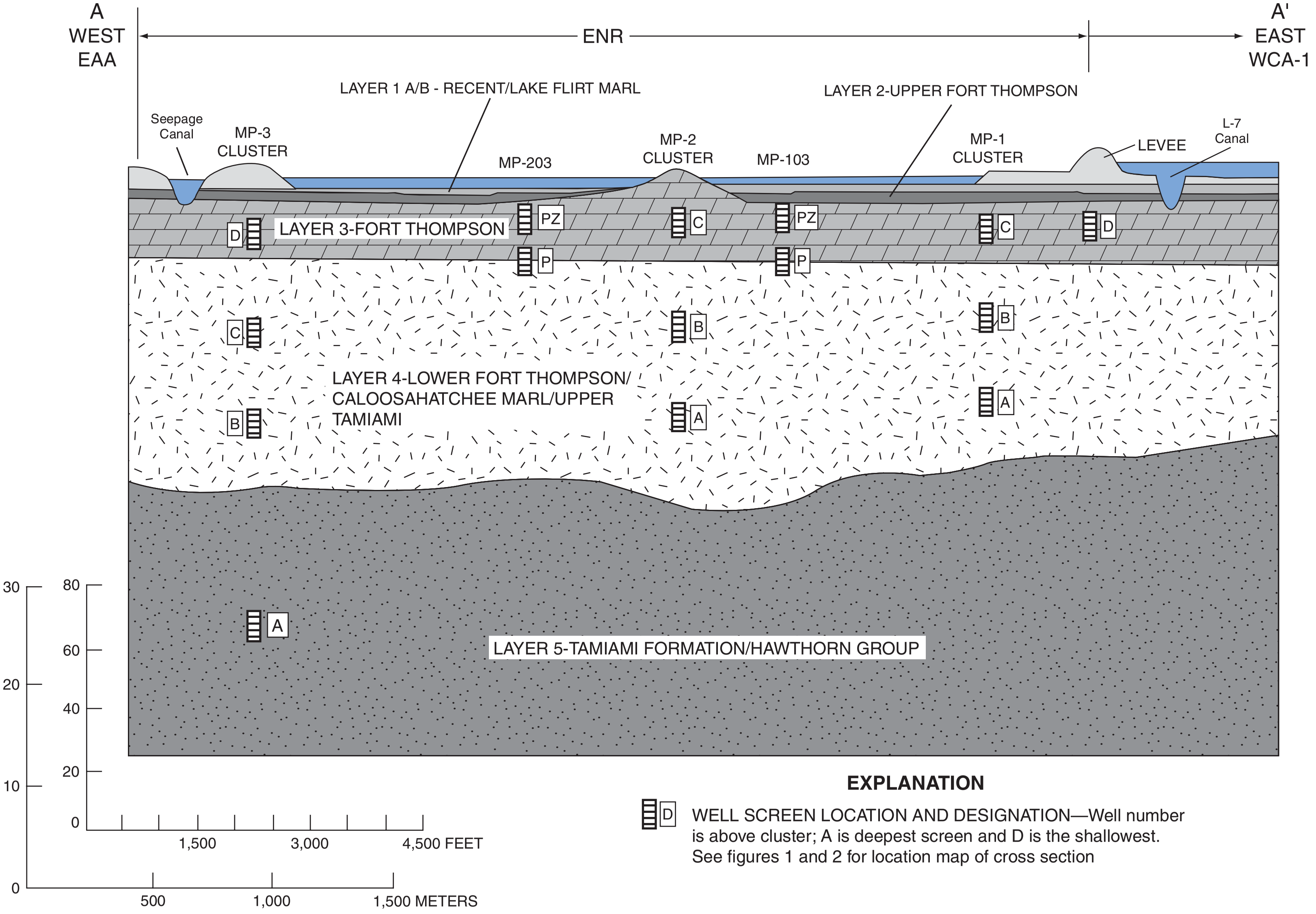


Figure 4. Lithostratigraphic cross section with formation names, Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida.

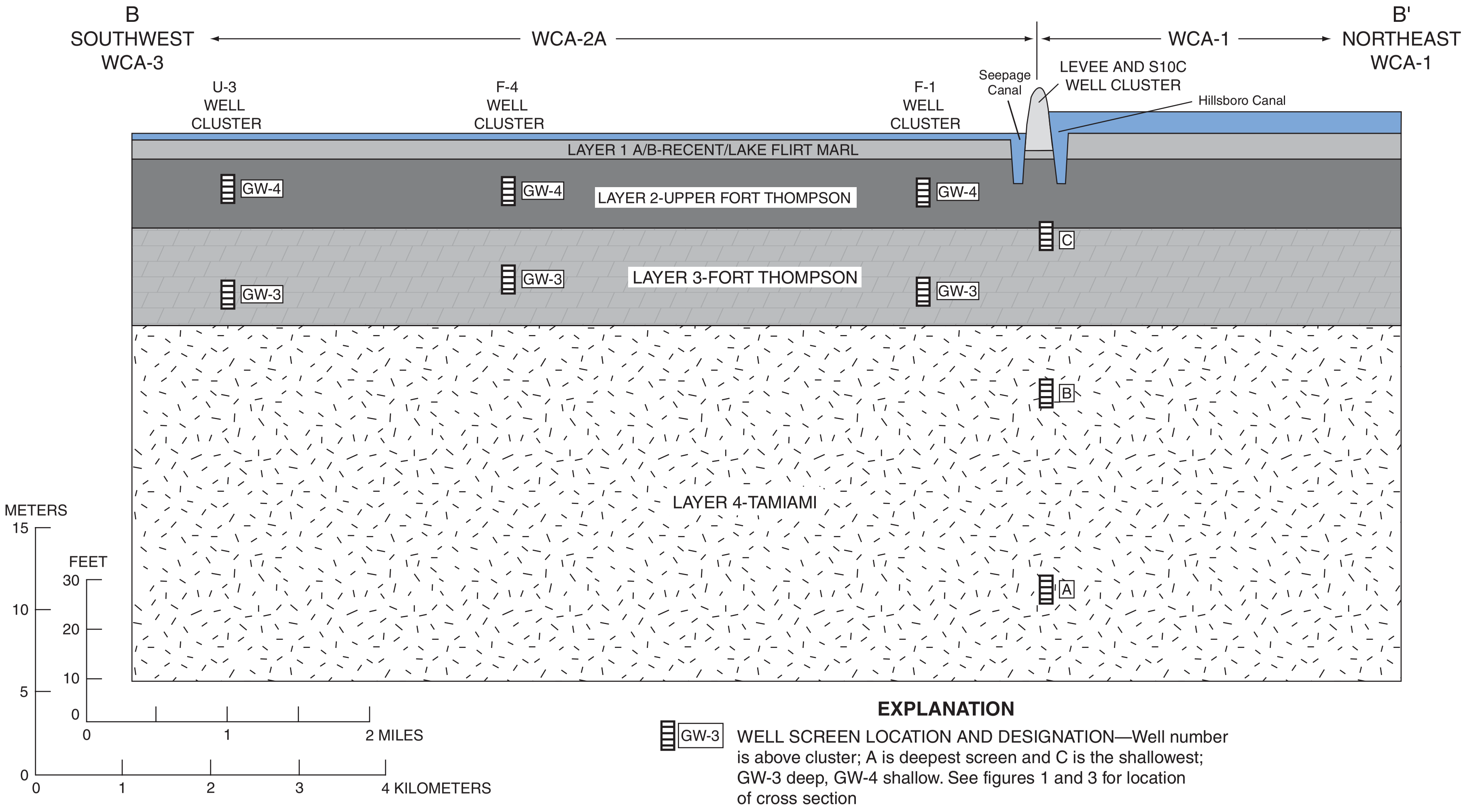


Figure 5. Lithostratigraphic cross section with formation names, Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida. Note that this section shows only the top half (approximately 100 feet) of the Surficial aquifer in this part of the study area.

S10C, were sampled by standard penetration tests (SPT) for at least 75 percent of their lengths, indicating mostly unconsolidated sediments (figs. 2 and 3). Site MP2 in central ENR was sampled with roughly an equal combination of SPT and coring.

Additional information about sediment density is found in "blow count" summaries from the SPT sampling. Blow count refers to the number of times per foot that the split-spoon sampler was hammered by the drilling rig. Harder formations require more "blows" than softer formations to penetrate 1 ft. Blow counts are informative regarding relative sediment packing and density, as well as the presence or absence of caverns or solution features. Blow counts, therefore, are best used to compare boreholes between sites of similar lithology. Holtz and Kovacs (1981) classify sediment density based on *N*, the total of the uncorrected blow counts for the second and third 6-in segments of a standard 24-in sample. The number of samples at three sites (MP2, MOP2, S10C) separated into ranges of *N* is shown in table 3.

The results in table 3 indicate that the unconsolidated sediments at WCA-2A are less dense than those at ENR. Blow counts for sites S10C (in WCA-2A) and MOP2 (in ENR) are plotted with sample elevation in figure 6. Gaps indicate elevations where SPT sampling was not possible. Whereas the overall range of *N* values at the two boreholes is similar, variations are apparent. Near the top of the aquifer (5 ft NGVD) *N* is equal to 3 at S10C compared with 50 at MOP2. At –46 to –56 ft NGVD, the *N* values at MOP2 also are higher than those of S10C. The denser sands at ENR could be a result of differences in grain-size sorting or greater sediment compaction.

Grain-size analysis is a tool that is used for interpretation of depositional environments (Boggs, 1995) and for determination of the sediment hydraulic conductivity. To quantify variations in sample grain size, sorting, and sediment classification, samples were sieved according to ASTM Standard No. D-422 (American Society of Testing and Materials, 1991). The results were analyzed to determine the d_{10}, d_{17}, d_{20} and d_{60}; that is, the grain size for which the indicated fraction of sample (10, 17, 20, 60) is smaller. This information then was used to estimate hydraulic conductivity (Vukovic and Soro, 1992) and to determine the degree

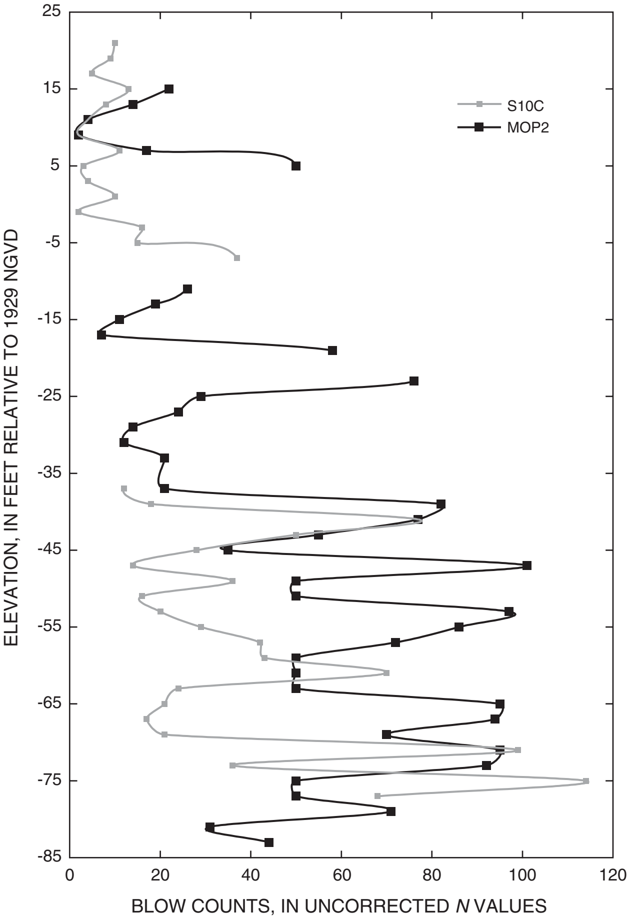


Figure 6. Standard penetration test *N* values from the Surficial aquifer at sites S10C (WCA-2A) and MOP2 (ENR), north-central Everglades, south Florida.

Table 3. Number of standard penetration test blows at three sites in the Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

Blows (*N* values)	0 - 4 Very loose	5 - 10 Loose	11 - 30 Medium	31 - 50 Dense	51 or more Very dense
Number of samples - MP2	0	0	1	7	11
Number of samples - MOP2	2	1	12	11	15
Number of samples - S10C	5	5	15	7	5

of sorting of the sand grains. The uniformity coefficient (d_{60}/d_{10}) and the gradation coefficient [$(d_{30})^2/(d_{10}*d_{60})$] were the selected measures of sorting (Kasenow, 1994). Whereas only selected data are given as part of this discussion, all sieve analysis data from this investigation are available in Harvey and others (2000).

The sorting of sediment grains may reflect depositional conditions and processes (Boggs, 1995). Sediments underlying the ENR generally were well sorted with some poorly sorted layers near the top of the Surficial aquifer (Harvey and others, 2000). Two ENR sites, MP1 and MP2, demonstrate well-sorted sediments throughout the depth of the boreholes (fig. 7). Several boreholes at the northern edges of the ENR study area had more poorly sorted sands in the upper portions of the Surficial aquifer. For example, poorly sorted sediments were found in the upper layers at MP3 (+10 to +2 ft NGVD), grading to mostly well sorted sediments below a limestone layer. MOP1 had poorly sorted sands at 6 to –4 ft NGVD. Well sorted sediments with a poorly sorted layer found at –18 to –22 ft NGVD were the primary sediments found at MOP2, located just south of ENR.

Sediment analyses of WCA-2A sediments are limited to the S10C borehole. The other sites were drilled using a modified wireline core barrel system that does not collect unconsolidated sediments (MacIntyre, 1975). Sands at S10C primarily were poorly sorted and coarser in grain size than the sands at ENR (table 4). The exception to poor sorting of sediments at S10C sediments is the interval between –50 to –60 ft NGVD, where the sediments are well sorted (fig. 7). These variations are reflective of the changing depositional processes in a marginal-marine environment.

Lithologic Comparison Between WCA-2A and ENR

At S10C, sediments generally are poorly sorted and the d_{20} in the complete borehole (Fort Thompson and Tamiami Formations) ranges from 0.12 mm (very fine) to 0.46 mm (medium). Various cycles of coarsening upwards and fining upwards appear in the S10C profile, which indicates periods of sea-level transgression and regression (fig. 8). In contrast, sediments from ENR site MOP2 have a d_{20} that ranges from 0.11 mm (very fine) to 0.25 mm (fine/medium) and primarily are well sorted. The ENR profiles show much smaller changes with elevations (fig. 7). The geometric mean of d_{10}, d_{17}, d_{20}, and d_{60} values and the uniformity coefficient (C_u) are all larger for WCA-2A compared with the ENR boreholes. Possible sub-areal caps and caliche crusts are present in the limestone core samples at varying depths and are described in Harvey and others (2000, p. 94 and 98).

These sedimentary differences support the theory that the depositional environments at WCA-2A were different than those at the ENR (Enos, 1977). This difference probably resulted because the ENR is located about 20 mi north of and slightly west of WCA-2A. Whereas both sites have similar land-surface elevations, WCA-2A is closer to the current and paleo-shorelines of peninsular Florida and would have been flooded earlier, longer, and possibly more frequently by sea-level transgressions and regressions. Because of the changing sea levels, the chemical composition of the water within the aquifer and the depositional processes varied. Future work could involve correlating the sub-aereal caps and caliche crusts and the effect of these sedimentary structures on ground-water quality.

Table 4. Mean uniformity and gradation coefficients at six boreholes in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

	Site					
	MP1	**MP2**	**MP3**	**MOP1**	**MOP2**	**S10C**
	Geometric Mean					
Gradation coefficient (Cc)	0.93	0.09	0.80	0.76	0.85	0.52
Uniformity coefficient (Cu)	2.1	3.7	4.5	3.6	3.2	10.9

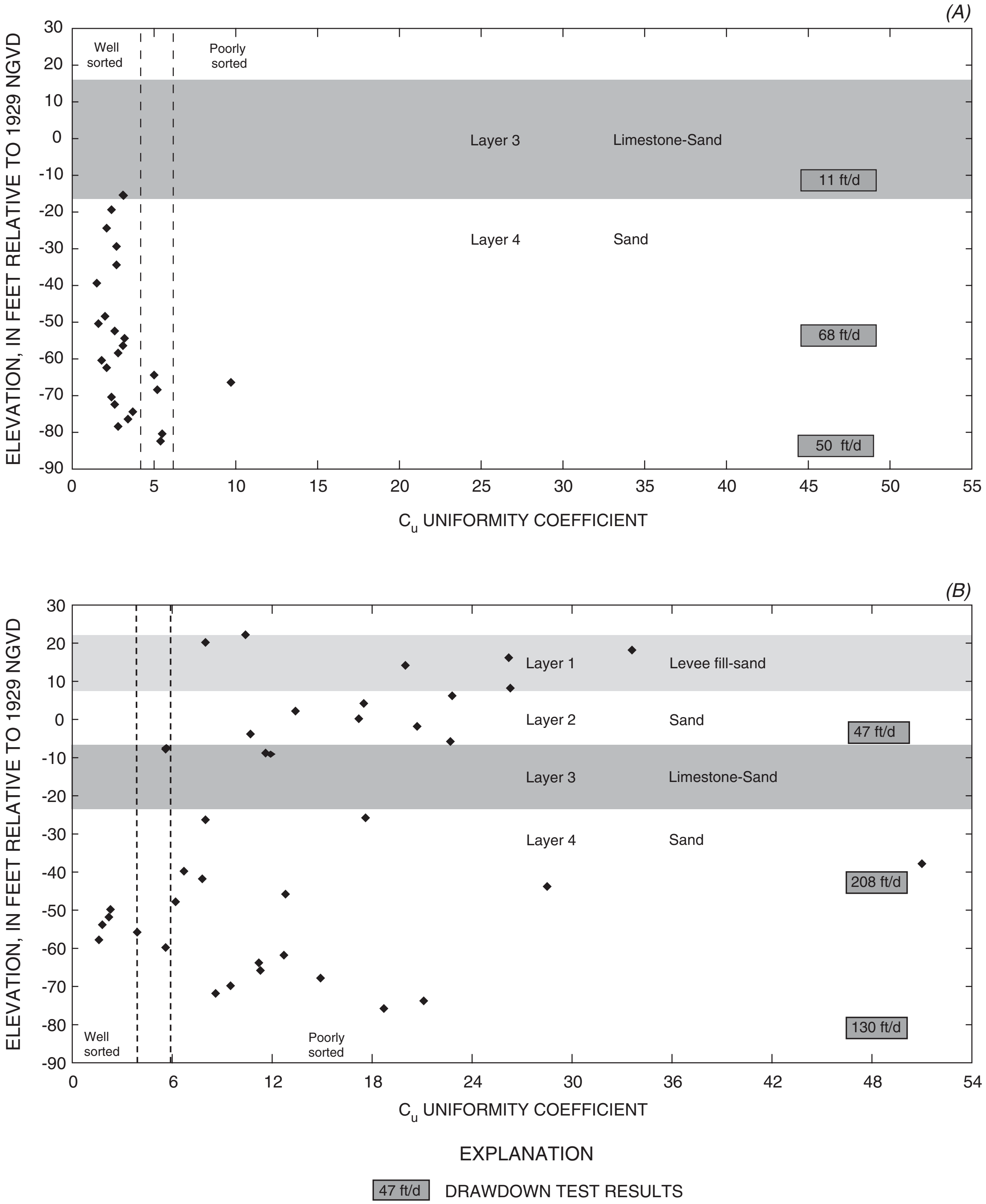


Figure 7. Uniformity coefficients, hydraulic conductivities from drawdown tests, and generalized lithology from the Surficial aquifer at sites MP2 (ENR) *(A)* and S10C (WCA-2A) *(B)*, north-central Everglades, south Florida.

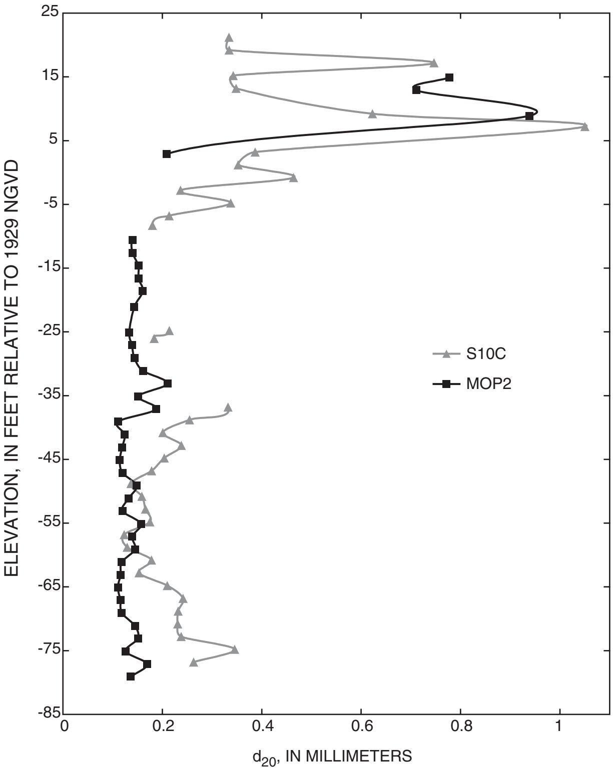


Figure 8. Grain size from the Surficial aquifer at site S10C (WCA-2A) and site MOP2 (ENR), north-central Everglades, south Florida.

Geophysical Logging Results and Correlations

The deepest boreholes at the levee sites were logged with geophysical probes prior to casing installation. Whereas the underlying lithology cannot be determined solely by geophysical logs, the general characteristics of lithology and water content can be summarized (Boggs, 1995). The log traces of each borehole and all geophysical data are summarized graphically on north-south and east-west cross-sections and shown by Harvey and others (2000). The standard suite of geophysical logs collected during this investigation included caliper, natural gamma ray, neutron, and lateral logs. This report mainly discusses the caliper, gamma ray, and neutron logs because these tools were the most responsive during the logging operations and indicate intervals of lithologic change.

Caliper Logging

Caliper traces of ENR wells consistently showed evidence of washouts throughout the length of the boreholes. Washouts often occur where there are heaving sands because of excessive hydraulic pressures, changes in lithology, solution holes, or a lack of sediment compaction. Washouts were most extensive at sites MP2 and MOP2, and were present in both limestone layers and well-sorted sand layers. These washouts probably indicate layers with varying degrees of cementation or compaction. The largest washout was seen at the MP3-A borehole at an elevation of –13 ft NGVD and extended 16 in from the center of the borehole. This elevation coincides with a lithologic change from sandy limestone to well-sorted sand. The caliper log from borehole S10C showed minimal evidence of washouts.

Natural Gamma Ray Logging

Natural gamma ray logs traditionally have been used in Florida to correlate formations regionally and to identify clays or formations with natural radioactivity, such as the Hawthorn Group (Scott, 1988). Recent work in Florida by Krupa (1999) and Cunningham (1998) indicates that natural gamma ray responses from sediments in the Surficial aquifer do not always coincide with the phosphatic sediments.

In the ENR, the natural gamma ray logs have peaks in layers from 0 to –25 ft NGVD at each site. However, only sites MP1-A, MOP1, MOP2, and MOP3 show natural gamma ray peaks in the interval between –25 to –40 ft NGVD. At greater depths, the logs generally are featureless, with a few smaller peaks. Further south at S10C, the natural gamma ray peaks occur below a depth of –35 ft NGVD, as seen in Harvey and others (2000, p. 118 and 121).

There is limited geophysical information surrounding WCA-2A and data are not available within WCA-2A; therefore, an available gamma ray log from well PB-00019 (Swayze, 1988) was used. This site is located 6 mi southeast of the S10C site.

Two correlations of natural gamma ray logs were prepared. The correlation of the west – east ENR transect is shown in Harvey and others (2000, p. 120-129). The gamma ray correlations along the north-south ENR/WCA-2A transect are shown in figure 9. Whereas the natural gamma ray logs at S10C and PB-00019 show only minor inflections to a depth of –30 ft NGVD, the ENR traces show appreciable peaks on the gamma logs to a depth of about –35 ft NGVD.

The natural gamma ray peaks below –35 ft NGVD are similar in both the ENR and WCA-2A (fig. 9). The sediment analysis did not indicate a lithologic explanation for the peaks, such as clays or phos-

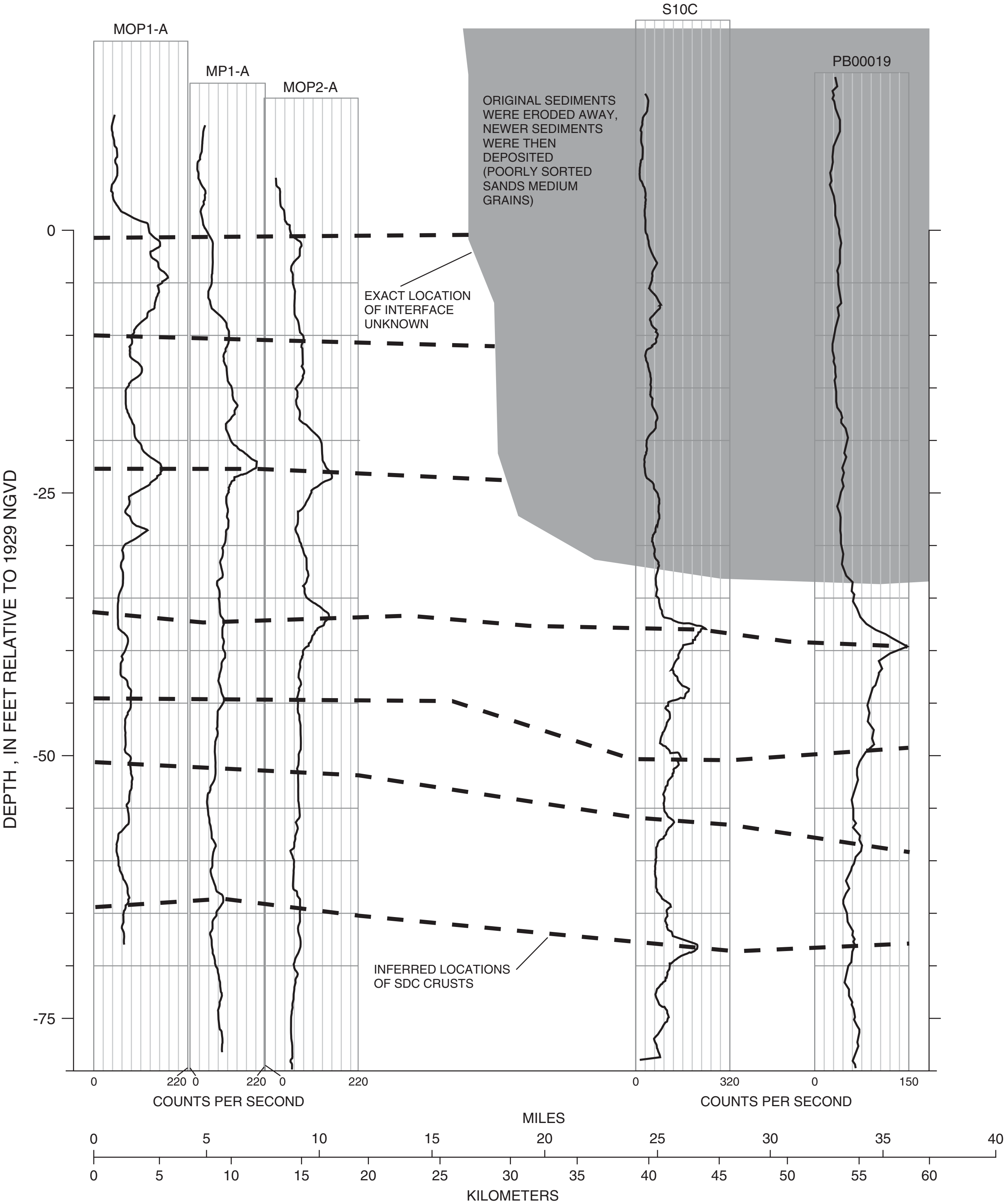


Figure 9. North (left) to south (right) changes in borehole gamma counts, showing inferred layers of secondary depositional crusts (SDC) and southern zone of erosion and deposition of poorly sorted sands with medium grain size, north-central Everglades, south Florida.

phatic deposits. Therefore, they may be SDCs or erosional surfaces, which potentially can restrict vertical and lateral ground-water flow within the Surficial aquifer. Additional research would be needed to evaluate the effect of SDCs on water quality and flow.

It is likely that SDCs were formed over thousands of years during the normal fluctuations of the ground water within the vadose zone in the sediments. Because S10C is closer to the Atlantic Ocean, it is more likely affected by tidal and nearshore processes. Thus, SDCs probably formed within both sites but subsequently were eroded away at the S10C site. After the erosion, poorly sorted sediments then were deposited over the area at S01C.

Neutron Logging

The neutron log is a hydrogen detector and measures amount of hydrogen within the sediment pore space; therefore, it is an indicator of porosity. Elevated hydrogen content above the natural background can be attributed to lower porosity within the sediments. The neutron tool utilized in this investigation had not been calibrated recently. Therefore, the neutron log traces only are used to describe general characteristics and trends within the aquifer.

The major peaks in the neutron logs occur at shallow (less than –30 ft NGVD) depths in the ENR, whereas peaks occur throughout the entire borehole at S10C (+18 to –77 ft NGVD). The neutron log activity at S10C indicates zones of reduced porosity. The neutron logs at sites MP1, MP2, MP3, MOP1, MOP2, and MOP3 all show elevated hydrogen levels at shallow depths (less than 20 ft) than at deeper depths, indicating lower porosity (table 5). At S10C, the neutron log showed a distinct deflection to the left (low hydrogen content) at an elevation of 5 to 11 ft NGVD. This deflection occurred in a layer of well-sorted sand and gravel and could indicate a layer of high porosity. The remainder of this log traces displayed elevated hydrogen levels at elevations of +2, –2.5, and –42.5 ft NGVD. These elevated levels also are in layers of well-sorted sand with gravel and indicate layers of lower porosity. These deflections correlate to deflections on the gamma ray log and also could indicate SDCs.

Electric Logs

Electric or resistivity logs measure the electrical properties of the formation such as the resistivity of fluid in interconnected pores or the effective porosity (Keys, 1990). The resistivity of the formation is affected by lithology, porosity, and water quality. The long-normal (LN) resistivity profiles sometimes can provide a view of the preferential flow paths and associated water quality (Keys, 1990). Deflections or peaks occur when formation water of different resistivity is encountered by the probe. These logs are composed of "shallow" and "deep" penetrating sondes with each sonde investigating at a different distance into the formation, from the center of the borehole. In this study, the LN and short normal (SN) were used. The LN measures 64 in. into the formation and the SN measures 16 in. into the formation.

Typical resistivity traces of the shallow aquifers in Florida show higher resistivity at or near the surface, which generally declines with depth. In the Surficial aquifer, the shallow, more resistive water is recharged from the surface. Relict seawater in the deeper portion of the Surficial aquifer has lower resistivity. Resistivity traces that indicate underflow or preferential flow have

Table 5. Peaks in neutron geophysical logs and the corresponding lithology at Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida

[1929 NGVD, National Geodetic Vertical Datum of 1929 in feet; *K*, hydraulic conductivity; ft/d, feet per day]

Site	Elevation at neutron peak (1929 NGVD)	Elevation of core sample (1929 NGVD)	Laboratory		Lithology
			Vertical *K* (ft/d)	Porosity (percent)	
MP1	-1.0 to -5.0	-0.9 to -5.9	0.002	11	Sandy limestone
MP2	-2.0 to -5.0	-4.4 to -9.4	1.1	12	Hard sandy limestone
MP2	-13.3 to -16.0	-15.4 to -19.4	0.28	22	Very sandy limestone
MOP1	-5.5 to -7.0	-6.5 to -7.5	0.12	16	Sandy limestone
MOP2	2.0 to -2.0	5.9 to -0.9	0.04	16	Sandy limestone

the same gentle slope with periodic areas of reduced resistivity shown by a deflection, usually to the left, in the resistivity trace. This trace generally indicates a more dormant area (higher specific conductance) of the ground water.

When the natural layering of water within an aquifer is disturbed from anthropogenic activities, mixing occurs. The resistivity logs showed that anthropogenic activities had affected the sites. The upper 20 ft of the Surficial aquifer showed freshwater on the resistivity logs, indicating that relict seawater had been replaced by freshwater recharge. This recharge is likely from surface water in the western part of the ENR. The SN and LN traces in this study are generally smooth, with resistivity steadily decreasing with depth. This result is shown at MOP3 by the three electric traces exhibiting higher resistivity in the upper sediments and smooth traces of steadily decreasing resistivity in the bottom of the borehole. In contrast, site MP3 shows deflections to the left and right at elevations between –60 and –80 ft NGVD. This well is on a levee at the northwestern corner of the ENR. The resistivity traces at ENR sites MP1 and MOP2A show the highest resistivity levels with measurements of 400 ohm-m in the top 10 ft of the borehole.

The water underlying S10C shows relatively high resistivity at depth. This high resistivity indicates deeper recharge of freshwater, likely as a result of anthropogenic activity. Results of the lateral logging suggest some preferential flow paths, indicated by the deflections in the trace seen throughout the depth of the borehole. The SN resistivity log had an increase in resistivity to the right at –50 ft NGVD indicating a possible preferential flow path or freshening of the ground water. These differences may indicate water from different recharge sources.

Hydraulic Conductivity of the Surficial Aquifer

Horizontal hydraulic conductivity (K_h) of the Surficial aquifer at the different sites was estimated by three methods: calculations based on sieve analysis results of unconsolidated samples, steady-state air permeability tests on limestone cores, and slug tests. The permeability tests also directly estimated vertical hydraulic conductivity (K_v). K_v also was mathematically inferred from sieve and slug test results (Walton, 1987). Hydraulic conductivity (K) of the peat was determined using bail tests from drive points, seepage meter data, and head data from drive points and surface water (Harvey and others, 2000).

Hydraulic conductivity was calculated for the unconsolidated samples obtained from six boreholes, using a software program by Vukovic and Soro (1992). This approach determines K_h by averaging the results of 10 different calculations of conductivity. Resulting K_h estimates for unconsolidated samples ranged from 5.9 to 510 ft/d. Detailed results for each borehole are listed in Harvey and others (2000, p. 132–145).

Permeability tests were conducted on 16 core samples from the ENR and 11 samples from WCA-2A (Core Laboratories, Inc., 1999). Porosity and vertical and horizontal hydraulic conductivity were determined. The minimum, maximum, and average horizontal hydraulic conductivity values for all sites ranged from 0.02 to 510 ft/d. Detailed results from ENR core samples are provided in Harvey and others (2000) while data from all WCA-2A sites are presented in table 6.

Core samples from the ENR boreholes generally were limestone with varying amounts of sand. One sample at MOP1 was cemented limy sand. The majority of samples were moldic, had pinpoint porosity, and contained a variety of fossils. The total porosity of these ENR samples ranged from a low of 9.4 percent in a shallow layer at MP3 to a high of 32 percent in a deep layer in the same borehole. The geometric mean of all porosities in the ENR samples was 17 percent.

The K_h of the core samples from ENR ranged from less than 0.02 ft/d to about 510 ft/d, with a geometric mean of 31 ft/d. This mean value is much higher than the average reported K_h of limestone of 5.9 ft/d (Kasenow, 1994). The K_v of the sediments ranged from 0.002 to 3400 ft/d with a geometric mean of 7.5 ft/d. This value is slightly higher than the reported average K_v of 3.1 ft/d (Kasenow, 1994). The ratios of vertical to horizontal hydraulic conductivity (K_v/K_h) ranged from a minimum of 0.002 to a maximum of 8, with a geometric mean of 0.2. The mean ratio of 0.2 is slightly lower than the average value reported for limestone (0.5) by Kasenow (1994). Because of this lower K_v/K_h ratio, the preferential flow is more likely to be horizontal where the consolidated material is present.

Cores from WCA-2A primarily were limestone with varying amounts of sand. One sample at U1GW3 contained very fine limy sand. Limonite, formed by oxidation of iron-bearing minerals or by precipitation in bogs, was seen in shallow samples at E4GW3 and F4GW3. Fossils were found in most samples and pin-

Table 6. Results of core analysis from boreholes in Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[bls, below land surface; 1929 NGVD, National Geodetic Vertical Datum of 1929 in feet; ft/d, feet per day; mean refers to an arithmetic mean; LS, limestone; pp, pinpoint porosity; v, very; sl, slight; qtz, quartz]

Well name	Sample depth (feet bls)	Elevation in feet (1929 NGVD)	Vertical hydraulic conductivity (ft/d)	Horizontal hydraulic conductivity (mean in ft/d)	Porosity (percent)	Lithographic description
S10C-A	36 - 41	-13.6 to -18.6	8.3	4.1	25	LS, chalky, slightly sandy, pp
S10C-A	30 - 35	-7.6 to -12.6	16	85	24	LS, fossils, very sandy, pp
U1-GW3	5 - 10	5.9 to 0.9	26	61	17	LS, fossils, quartz sand, moldic
U1GW3	15 - 20	-4.1 to -9.1	6.1	45	19	Tan, fine-grained sand, v limy, sl rootlets
E4-GW3	0 - 5	12.0 to 7.0	40	29	17	LS, fossils, adundant quartz sand, limonite
E4-GW3	10 - 15	2.0 to -3.0	430	450	25	LS, fossils, quartz sand, slightly moldic
E4-GW3	15 - 20	-3.0 to -8.0	16	4.6	11	LS, slight quartz sand, slightly fractured
F4-GW3	0 - 5	11.5 to 6.5	7.5	180	22	LS, fossils, quartz sand, limonite, sl moldic
F4-GW3	10 - 15	1.5 to -3.5	90	500	19	LS, fossils, qtz sand, sl pinpoint porosity
U3-GW3	10 - 15	1.2 to -3.8	8.5	24	14	LS, fossils, slight quartz sand, sl rootlets
U3-GW3	20 - 25	-8.8 to -13.8	130	500	31	LS, fossils, slight quartz sand

point porosity was seen at sites F4GW3 and S10C. About half the samples were moldic or showed rootlets. The porosity of WCA-2A samples ranged from 10.9 percent between –3 to –8 ft NGVD (E4GW3) to 31.3 percent at –20 to –25 ft NGVD (U3GW3). The geometric mean of all porosities in the WCA-2A core samples was 19.6 percent.

The K_h of the cores ranged from 4.1 ft/d to nearly 502 ft/d, with a geometric mean of 63 ft/d. This geometric mean is an order of magnitude larger than the mean published value of 5.9 ft/d (Kasenow, 1994). Likewise, K_v of the cores ranged from 6.1 to 430 ft/d with a geometric mean of 26.4 ft/d, an order of magnitude larger than published averaged values. The ratios of vertical to horizontal hydraulic conductivity (K_v/K_h) ranged from 0.04 to 3.5 with a geometric mean of 0.4. The mean ratio of 0.4 is similar to the mean values calculated for limestone (0.52) using data from Kasenow (1994).

Comparison of Hydraulic Conductivity in ENR and WCA-2A

ENR cores had the largest variations in hydraulic conductivity at shallow elevations (10.6 to –12.6 ft NGVD) as shown in table 7. The low vertical and horizontal *K* measurements at shallow elevations in the ENR indicate a restrictive layer or caprock, as suggested by Rohrer (1999). Although the restricting layer is common in limestone above 0 ft NGVD, it is not spatially continuous, as evidenced by many cores with K_v values higher than 1 ft/d. This discontinuous restrictive layer was observed during drilling operations at site M301. Here, the drilling fluids did not return to the surface for subsequent re-circulation, but emerged 18 ft away from the drill rig.

Core analyses found large variations in K_v in the consolidated sediments of the ENR boreholes. Less variation was seen in WCA-2A cores. A thin layer with very low K_v (0.001 - 0.1 ft/d) was found to overlie a layer of high K_h and K_v at sites MP1, MOP1, and MOP2. The elevation of these restricted flow/high flow layers varies at each site; the restrictive layer was between 5.9 and –7.5 ft NGVD and the high flow layer was between –4.6 and –15.9 ft NGVD. The layers of high hydraulic conductivity act as preferential flow paths encouraging horizontal flow because of the overlying restrictive layer. When this restricting layer is eroded or fractured, a preferential pathway for vertical transport of water and its constituents is created because the K_v is much higher than the K_h. The vertical and horizontal hydraulic conductivity and porosity for two shallow layers in ENR sites MOP1, MOP2, and MP1 are shown in table 8. The extreme differences in K_v at the different elevations at these sites can be seen clearly in table 8.

A variety of methods was used to estimate the average hydraulic conductivity of the peat. The methodology is addressed by Harvey and others (2000). In the ENR, the *K* of the peat is two orders of magnitude less than the *K* of layer 2 (table 9). In WCA-2A, the *K* of the peat also is appreciably less than the *K* of layer 2.

Properties of the core samples, such as the silica/calcium carbonate content, color, and fossil content, were used to identify the formation and Q series of the sediments. Quartz content of these four boreholes var-

Table 7. Hydraulic conductivity determined from core samples beneath Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[1929 NGVD, National Geodetic Vertical Datum of 1929 in feet; *K*, hydraulic conductivity; ft/d, feet per day]

Site name	Sample elevation (1929 NGVD)	Vertical *K* (ft/d)	Maximum horizontal *K* (ft/d)	Minimum horizontal *K* (ft/d)	Porosity (percent)
MP1	-0.9 to -5.9	0.002	0.03	0.01	11
MP2	10.6 to 5.6	0.68	20	13	11
MP3	2.2 to -2.8	6.5	3.4	3.0	9
MOP1	-6.5 to -7.5	0.12	77	0.31	16
MOP2	0.4 to -4.6	3,100	690	98	22
M203	0.63 to -4.4	100	130	110	22
S10C	-7.6 to -12.6	16	140	29	24

Table 8. Hydraulic conductivity compared in two layers at several sites in Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida

[1929 NGVD, National Geodetic Vertical Datum of 1929 in feet; *K*, hydraulic conductivity; ft/d, feet per day; –, not applicable]

Site Name	Sample elevation (1929 NGVD)	Vertical *K* (ft/d)	Maximum horizontal *K* (ft/d)	Minimum horizontal *K* (ft/d)	Porosity (percent)
MOP1	-6.5 to -7.5	0.12	77	0.31	16
MOP1	-7.5 to -12.5	3,400	–	–	29
MOP2	5.9 to 0.9	0.04	20	17	16
MOP2	-4.6 to -9.6	1,000	550	470	24
MP1	-0.9 to -5.9	0.002	0.03	0.01	11
MP1	-10.9 to -15.9	400	260	250	26

Table 9. Hydraulic conductivity of peat, peat-to-rock transition zone, and shallow underlying sand layer at Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[*K*, hydraulic conductivity; ft/d, feet per day; ft, feet; cm/d, centimeter per day; –, not applicable]

Area	Sediment Layer	Approximate sediment depth (cm)	Approximate sediment depth (ft)	Mean *K* (cm/d)	Mean *K* (ft/d)
ENR	Peat and transition layer	105	3.4	8.1	0.3
WCA-2A	Peat and transition layer	131	4.3	43	1.4
	Underlying sand	–	–	270	8.9

ied greatly by both site and elevation as shown in table 10. These differences indicate changing depositional environments. As stated previously, shallow water marine carbonates and siliciclastic material dominate the Quaternary and portions of the Pleistocene deposits in south Florida. The lithology of the core samples from WCA-2A sites E-1, F-1, F-4 and ENR site M-204 were described in detail in by Harvey and others (2000, p. 96–98).

South Florida Water Management District staff sorted though the sieved samples for whole and partial fossils to assist in stratigraphic correlation. Fossils were identified and logged. Because of the large number of fossil species identified, each species was assigned a numerical identification number. Preliminary descriptions are provided in Harvey and others (2000). A stratigraphic correlation was not in the scope of this study.

Table 10. Summary of quartz content of selected boreholes in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[ft, feet]

Borehole	Depth below land surface (ft)	Quartz content	
		Minimum (percent)	Maximum (percent)
E1	6.5 to 15	30	40
F1	4.5 to 29	5	40
F4	5 to 26	10	37
M204	4.5 to 20	5	45

Comparison of Hydraulic Conductivities to Other Studies

The field methodology for drawdown (slug) tests in wells is described in Harvey and others (2000). The formulations of Bouwer (1989) and Bouwer and Rice (1976) were used to determine the hydraulic conductivity for the partially penetrating wells in an unconfined aquifer. The results of the drawdown tests show great variation and are shown in table 11. The lowest hydraulic conductivity was 1.0 ft/d at MP3-A. At this well, the bottom of the screen is at –174 ft NGVD and is in silty sediments. The highest hydraulic conductivity measured at ENR, 242 ft/d, was at MP3-C in fine- to medium-grained sand at an elevation of –47 ft NGVD. The mean hydraulic conductivity of all ENR wells, determined by drawdown tests, was 32 ft/d.

The variation of K_h among wells was greatest in WCA-2A. Site U1 had the lowest and highest hydraulic conductivities in WCA-2A. U1GW4 had a K_h of 32 ft/d at an elevation of –5.8 ft NGVD, and U1GW3 had a K_h of 1261 ft/d at –13.4 ft NGVD. The mean hydraulic conductivity of all the wells in WCA-2A, determined by drawdown tests, was 116 ft/d. The variation in K_h within the same lithologic layers in the study area as well as the minimum, maximum, and mean K_h in each layer are shown in table 11. Three of the layers have a maximum K_h greater by an order of magnitude than the minimum K_h.

The results from the drawdown tests were compared to results from earlier tests in eastern Broward and Palm Beach Counties by Dames and Moore (1988) and Fish (1988), along with Rohrer's (1999) results from ENR. The hydraulic conductivity values from this study were higher than results from these earlier Surficial aquifer studies. Results from these investigations and this study are shown in table 12.

Hydraulic conductivity values in comparable lithologic units (for example, sand) vary significantly with each study. Dames and Moore (1988) completed slug tests at 11 wells in coastal south Palm Beach County at elevations of –15 ft to –85 ft (1929 NGVD). These wells, completed in poorly sorted sands, have hydraulic conductivity values that range from 1 ft/d to 7 ft/d with a mean of 2.8 ft/d. Slug tests done in Rohrer's (1999) ENR seepage investigation have hydraulic conductivity values ranging from 0.04 ft/d to 150 ft/d with a mean of approximately 5 ft/d. It should be noted that the wells in the Rohrer study generally were constructed on or near the levees surrounding the ENR. Some of these wells have screens in the unconsolidated levee material, and may not reflect the hydraulic conductivity of the undisturbed aquifer material. This screen placement could affect the average hydraulic conductivity value determined from that study.

This study found the mean horizontal hydraulic conductivity to be approximately 31 ft/d in ENR and 120 ft/d in northern WCA-2A. Sand layers were found to have hydraulic conductivities of 15 ft/d in ENR and 30 ft/d in WCA-2A. Dames and Moore (1988) reported a value of about 3 ft/d. This difference in K further demonstrates the large variation of hydraulic conductivity found in the study areas.

Table 11. Summary of horizontal hydraulic conductivity as determined by drawdown tests in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[1929 NGVD, National Geodetic Vertical Datum of 1929 in feet; K_H, mean hydraulic conductivity calculated using geometric mean; K_{HA}, mean hydraulic conductivity calculated using arithmetic mean; ft/d, feet per day; –, not applicable]

Site/Layer	Type of measurement	Elevation at bottom of well screen (1929 NGVD)	K_H (ft/day)	K_{HA} (ft/day)
ENR Layer 3	Minimum (at M204-P)	-19.1	5	–
	Maximum (at M303-P)	-18.2	170	–
	Mean	–	28	45
ENR Layer 4	Minimum (at MOP1-B)	-52.5	16	–
	Maximum (at MP3-C)	-46.3	240	–
	Mean	–	48	64
WCA-2A Layer 2	Minimum (at U1-GW4)	-5.8	32	–
	Maximum (at E1-GW4)	0.7	130	–
	Mean	–	65	83
WCA-2A Layer 3	Minimum (at F4-GW3)	-13.5	58	–
	Maximum (at U1-GW3)	-13.4	1260	–
	Mean	–	270	660

Evidence for Layers Restricting Vertical Flow

Sediment deposition, sedimentary processes, and sediment weathering are important in creating layers in the Surficial aquifer where preferential horizontal flow occurs, or where vertical flow of ground water is restricted. Anthropogenic practices, such as peat removal and blasting for canals, also are locally important. The lithology of the Surficial aquifer in the two study areas is primarily sand with limestone layers concentrated between 10 and –30 ft NGVD. Whereas sands generally are fine grained and well sorted in the ENR, they are coarser and more poorly sorted at S10C in WCA-2A. The presence of the gravel-size fraction changes from not present in the northern part of ENR to gravel in every sample from the southern part of the study area at S10C. The upper sand layer (layer 2) is relatively thin compared to other sand layers or absent, and the limestone layer (layer 3) is thicker in ENR compared with the limestone layer at S10C in WCA-2A.

Core samples include sandy limestone and limestone with varying porosities (11 to 31 percent) and up to 45 percent quartz composition. The sandy limestone primarily was found at approximately –18 ft NGVD. Generally, porosity was controlled by secondary processes. The depositional sequences at the ENR and WCA-2A initially were similar, but subsequent erosion of the upper 60 ft of south Palm Beach County sediments, including WCA-2A, occurred during the transgressive period of the Upper Miocene/Pleistocene epochs. Periods of sea-level regression followed, which deposited new sediments of larger grain size than originally deposited. These new sediments have higher hydraulic conductivity than the older sediments. The limestone formed in and near the WCA-2A is not as hardened by post-depositional processes and is not as vertically restrictive to ground-water flow as the limestone in ENR.

Preferential flow paths in sand generally are in the shallower sand at S10C (layer 2) but distributed at varying depths in the ENR. ENR preferential paths were seen in layers 2, 3, and 4 with the majority in the deeper sands of layer 4 (fig. 4). Results from slug tests show that *K* values are higher in WCA-2A by approximately an order of magnitude. This difference is greatest in the shallow layer of WCA-2A.

Evidence for restricted vertical flow comes mainly from the ENR site. Dense, low-porosity limestone with low vertical hydraulic conductivity was found at elevations ranging between 3 and –7 ft NGVD in that area. With vertical hydraulic conductivities as low as 0.002 ft/d, those layers locally act as an aquitard. Rohrer (1999) also observed a vertically restrictive layer for flow that he referred to as "caprock."

Table 12. Summary of horizontal hydraulic conductivity values from the Surficial aquifer in Palm Beach County and eastern Broward County, north-central Everglades, south Florida. Investigations with less than three samples were not included

[*K*, hydraulic conductivity; ft/d, feet per day]

Publication	Aquifer Material Type	Number of Samples	Minimum *K* (ft/d)	Mean *K*[1] (ft/d)	Maximum *K* (ft/d)
Fish, 1988, Eastern Broward County[2]	Fine to medium sand	3	16.	29	44
Rohrer, 1999, ENR[2]	Sand/ limestone	20	0.04	5	150
Dames & Moore, 1988, Eastern Palm Beach County[3]	Sand	11	1.0	3	7
Harvey and others, 2000, ENR[3]	Sand/ limestone	23	1.0	32	240
Harvey and others, 2000 WCA-2A[3]	Sand/ limestone	15	32.	120	1300
Harvey and others, 2000, ENR[4]	Sand	121	6.0	15	180
Harvey and others, 2000, WCA-2A[4]	Sand	37	8.0	30	510

[1] Mean hydraulic conductivity is the geometric mean.

[2] Slug test.

[3] Drawdown test.

[4] Calculated from grain-size sieve analysis.

Interpretations made here differ from Rohrer's interpretations in that this study found the vertical restricting layer is not horizontally continuous enough over the area to serve as the primary layer restricting vertical flow. It also is likely that blasting to create canals and borrow pits produced important avenues of vertical exchange and may have affected hydraulic properties throughout the ENR. The data from interior areas of the ENR show core samples with very high vertical values of *K*. Also, the return of drilling fluids once was observed to occur 18 ft away from a drill site, at a location far removed from canals or blasting. These observations further support the conclusion that a vertical restricting layer in limestone beneath ENR is not as laterally continuous as the peat layer (with *K* less than 1 ft/d) that overlies the aquifer. Additional support for this conclusion comes from the Danish Hydraulic Institute (1999), which had to increase vertical *K* in its simulations of ground-water flow in ENR above what would be expected for a horizontally continuous layer that restricts ground-water flow.

The peat layer, with relatively low vertical hydraulic conductivity on the order of 1 ft/d, most likely functions as the restrictive unit to vertical ground-water flow. Whereas certain limestone layers have vertical *K* values less than peat by an order of magnitude or more, the horizontal continuity of the peat layer proves its primary importance as the layer that restricts vertical flow.

QUANTIFYING RECHARGE AND DISCHARGE IN THE NORTH-CENTRAL EVERGLADES AND IDENTIFYING THE KEY CONTROLLING FACTORS

A better understanding of how water-resources management has altered natural hydrologic patterns in the Everglades is required for successful restoration. Inseparable from natural patterns of surface-water flow and ground-water flow in the Everglades are the interactions between them. Those interactions affect water flow in both the wetlands and aquifer, and are, therefore, important to the overall water balance of the Everglades as well as the movement and fate of chemicals, including contaminants.

Interactions between surface water and ground water are well studied in certain areas of the Everglades. Most investigations were conducted in the immediate vicinity of levees and/ or canals (Klein and Sherwood, 1961; Miller, 1978; Chin, 1990; Sonenshein, 2001). Very few investigations have considered interactions between surface water and ground water in the expansive interior areas of the Everglades. Merritt (1996) combined surface- and ground-water flow models in Everglades National Park, showing the importance of wetland-ground water interactions. A drawback of Merritt's approach was that the model was calibrated mostly on hydraulic heads, an approach known to produce non-unique solutions that could result in uncertainty in model fluxes. The best way to improve the accuracy of modeling is to acquire more detailed data sets or complementary data of a different type.

At a regional scale, the Hydrologic Systems Modeling Group of the South Florida Water Management District (SFWMD) has conducted the most comprehensive hydrologic modeling in the Everglades. An important accomplishment of that group was developing the South Florida Water Management Model (SFWMM), a coupled model of surface-water and ground-water flow for the present-day Everglades. A companion model, the Natural Systems Model (NSM), simulates hydrologic patterns across the pre-drainage Everglades topography using the same algorithms and input data. Both the SFWMM and NSM operate by computing water flow and storage in a network of 2-mi by 2-mi grid cells covering much of the eastern two-thirds of south Florida. The SFWMM and NSM models are most appropriate for regional-scale simulations of surface-water flow and often have not been tested against detailed measurements or models.

The purpose of the present project was to collect and analyze detailed hydrologic and geochemical data at indicator sites in the north-central Everglades in order to develop reliable estimates of recharge and discharge. Therefore, this study project complements the regional-based SFWMM and NSM models by providing site-specific data sets for comparison with those models. The ultimate goal is to improve the accuracy of local and regional hydrologic models that will be used for testing hypotheses about Everglades hydrology, or for testing future water-resources management scenarios.

The specific questions addressed in this section are:

1.) What are the dominant pathways of ground-water flow in the north-central Everglades? How have they changed from pre-drainage conditions? Are present-day flow directions persistent over seasons or years?
2.) What are the major factors controlling recharge and discharge in the wetlands and the spatial and temporal variability of those fluxes?
3.) Are recharge and discharge substantial in comparison to other water-balance fluxes? What is the relative importance of recharge and discharge in interior areas of wetlands? Are the important factors that control recharge and discharge near levees the same in the interior areas of the wetlands?

Approach

Ground-water recharge and discharge in the Everglades usually has been estimated by surface-water mass balance modeling (MacVicar and others, 1994; Choi and Harvey, 2000). The precision of those estimates is linked closely to the density and quality of surface-water flow and stage measurements (Choi and Harvey, 2000). This investigation builds on former studies through analysis of ground-water hydraulic data, peat hydraulic properties, and through direct measurements of vertical fluxes between ground water and surface water using seepage meters. Those additional measurements allowed characterization of spatial and temporal variability of recharge and discharge at the study sites.

The purpose of this approach was broader than just improving the accuracy of previous estimates of recharge and discharge. As mentioned previously, hydraulic data from ground water have the advantage of pinpointing locations of recharge and discharge. By determining the spatial distribution of recharge and discharge, it was possible to test hypotheses about the factors that are most important in controlling recharge and discharge in the Everglades. In particular, most previous work assumed that ground-water flow beneath levees dominates discharge and recharge in the Everglades. The present study quantified those processes in interior areas of the wetlands to test that assumption. Results were expected to be used in guiding future improvements of regional models such as SFWMM.

Detailed methods were published previously in Harvey and others (2000). The only information given here is that which is immediately relevant to understanding the results presented in this section. Harvey and others (2000) should be consulted for all further information concerning survey accuracies, well and seepage-meter design and emplacement, slug tests in peat, and measurement of surface-water and ground-water levels.

Regional horizontal hydraulic gradients were computed for ENR or WCA-2A ground water in a given aquifer layer by calculating the inclination and direction of a plane that matched most closely the measured heads. By convention, a negative gradient indicated flow in a direction from areas of higher to lower hydraulic head. The average computed directions of horizontal flow are reported in table 13. Those flow directions were compared with the orientation of three research transects (one in ENR and two in WCA-2A) that had been established previously (fig. 1, also see figs. 2 and 3). Research transects in ENR and WCA-2A

Table 13. Horizontal hydraulic gradients and solute velocities of ground-water flow beneath Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), in the north-central Everglades, south Florida

[NGVD, National Geodetic Vertical Datum of 1929; *K*, horizontal hydraulic conductivity; ft, feet; ft/d, feet per day]

ENR - Intermediate Layer (*K*=28 ft/d; depth = +5.76 to -22.0 ft NGVD)

	WET–8/19/1997	DRY–6/15/1998
Flow direction (degrees)	296	297
Solute velocity[1] (ft/d)	0.07	0.06
Gradient (ft/ft)	-0.002	-0.001

ENR - Deep Layer (*K*=48 ft/d; depth = -40.0 to -90.0 ft NGVD)

	WET–8/19/1997	DRY–6/15/1998
Flow direction (degrees)	310	311
Solute velocity[1] (ft/d)	0.10	0.09
Gradient (ft/ft)	-0.002	-0.001

WCA-2A - Shallow Layer (*K*=73 ft/d; depth = +5.0 to -5.8 ft NGVD)

	WET–8/19/1997	DRY–6/15/1998
Flow direction (degrees)	224	173
Solute velocity[1] (ft/d)	0.01	0.01
Gradient (ft/ft)	-0.0002	-0.0001

WCA-2A - Intermediate Layer (*K*=156 ft/d; depth = -6.0 to -19.0 ft NGVD)

	WET–8/19/1997	DRY–6/15/1998
Flow direction (degrees)	219	190
Solute velocity[1] (ft/d)	0.03	0.01
Gradient (ft/ft)	-0.0002	-0.0001

[1] Calculated from ground-water flow divided by porosity (0.3).

were chosen because the orientation of transects was thought to be similar to average regional directions of ground-water flow. Horizontal hydraulic gradients along the research transects were computed by dividing the difference in head in two wells screened in the same layer by the distance between the wells. Because the general orientation of transects did compare well with the computed regional gradients in table 13, it was possible to make further computations of horizontal gradients using only the transect data. The advantage of computing gradients from transect data, instead of relying on regional horizontal gradients alone, was the ability to compare results between specific areas of interest, such as areas close to and far from levees.

Vertical hydraulic gradients also were computed using data from all of the study sites in ENR and WCA-2A where two or more wells were screened at different depths. The computation used the difference in head between surface water and shallow wells divided by the peat thickness. The sign convention resulted in a positive vertical gradient when recharge is occurring (downward flow from surface water to ground water) and a negative gradient when discharge occurs (upward flow from ground water to surface water).

Hydraulic conductivity (*K*) of peat was estimated in the peat by slug tests in piezometers. Slug-test results were compared with an independent estimate based on seepage-meter measurements that were combined with measured vertical hydraulic gradients to calculate *K* using Darcy’s law. Detailed methods and complete results are provided in Harvey and others (2000).

Recharge and discharge fluxes through peat were estimated using seepage meters or, alternatively, Darcy-flux computations. For reasons explained later, only seepage-meter results are reported for ENR sites and only Darcy-flux calculations are reported for

WCA-2A sites. The seepage-meter approach, meter design, procedures for installation and use, major assumptions, and precision and limit of detection, all are described in Harvey and others (2000).

In contrast to results from ENR, seepage-meter measurements at WCA-2A were judged as unreliable. The major evidence for rejecting seepage-meter results at WCA-2A was that the direction of fluxes measured on particular sampling dates often did not agree with the direction indicated by hydraulic gradient data. For example, on the westernmost transect in WCA-2A (F1-F4-U3), seepage-meter measurements often indicated recharge at the same time that hydraulic gradient data suggested discharge (Harvey and others, 2000).

The seepage-meter measurements at WCA-2A may have been compromised by problems that were specific to WCA-2A. For example, errors were caused in part by the higher hydraulic conductivity of peat at WCA-2A (table 9), which may have been high enough to cause measurement errors due to stretching or compression of seepage bags because of wind or moving vegetation. It should be noted that seepage-meter data collected at single sites in WCA-2B and WCA-3A were judged as reliable. This reliability was because seepage measurements from triplicate meters at WCA-2BS and WCA-3B15 tended to be similar and close to or slightly above detection limits.

The alternative to seepage meters was calculation of vertical fluxes through peat using Darcy’s law. Briefly, the Darcy-flux approach used a measured vertical hydraulic gradient across the peat and a vertical hydraulic conductivity for peat to compute a vertical water flux between ground water and surface water. The vertical gradient was estimated as the difference between surface-water stage and water elevation in the shallowest monitoring well (generally the "GW4" well located approximately 10 ft below the peat surface), divided by the thickness of the peat at that location.

Land-Surface Topography, Surface-Water Slope, and Water-Level Fluctuations

WCA-2A

The present slope of the land surface in WCA-2A is similar to pre-drainage conditions, 3.3 x 10^{-5}, towards the south-southeast. The water surface in WCA-2A generally slopes toward the southwest on a grade similar to the average land-surface slope. Sometimes, the water surface slopes toward the southeast, depending on where the water releases through structures are occurring (Romanowicz and Richardson, 2000). During the wet season, particularly when water is released from WCA-1 to WCA-2A, the water-surface slope can increase by as much as a factor of 2.

Long-term data collected by USGS and simulations by SFWMD suggest that water management imparts the dominant control on water-level fluctuations in WCA-2A. The largest and most rapid fluctuations in surface-water level in WCA-2A are caused by water releases from WCA-1, and not by precipitation and evapotranspiration. Comparisons between the Natural Systems Model and South Florida Water Management Model showed that the amplitude of water-level fluctuations for the pre-drainage Everglades in the vicinity of WCA-2A typically were 25 to 50 percent of present-day fluctuations.

A constructed berm on the extreme south side of the Hillsboro canal/levee complex (fig. 3), adjacent to WCA-2A, has an important effect on surface-water releases from WCA-1, and on water flow in WCA-2A. The purpose of the berm is to direct flow in the canal toward the east side of WCA-2A before the water enters the wetland and flows southward. When the water level rises rapidly in the tailwater canal because of a water release from WCA-1, overtopping of the berm eventually will result (at approximately 13.5 ft NGVD). After overtopping occurs, sheet flow across the berm supplies surface water directly to the wetland at all points along the Hillsboro levee.

ENR

The slope of the land surface in ENR is much steeper than in WCA-2A, because of the engineering involved. Because of subsidence, the land surface slopes in the direction opposite (northwest) of the estimated pre-drainage topographic gradient (southeast). The area of steepest slope (0.001) is immediately to the west of the L-7 levee and continues across the eastern third of ENR. Continuing to the west the ground slope is 2 x 10^{-4} across the western two-thirds of ENR. Those slopes are approximately 30 times and 7 times greater, respectively, than the average land slope in WCA-2A. The ENR was designed so that surface water would flow toward the southwest. The engineered slope in that direction also is relatively steep (1 x 10^{-4}). Even though the land-surface slope is much greater than

WCA-2A, the average water-surface slopes are similar (approximately 3 x 10^{-5}).

Average differences in water level across the WCA-1 levee are similar at ENR and WCA-2A, 2.4 and 2.8 ft, respectively. Variability of those water-level differences was greater at WCA-2A. Expressed as a coefficient of variation, the temporal variability of water-level differences across levees was 50 percent at WCA-2A compared with 18 percent at ENR. At ENR, surface-water levels are more widely monitored and tightly controlled by water-resources managers in an attempt to maintain relatively stable water levels in ENR. Greater variability at WCA-2A results because of water releases that can substantially decrease WCA-1 levels and increase WCA-2A levels in a matter of hours.

Horizontal Hydraulic Gradients

Average directions of ground-water flow were toward the northwest in the vicinity of the ENR, and toward the southwest in north-central WCA-2A (table 13). At ENR, there was relatively little change between wet and dry seasons in the direction of ground-water flow. Ground-water flow at ENR was toward the northwest during both wet and dry periods, toward 296 and 297 degrees (clockwise from north) at intermediate depths in the Surficial aquifer (table 13). The direction of ground-water flow in the deeper part of the aquifer also was stable over time but was more northerly in direction (310 degrees). It is possible that the estimated differences in flow direction at different levels in the aquifer are erroneous, the result of having fewer deep wells to use in the calculation of flow direction.

The magnitude of horizontal hydraulic gradients at ENR increased by 15 to 20 percent during wet conditions compared with dry conditions (table 13). Increased hydraulic gradients during wet conditions reflect the greater wet-season differences in water level between WCA-1 and the agricultural area.

At the WCA-2A study site, ground-water flow was toward the south-southwest (toward WCA-3A). During the wet season hydraulic gradients varied only a few degrees between intermediate and deeper wells (flow directions of 224 degrees and 219 degrees, respectively). Between wet and dry seasons, WCA-2A horizontal hydraulic gradients shifted considerably. The direction of flow in the shallow layer was toward 224 degrees during the wet season compared with 173 degrees during the dry season. The more easterly component of flow in dry conditions reflects the effect of seasonally low water levels to the east where ground-water pumping is from a well field between the Everglades and the Atlantic Coastal Ridge (Miller, 1988).

The magnitude of horizontal hydraulic gradients at WCA-2A increased by approximately a factor of 2 during wet conditions. Increased ground-water hydraulic gradients during wet conditions likely are the result of opening spillways between WCA-1 and WCA-2A, and between WCA-2A and WCA-3A, which reduces ponding in WCA-2A and increases the surface-water slope.

The importance of land and water-surface slopes in affecting ground-water flow is apparent on plots of water-surface slope and hydraulic gradient along each research transect (fig. 10). The largest horizontal hydraulic gradients in ground water are near levees in ENR and WCA-2A. Hydraulic gradients near levees were approximately 4 times greater at ENR compared with WCA-2A. That difference largely is the result of the geographic position of the ENR on the boundary between WCA-1 and the EAA, where the land-surface and water-surface slopes are relatively steep because of subsidence in the EAA.

Greater seasonal variability in horizontal hydraulic gradients beneath WCA-2A, compared with ENR, results in large part from greater variation in the difference between surface-water levels across the levee that borders WCA-1 (Harvey and others, 2000). As reported earlier, temporal variability in water-level differences across levees was greater at WCA-2A (coefficient of variation of 50 percent compared with 18 percent for ENR). More variable horizontal gradients at WCA-2A also result from larger fluctuations in surface-water level in WCA-2A compared with ENR. For example, over a period of approximately a year and a half (June 1997 to October 1998), water levels in the interior wetlands of WCA-2A varied over 5 ft compared with only 2 ft at ENR (Harvey and others, 2000).

Horizontal Ground-Water Flow Velocities

Horizontal ground-water flow velocities were computed based on hydraulic gradients computed from all of the available well data. Calculations of ground-water flow velocities for both wet and dry conditions are compared in table 13. An average depth-weighted hydraulic conductivity for the Surficial aquifer was used in the calculation (Harvey and others, 2000, p. 175). Results are reported in terms of a solute velocity (Darcy-flow velocity divided by porosity). A porosity of 0.30 was used for all calculations.

Ground-water flow velocities were higher at ENR than WCA-2A by approximately a factor of 6 and 4 in intermediate and deeper layers during the wet season, respectively (table 13). During the dry season, flow rates were approximately an order of magnitude higher in ENR compared with WCA-2A (table 13). If vertical mixing in the Surficial aquifer is ignored (as a first-order assumption), and if all recharge is assumed to occur at the headwater canal adjacent to the levee, the velocities presented in table 13 are consistent with horizontal travel times on the order of hundreds of years beneath ENR and thousands of years beneath WCA-2A. Those estimates of travel time are useful as general indicators of flow, although they are unlikely to accurately reflect the actual ground-water ages because recharge in the wetland interior and vertical mixing are not considered. Although realistic calculations of the ground-water travel time are desirable, those are difficult to compute with confidence at the present time because the spatial distribution of recharge across the wetland and the extent of vertical mixing in the aquifer is still not well enough known.

Vertical Hydraulic Gradients

ENR

The spatial distribution of recharge and discharge at ENR is shown by a contour map of vertical hydraulic gradients for a representative day in the wet season (fig. 11). Recharge occurs over all of the western two-thirds of ENR, and, based on the direction and high magnitude of the gradients, recharge appears to be the dominant interaction with ground water at ENR. Concluding that recharge is the dominant interaction with ground water from vertical gradients is consistent with the results of Choi and Harvey (2000), who found that recharge was an order of magnitude greater than discharge in ENR on the basis of a water and chloride budget.

Both the steep land-surface slope across the ENR and the abrupt drop in water elevation across the western boundary levee contribute to the substantial driving force for recharge. Water level in the eastern part of ENR ranges between 14 and 15 ft and declines to between 11 and 12.5 ft on the western side of ENR. Water level then declines another 3.75 ft across the western boundary levee to the seepage canal located just outside the ENR (fig. 2). The water level in the seepage canal nearly always was held constant at just below 8 ft (relative to 1929 NGVD).

The magnitude of vertical hydraulic gradients correlated positively with surface-water level in ENR (Choi and Harvey, 2000). Choi and Harvey (2000) showed that recharge in ENR was controlled by the rate of surface-water pumping into ENR, because that source of water strongly affects surface-water level, which in turn affects the driving force for recharge. Surface-water pumping generally is greatest in ENR during the wet season, which causes increases in ground-water recharge by as much as a factor of 3 during that season (Choi and Harvey, 2000).

Ground-water discharge occurred along a relatively narrow band on the eastern side of ENR (fig. 11). The driving force for discharge was the water level across the L-7 levee in WCA-1, which was 2.4 ft higher on average (between June 1996 and October 1998) compared with ENR. Discharge was correlated positively with water-level differences across the L-7 levee, with highest water levels in WCA-1 and greatest water-level differences usually occurring in the wet season (Choi and Harvey, 2000). As pointed out by Choi and Harvey (2000), ground-water discharge in ENR was small (approximately one-tenth) compared to recharge. Although the largest vertical hydraulic gradients were near levees, vertical hydraulic gradients also were discernable in interior areas of ENR. An example from site MP102, a site that consistently showed downward hydraulic gradients with a magnitude of approximately 0.005, is shown in figure 12. Most of the interior areas of the western two-thirds of ENR had similarly small downward hydraulic gradients, which, in total, accounted for approximately 6 percent of all recharge in ENR (Harvey and others, 2000).

WCA-2A

Highest vertical hydraulic gradients in WCA-2A were observed near the levee at site S10-C (Harvey and others, 2000). Similar to ENR, vertical hydraulic gradients at S10-C varied positively with the water-level difference across the levee. Normally, the water-level difference across the Hillsboro levee is about 2.8 ft, which is similar to the condition on the east side of

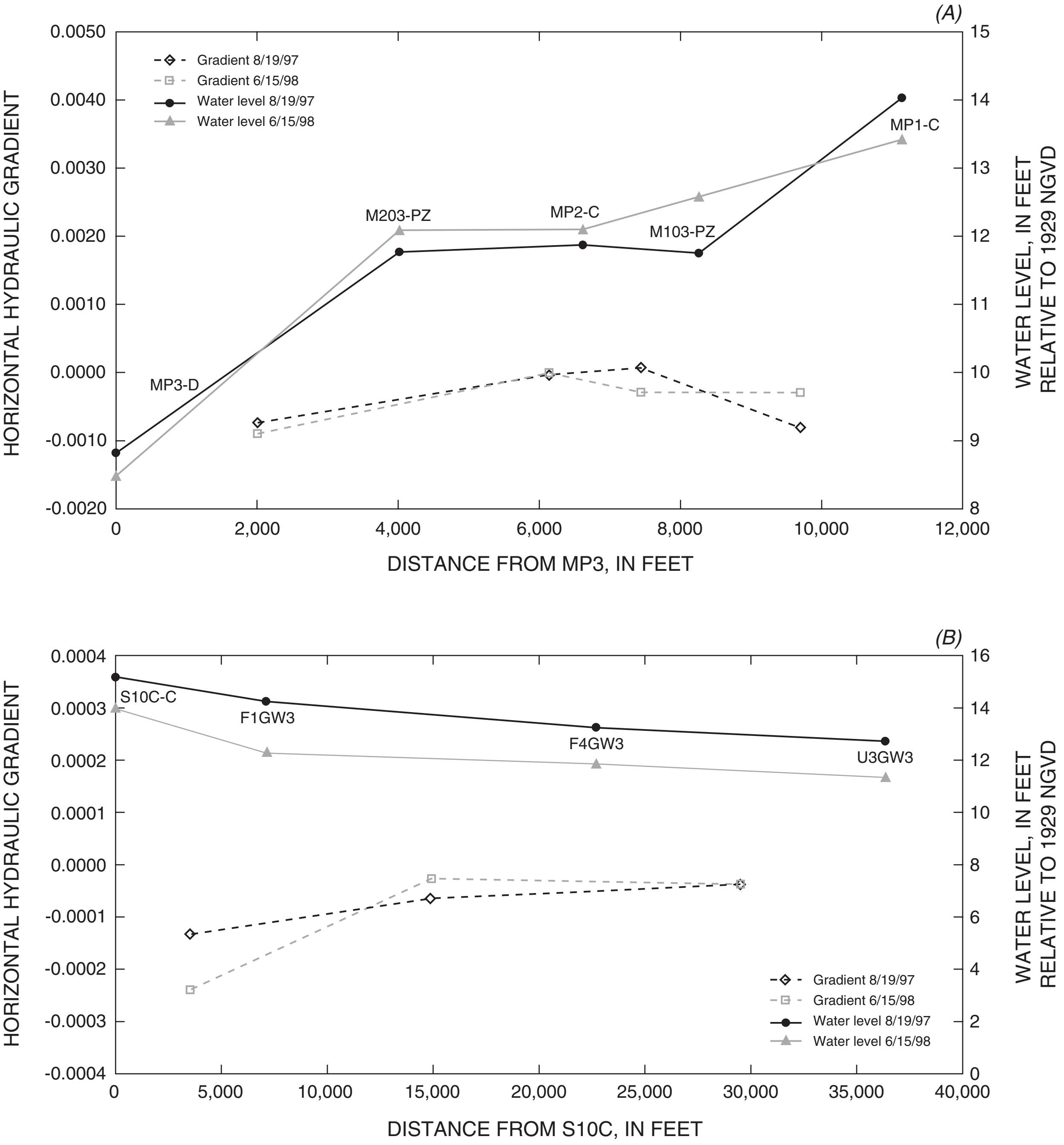


Figure 10. Water levels and horizontal hydraulic gradients along research transects in Everglades Nutrient Removal (ENR) project *(A)* and Water Conservation Area 2A (WCA-2A) *(B)*, north-central Everglades, south Florida. Wet conditions (August 1997) and dry conditions (June 1998) are compared. A negative gradient indicates flow towards the northwest (ENR) or southwest (WCA-2A). See figures 2 and 3 for transect locations.

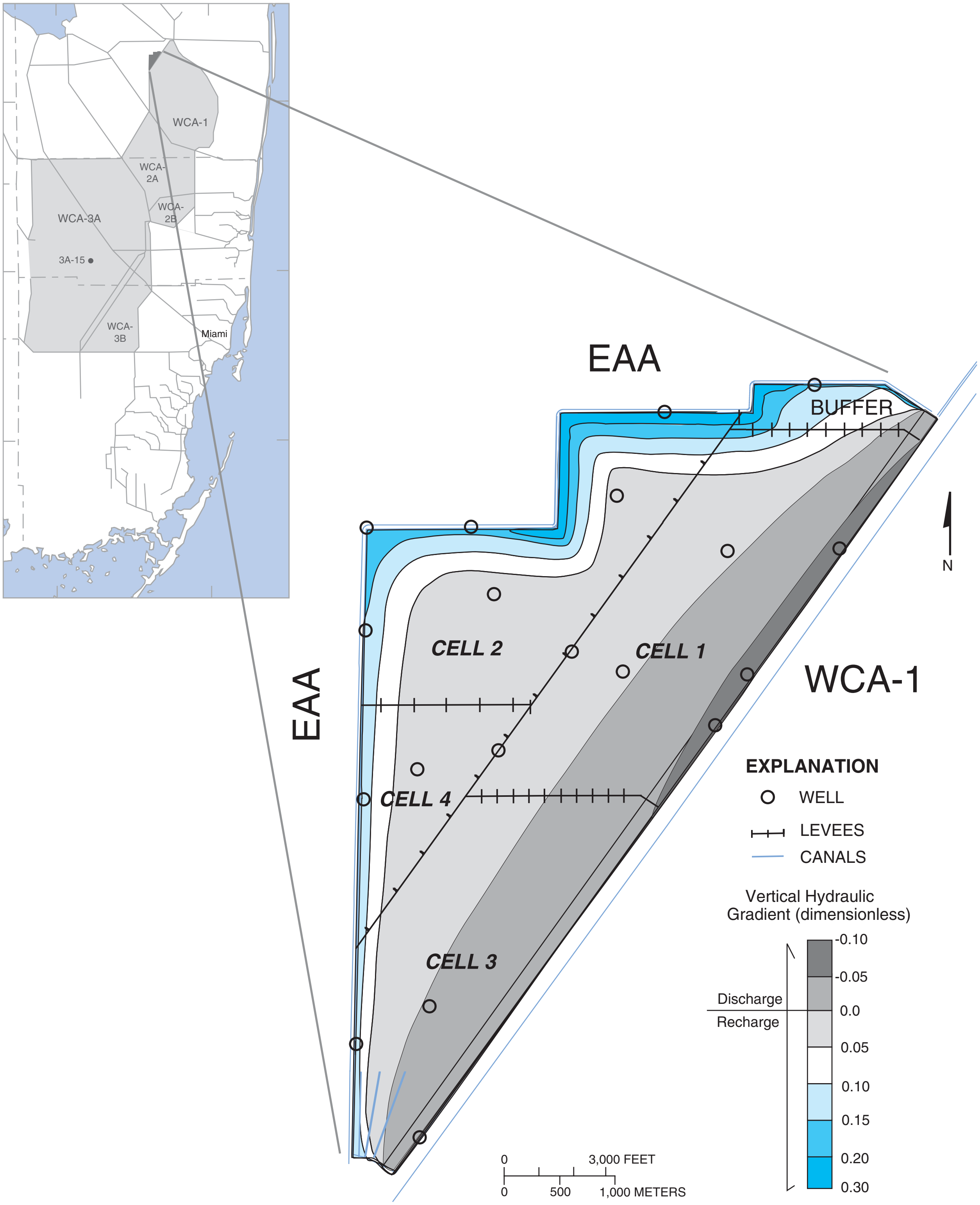


Figure 11. Distribution of vertical hydraulic gradients in Everglades Nutrient Removal Area (ENR), north-central Everglades, south Florida

ENR. Unlike the L-7 levee, the Hillsboro levee contains spillways, called the S10 structures, that are opened periodically to release water from WCA-1 into WCA-2A. During the wet season, it is not uncommon for the S10 spillways to be opened, allowing drainage from WCA-1 into WCA-2A. When spillways open, water levels in the S10C headwater canal drop rapidly while water levels increase rapidly in the tailwater canal. Vertical hydraulic gradients at S10C temporarily decline by approximately a factor of 3 when the spillway is open (Harvey and others, 2000, p. 222).

Sites in the interior of WCA-2A had lower vertical hydraulic gradients compared with the S10C site (Harvey and others, 2000). Representative water levels and vertical gradients with time at site F1 are shown in figure 13. Surface water-level measurements and ground-water head measurements at interior sites typically tracked each other very closely, often differing by only hundreds of a foot. Many of the vertical gradient calculations are below 0.002, corresponding to approximately a 0.03-ft head difference. Three-hundredths of an inch is near the limit of maximum achievable accuracy in measuring vertical head differences in the Everglades, because of the fundamental limits of the equipment used. Because of this limitation, determining with confidence the direction of the vertical hydraulic gradient in the interior of WCA-2A sometimes was challenging.

Despite the limitations on estimates of vertical gradients, patterns were apparent in vertical hydraulic gradients in interior areas of WCA-2A. The following interpretations are based on gradients between the shallowest instrumented layer in the aquifer (layer 2 instrumented with the GW-4 well) and surface water at all interior study sites. During the dry season, upward flow (discharge) was indicated on the western transect (F1 – F4 – U3) and neutral or possibly downward flow (recharge) was indicated on the E transect (E1 – E4 – U1) (fig. 3). During the wet season, there was greater variability in vertical hydraulic gradients.
Surface-water and ground-water interactions in interior wetlands of WCA-2A appear to be affected most by occasional large water releases from WCA-1 after heavy rains near the end of the dry season. If those water releases are large enough to bring the water level in the tailwater canal above 13.5 ft (relative to 1929 NGVD), surface water from the tailwater canal will overflow a berm and flow to the south through the WCA-2A wetland. Flow over the berm usually occurs at least once and often occurs two or more times per year (Harvey and others, 2000). Over a period of weeks to months following a water release, a wave of water initially1 to 4 ft high propagates southward through the wetland. As the wave peak passes a site on the transect, the direction of vertical ground-water flux reverses, from discharge to recharge (fig. 13).

Summary of Vertical Hydraulic Gradients

Vertical hydraulic gradients from both ENR and WCA-2A are greatest near levees within approximately 0.5 km of levees. The direction of vertical gradients near levees generally was constant with time, although magnitudes varied by a factor of 2 or 3 depending on the surface-water level difference across the levee. Vertical hydraulic gradients near levees generally were smaller in WCA-2A than ENR (figs. 12 and 13). Because the water-level differences that drive flow beneath levees are similar at both sites, smaller vertical gradients probably are associated with the higher hydraulic conductivity (*K*) of the Surficial aquifer at WCA-2A (Harvey and others, 2000)

Vertical gradients were approximately 50 to 100 times smaller in interior areas of the wetlands compared to sites near levees. Nevertheless, those fluxes are important to the basin-wide water balance because of the much larger areas of wetland involved. Recharge and discharge in interior areas of the wetlands are not primarily the result of ground-water flow beneath levees. In ENR, the greater than normal topographic and water-level slope toward the northwest (because of land subsidence and human engineering of the ENR wetland), exerts a major control over recharge in interior areas of ENR. The release of water from WCA-1 into WCA-2A, a necessary part of water management in WCAs, also appeared to have an important effect on the direction of vertical flux in WCA-2A, causing relatively rapid reversals between recharge and discharge at research sites.

Peat Hydraulic Properties

The overall mean estimate of *K* determined for Everglades peat was 26 cm/d or 0.84 ft/d (Harvey and others, 2000). That estimate of *K* is similar to that of very fine sand, but lower by approximately 2 orders of magnitude than the limestone and sand aquifer underlying the peat. That finding, and because the peat is laterally extensive, is the basis for concluding that peat is

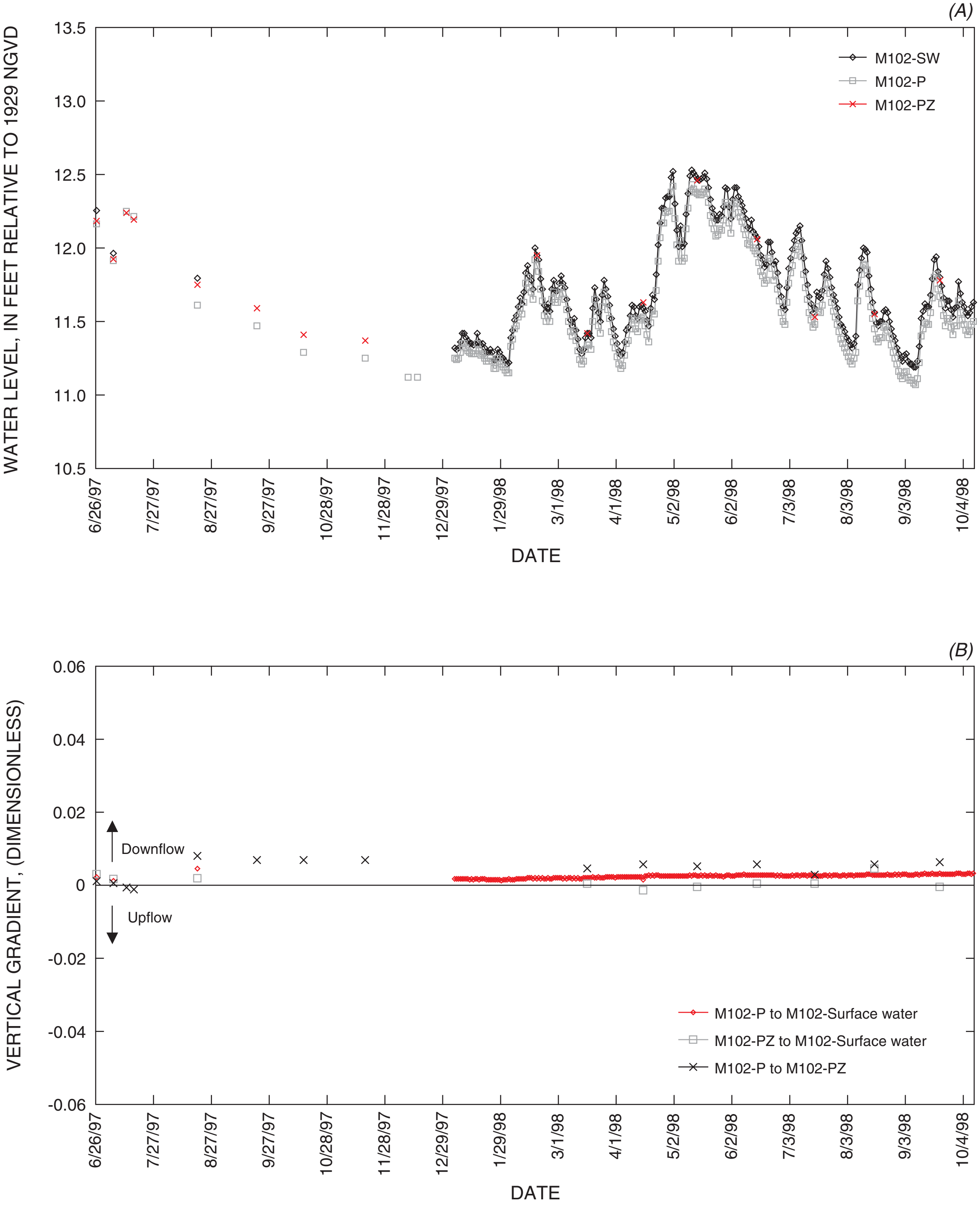


Figure 12. Water levels *(A)* and vertical hydraulic gradients *(B)* at Everglades Nutrient Removal (ENR) project site M102, north-central Everglades, south Florida. Vertical gradients are calculated relative to each well and to surface water. A positive gradient indicates the potential for downward flow, also known as recharge.

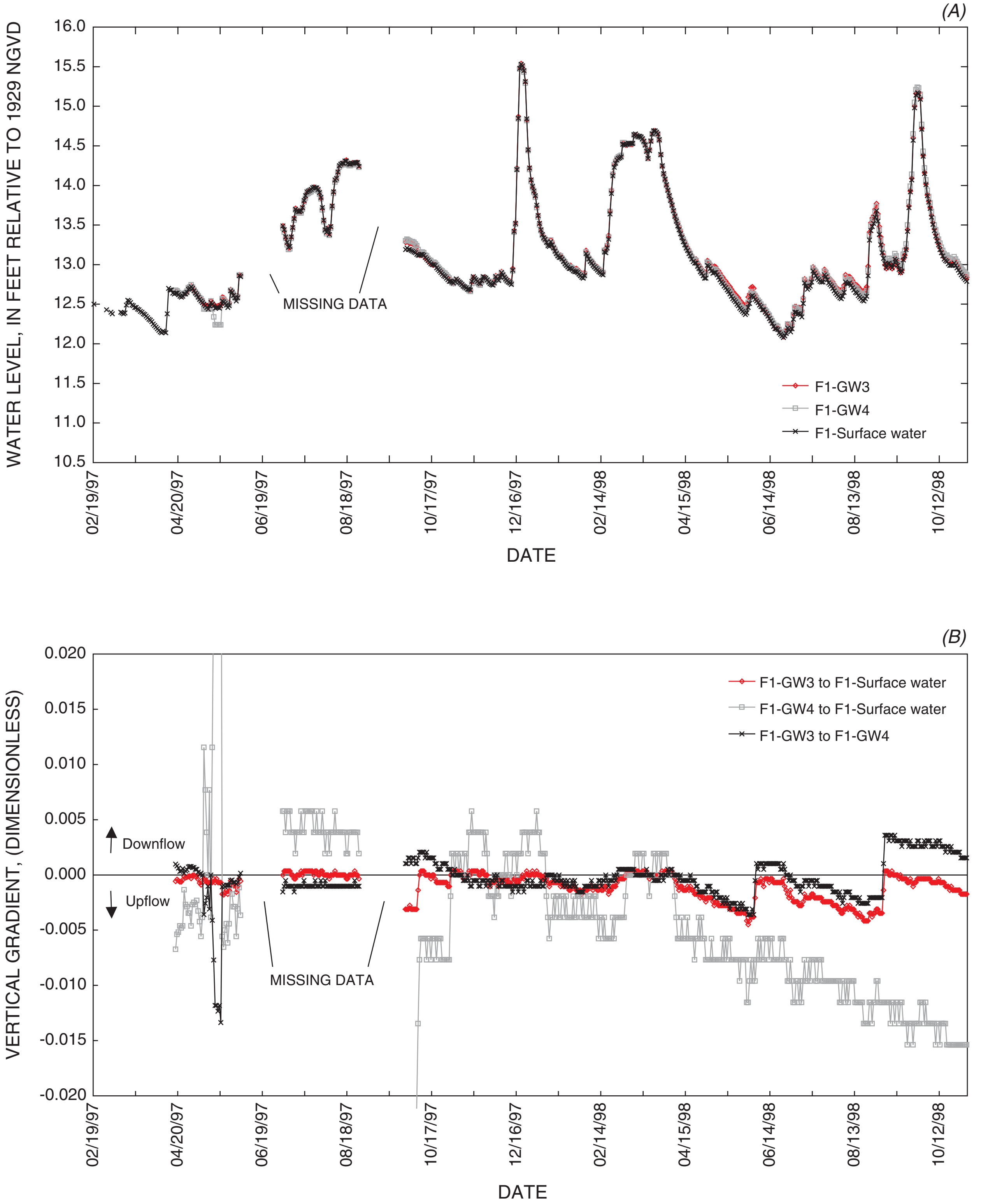


Figure 13. Water levels *(A)* and vertical hydraulic gradients *(B)* at Water Conservation Area 2A (WCA-2A) site F1, north-central Everglades, south Florida. Vertical gradients are calculated relative to each well and to surface water. A positive gradient indicates the potential for downward flow, also known as recharge.

the most important aquifer layer restricting vertical movement of water between ground water and surface water. The mean estimate of *K* in peat was higher for WCA-2A compared with ENR (43 and 8.1 cm/d or 1.4 and 0.27 ft/d, respectively). Estimates of *K* in peat are plotted with depth at both sites in figure 14. Both sites indicated that *K* was higher at the bottom of the peat near the transition to sand or limestone. The average *K* from the upper part of the peat at WCA-2A (30 cm/d or 1 ft/d) was used in Darcy-flux calculations at WCA-2A, because that layer was more likely to control the vertical flux.

Measured Vertical Head Gradients Compared with Hydrogeologic Model Simulations

Factors affecting recharge and discharge were examined using a simple hydrogeologic model of ground-water flow beneath levees. An analytical solution from Barlow and Moench (1998) was used to compute the hydraulic head distribution in a "leaky aquifer" with a hydraulic restricting layer at the top (representing peat). One-dimensional (horizontal) flow through an aquifer with uniform hydrogeologic properties is assumed in the model, and allows for vertical leakage across the peat. The stress applied to the model was a sudden 1-m change in head at the left boundary (representing an increase in the water level of a canal that is separated from the wetland by a levee). Because of the one-dimensional flow assumption, the head at the left boundary of the aquifer (in contact with the canal) is equal to the canal water level and is constant with depth. That boundary condition is common to many models of interactions between surface water and ground water, and, in the present case, represents the hypothetical situation where the canal fully penetrates the aquifer (fig. 15a). A constant surface-water level in the wetland was simulated using the “source bed” option, which holds the hydraulic head constant at the top of the restricting layer. This option is the best way to simulate how surface water that discharged from the aquifer would quickly flow away from the levee vicinity toward the wetland interior, leaving surface-water levels in the vicinity of the levee approximately constant for the period of the simulation. The hydrogeologic parameters used in model simulations were as follows: aquifer depth –60 m, peat depth –1 m, *K* in aquifer –30 m/d, *K* in peat –0.3 m/d, and specific storage in both aquifer and peat –0.001 m.

The primary result of the hydrogeologic simulation was determining that the effect of ground-water flow beneath the levee extended only 0.5 km into the wetland (fig. 15b). Even in a simulation with a *K* value for peat that was two orders of magnitude smaller than measured values (approximately 0.3 m/d), the distance of interaction increased only by approximately a factor of 2. Beyond 0.5 km, the simulated vertical head gradient across the peat was 3 x 10^{-6} or less, which is much smaller than typical vertical hydraulic gradients actually measured in interior areas of WCA-2A (typically 0.003 or higher, fig. 13). Even an improved two-dimensional model of ground-water flow beneath the levee probably would not change the observed mismatch between model and observations in the interior part of WCA-2A. Therefore, it was concluded that ground-water flow beneath levees is not an adequate explanation for a substantial part of the recharge and discharge that occurs in interior areas of WCA-2A.

If water-level differences across levees and ground-water flow beneath the levee do not control recharge and discharge in interior areas of the wetlands, then what factors do? Other factors possibly controlling recharge and discharge may include fluctuations in surface-water levels in the wetlands. A constant surface-water level with no spatial or temporal changes in water-surface slope was assumed in the hydrogeologic model. Field observations discussed earlier indicated that surface-water levels and slopes change rapidly at times, because of water releases between WCAs. Surface-water slope in the wetland varies from essentially flat at certain times to a factor of 2 greater than the land-surface slope at other times. The effect of surface-water dynamics on interactions between surface water and ground water is discussed later as part of the interpretation of measured recharge and discharge fluxes.

Recharge and Discharge Estimates

Seepage-Meter Results from ENR

Seepage-meter measurements were made at ENR between August 1996 and April 1998. The absolute values of fluxes ranged from less than 0.04 cm/d (0.001 ft/d) to as much as 20 cm/d (0.66 ft/d). The typical uncertainty of a flux measurement was ±50 percent,

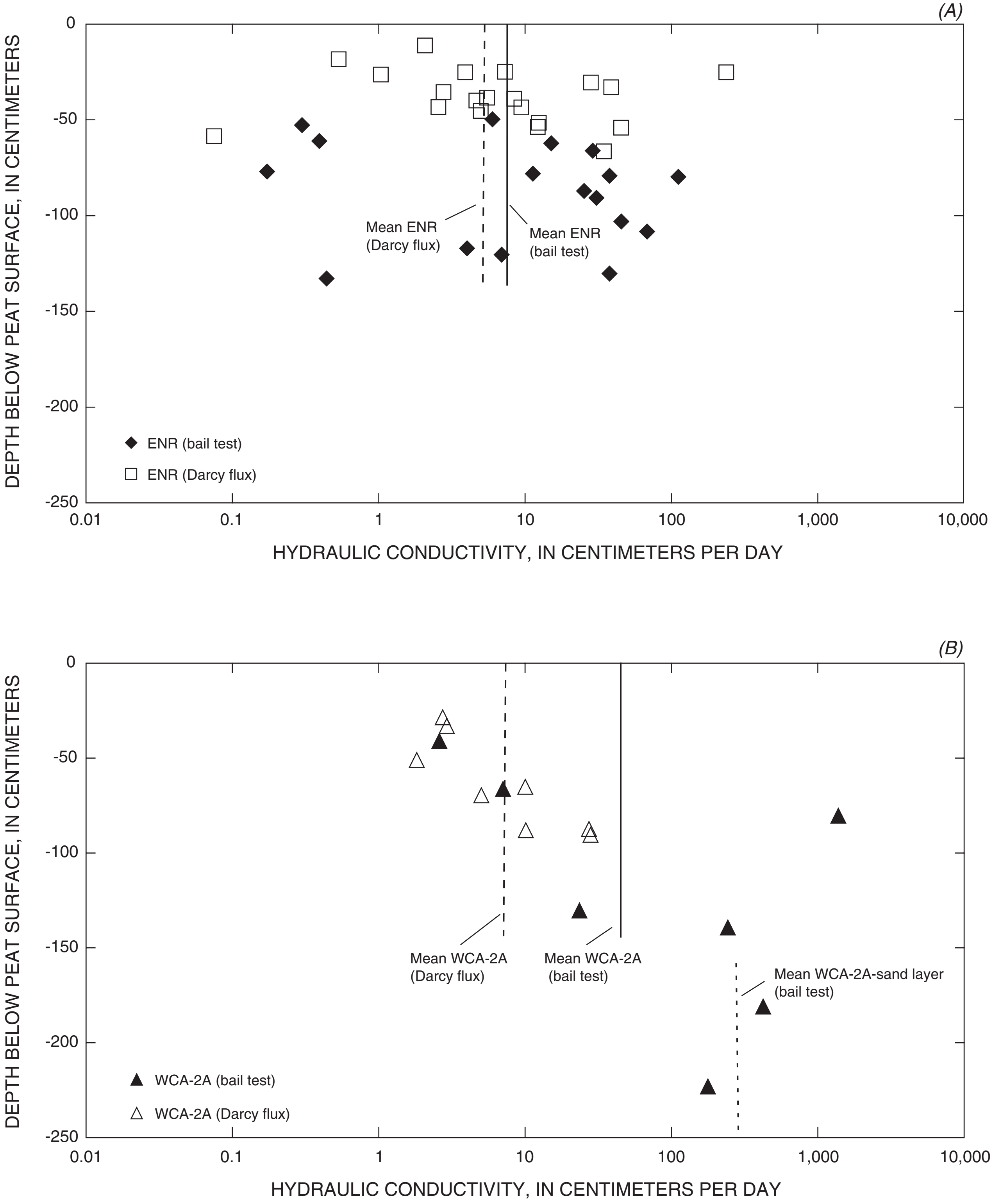


Figure 14. Hydraulic conductivity of wetland peat in Everglades Nutrient Removal (ENR) project *(A)* and wetland peat and underlying sand layer in Water Conservation Area 2A (WCA-2A*) (B)*, north-central Everglades, south Florida.

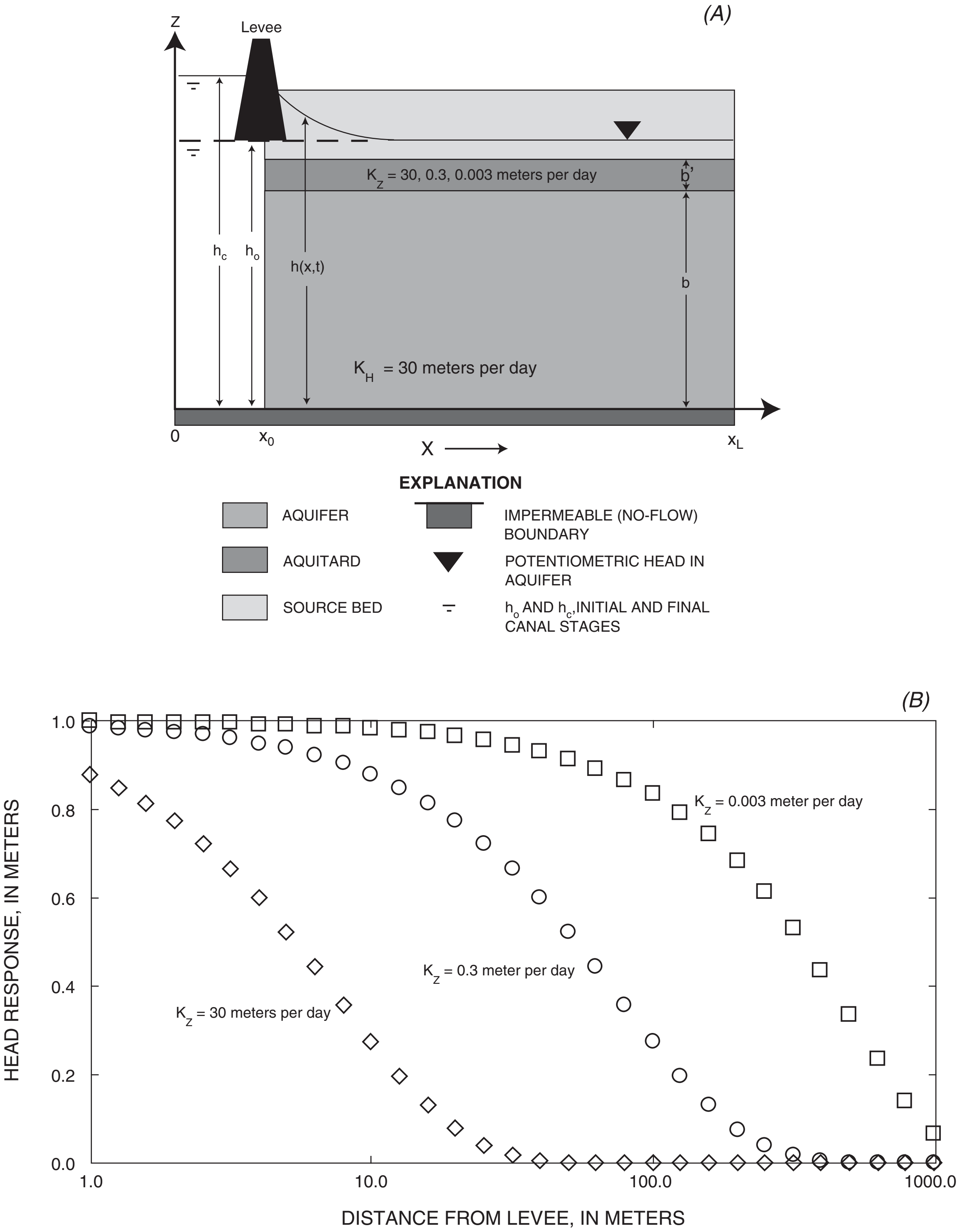


Figure 15. Hydrogeologic simulation of head change in aquifer capped with wetland peat responding to a change in water level at the left boundary (canal/levee complex). Schematic of simulated aquifer system *(A)*, equilibrium head distribution after 1-meter rise in water level in canal at left boundary *(B)*.

based on replicate measurements from side-by-side seepage meters (Harvey and others, 2000). The lower end of that measurement range is the estimated detection limit of seepage meters at the study sites. The higher end of the measurement range is two orders of magnitude higher than average daily precipitation and evapotranspiration in the Everglades (Harvey and others, 2000).

Seepage-meter measurements indicated that recharge occurred in most areas of ENR, which is consistent with the distribution of vertical hydraulic gradients (fig. 11). Time-averaged discharge and recharge fluxes on a transect across ENR are shown in figure 16. Fluxes were above detection at eight out of nine sites, and, for comparison, exceeded average annual precipitation (0.4 cm/d) at four out of nine sites.

All of the seepage-meter data at ENR over approximately a 2-year period are summarized and displayed graphically in table 14 and figure 17, respectively. The direction of vertical exchange at a site usually was constant over time, with recharge occurring at sites on the western side and in the interior and discharge occurring on the eastern side. The greatest contrast in fluxes was between sites near levees and sites in the interior of ENR. Fluxes near levees typically were two orders of magnitude higher than fluxes in the wetland interior. The observed pattern of decreasing fluxes with distance from levees is consistent with results from the hydrogeologic model used in this study, suggesting an exponential decrease in flux with distance from the levee (fig. 18).

Seepage-meter measurements and hydrogeologic modeling agree that proximity to levees was the most important factor affecting the magnitude of recharge and discharge at ENR (fig. 18). Temporal variability in vertical fluxes generally was much smaller than spatial variability at ENR. Vertical fluxes at a location typically varied over time by less than a factor of 3, whereas fluxes varied spatially across ENR by over an order of magnitude.

Darcy-flux calculations from WCA-2A

At WCA-2A, recharge and discharge fluxes were computed using Darcy's law. Daily calculations were made for all sites in WCA-2A for the period January 1997–December 1998.

Discharge occurred on the tailwater side of the S10C levee site at WCA-2A. The median flux was approximately 2.5 cm/d, which is similar to the sites nearest levees in the ENR (table 15). However, fluxes were more variable at the S10C site compared with ENR. Greater variability in fluxes at the S10C site compared with levee sites at ENR is consistent with the greater variability in surface-water levels and vertical hydraulic gradients discussed earlier. The important difference with ENR is that, at WCA-2A, the major water supply is through a spillway. When opened, the S10C spillway lowers the local water level in WCA-1 and raises water levels in WCA-2A in a matter of hours. In contrast, water is supplied to ENR by rapidly transporting water through a supply canal. Consequently, changes in the supply rate have less effect on the water-level difference between WCA-1 and ENR.

Recharge in the interior areas of WCA-2A was greater by approximately a factor of 4 compared with ENR (0.2 and 0.05 cm/d, respectively). Larger vertical fluxes in the interior of WCA-2A are caused, at least in part, by the larger hydraulic conductivity of the peat at WCA-2A. On average, hydraulic conductivity of peat is approximately a factor of 6 greater in WCA-2A compared with ENR. Also important in explaining larger vertical fluxes at WCA-2A are the larger surface-water level fluctuations compared with ENR. Larger fluctuations in surface-water level increase the driving forces for recharge and discharge. Although greater than ENR, recharge and discharge in the interior of WCA-2A still are relatively small, even when compared with average annual precipitation or evapotranspiration (approximately 0.40 and 0.35 cm/d).

Temporal variation in the interior fluxes at WCA-2A generally exceeded spatial variation, which is opposite of the result in ENR. Discharge occurred approximately 75 percent of the time at sites F1, F4, U3, and E4. Recharge occurred at site E1 approximately 75 percent of the time (table 15). Discharge and recharge each occurred approximately half the time at site U1. Fluctuations in recharge and discharge included reversals in flow direction at all sites except S10C (figs. 18 and 19). It was important, therefore, to characterize temporal variability of vertical fluxes at interior sites in WCA-2A. Flux percentiles for each site are shown in figure 19 and table 15. Over the period of the study, the vertical fluxes at most sites in the WCA-2A interior changed direction at least once. In general, recharge was more common at sites in the WCA-2A interior at the beginning of the 2-year period, and discharge was more common at the end (fig. 20). For sites E1, F1, and U3, the flux direction changed only once during the 2-year period. Flux direction

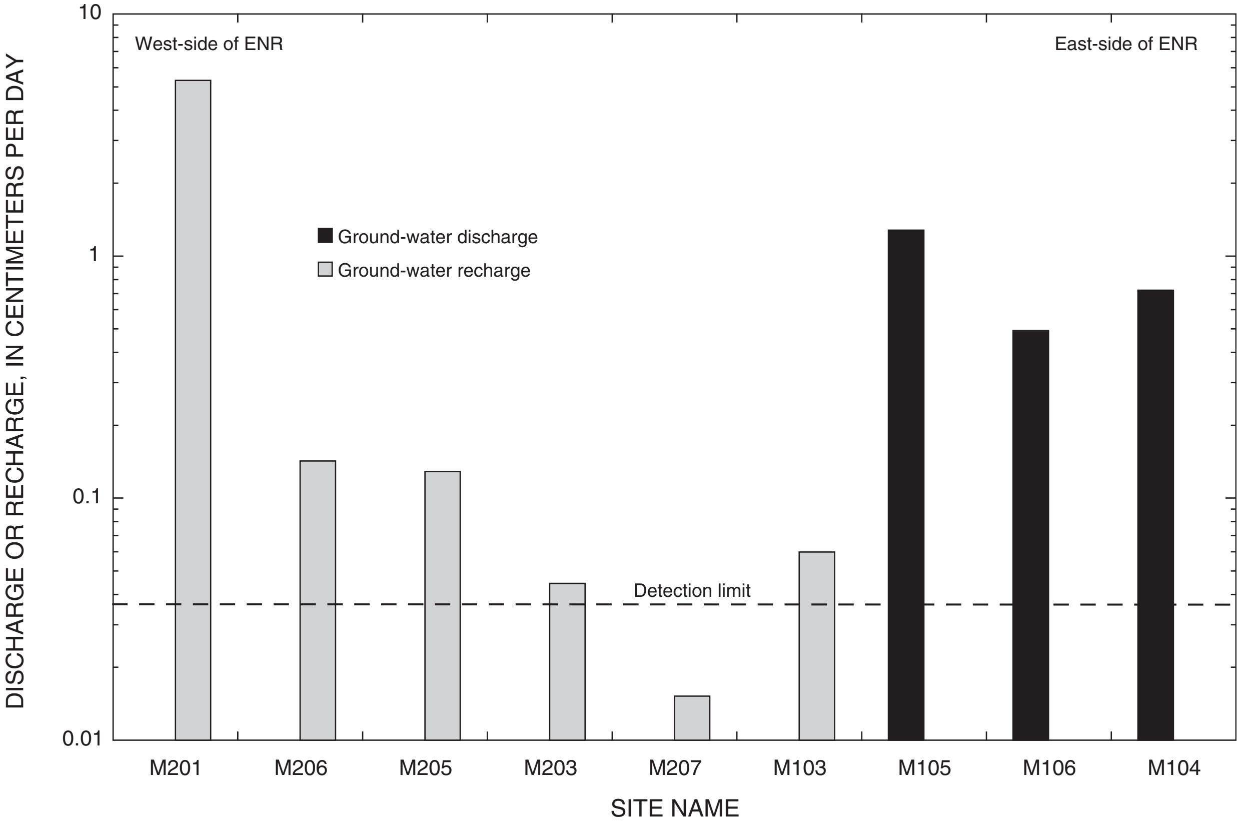


Figure 16. Time-averaged discharge and recharge fluxes across transect A-A' in Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida.

changed various times at sites E4 and F4. The flux direction changed frequently at site U1 (every 20 to 40 days) on cycles that appeared to correlate with surface-water levels (fig. 20).

There is no single method that is advisable for averaging vertical fluxes to account for spatial and temporal variability. For the purpose of a water balance (discussed in the next section), the approach used here was to average the median fluxes for "discharge" sites to characterize average discharge, and to do the same for "recharge" sites. The quotations mean that the definition of a discharge or recharge site depended on an ability to determine the dominant flux for a site, that is, where either discharge or recharge occurred at least 75 percent of the time. Neither discharge nor recharge dominated at site U1. That site was, therefore, not considered in the average calculations. The result of averaging across remaining sites was a discharge flux of 0.11 cm/d and a recharge flux of 0.18 cm/d. These results must be considered preliminary because data only were available for a relatively small number of sites. It is worth noting that other possible approaches to averaging the data set gave similar results, which provides some confidence in these preliminary estimates of discharge and recharge in WCA-2A.

Because water levels are always higher in WCA-1 compared to WCA-2A, it is clear that reversals between recharge and discharge are not consistent with the hypothesis that ground-water flow beneath levees is the main driving force. Instead, the results support the previous conclusions from hydrogeologic modeling, that ground-water flow beneath levees is effective mainly at distances less than 0.5 km from levees, and that vertical fluxes in the wetland interior are controlled by other processes. For example, regional gradients in water-table slope and surface-water level fluctuations are factors that could affect recharge and discharge in the wetland interior. The combination of those factors drives reversals between recharge and discharge at various timescales. For example, interannual rainfall variability, and its effects on regional water tables and water-resources management, drive multi-year fluctuations that explain the longest term trends in recharge and discharge. With only 2 years of data, however,

Table 14. Time-averaged vertical fluxes at study sites in Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida, 1997-98. Discharge fluxes are positive and recharge fluxes are negative

[cm/d, centimeters per day; n, sample number]

	Vertical Flux (cm/day)			
Percentile	**M104**	**M106**	**M105**	**M103**
10%	0.18	0.16	0.09	-0.21
25%	0.30	0.23	0.15	-0.12
50%	0.73	0.29	0.39	-0.03
75%	1.1	0.78	2.27	0.01
90%	1.3	4.7	4.7	0.02
Mean	0.760	1.2	1.5	-0.06
Max	3.145	8.4	8.4	0.13
Min	0.065	0.09	0.04	-0.32
n	110	43	40	37

Percentile	**M203**	**M205**	**M206**	**M201**
10%	-0.15	-0.36	-0.66	-12
25%	-0.06	-0.17	-0.11	-9.6
50%	-0.03	-0.07	-0.07	-3.3
75%	-0.009	-0.05	-0.06	-2.3
90%	0.008	-0.02	-0.04	-1.1
Mean	-0.05	-0.13	-0.14	-5.6
Max	0.22	0.19	-0.04	-0.20
Min	-0.63	-0.66	-0.99	-22
n	53	43	14	68

Table 15. Time-averaged vertical fluxes at study sites in Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida, 1997-98. Discharge fluxes are positive and recharge fluxes are negative

[cm/d, centimeters per day; n, sample number]

	Vertical Flux (cm/d)			
Percentile	**S10C**	**E1**	**E4**	**U1**
10%	1.3	-0.27	-0.28	-0.73
25%	2.0	-0.18	0.00	-0.30
50%	2.8	-0.18	0.09	0.00
75%	3.3	0.00	0.28	0.38
90%	4.3	0.27	0.37	0.85
Mean	2.7	-0.10	0.07	0.01
Max	4.8	0.59	1.9	1.2
Min	0.18	-0.99	-1.7	-2.6
n	262	526	545	461

Percentile	**S10C**	**F1**	**F4**	**U3**
10%	1.3	-0.12	-0.14	-0.05
25%	2.0	0.00	0.00	0.00
50%	2.8	0.18	0.08	0.06
75%	3.3	0.35	0.23	0.12
90%	4.3	0.47	0.38	0.24
Mean	2.7	0.17	0.11	0.06
Max	4.8	0.70	0.84	0.56
Min	0.18	-0.35	-0.69	-0.46
n	262	533	516	451

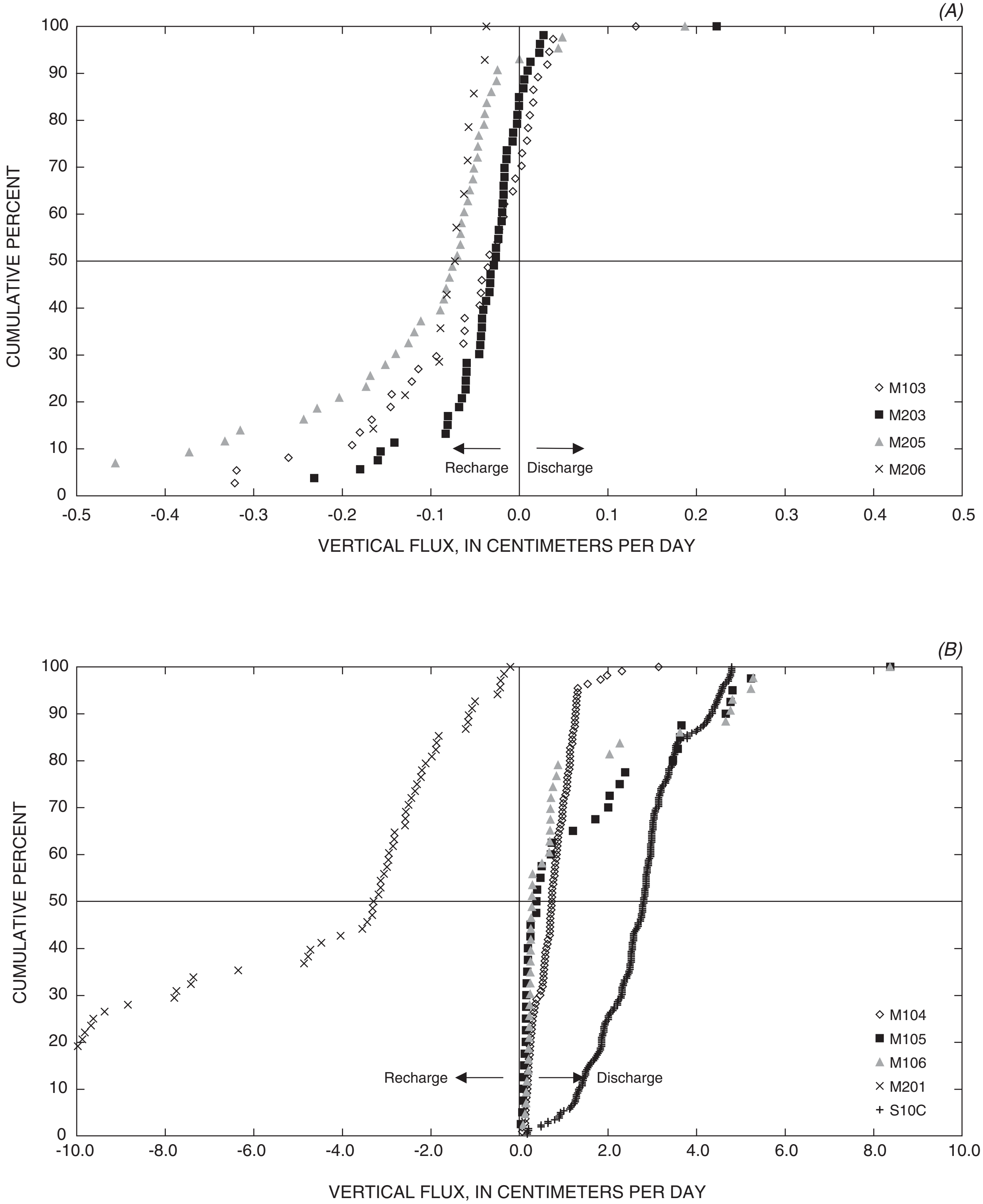


Figure 17. Cumulative distributions of vertical fluxes measured with seepage meters at sites in the wetland interior in ENR *(A)*, and at sites near levees in ENR and WCA-2A *(B)*. Note scale differences on x-axis (vertical flux).

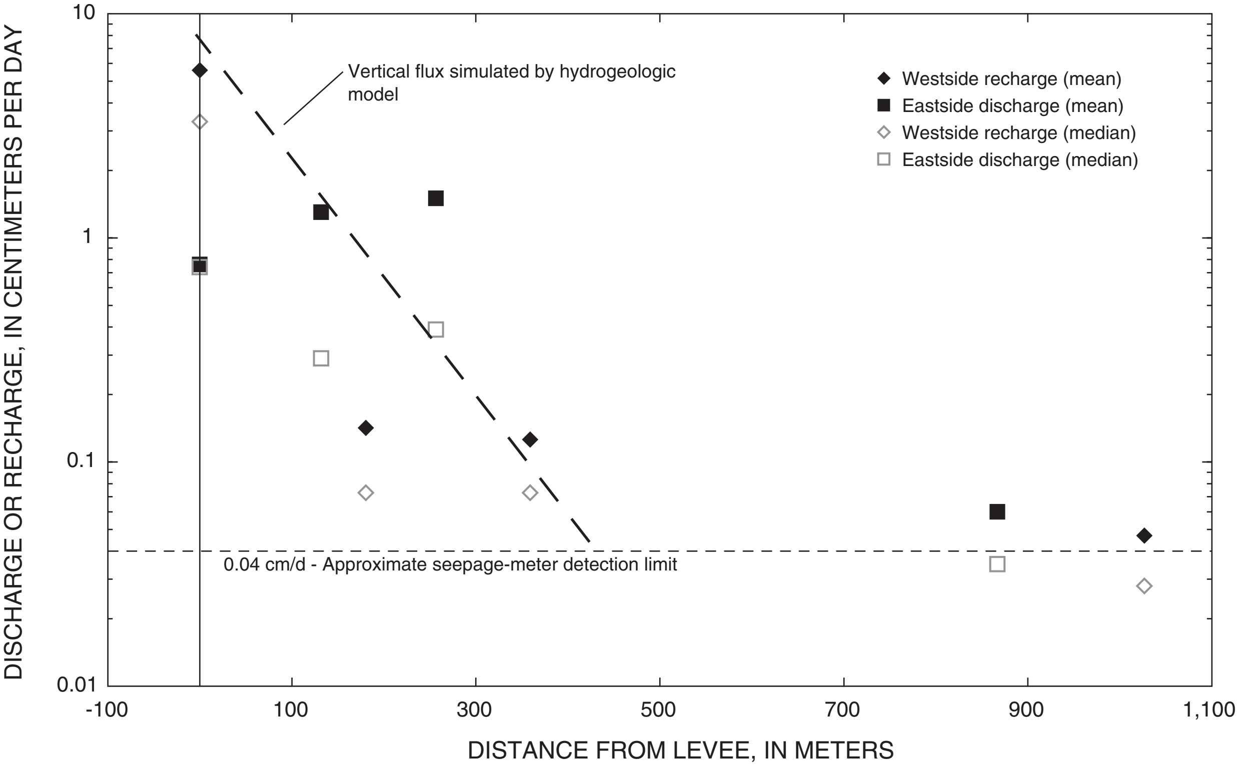


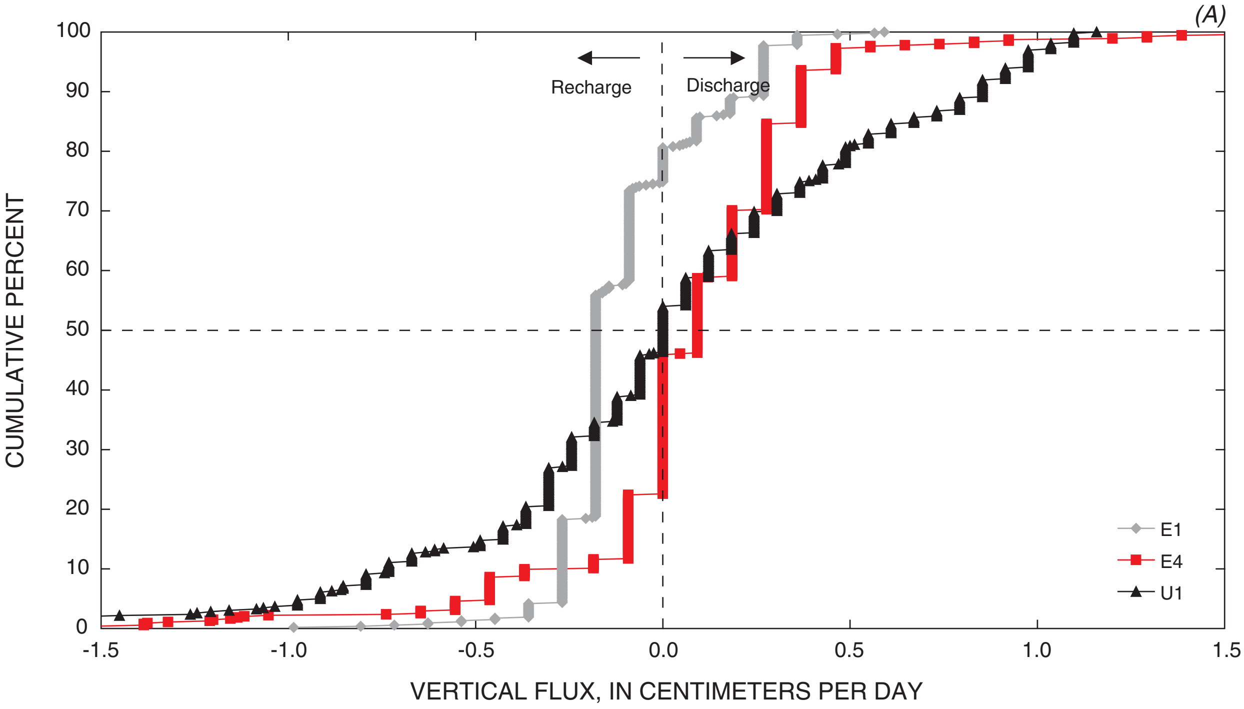
Figure 18. Observed discharge and recharge and simulated fluxes in Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida. Both mean and median fluxes are plotted for each study site.

those longer term trends are difficult to characterize except to indicate that long-term net recharge is correlated with multi-year periods of relatively wet conditions, whereas long-term discharge is correlated with multi-year periods of relatively dry conditions.

The present study showed that shorter timescale water-level fluctuations of weeks to months can control variations in recharge and discharge, including reversals in direction of fluxes. Water releases through spillways are important because those disturbances propagate as waves into the basin interior. Wave movement through the wetlands creates areas of high and low pressure over relatively short distances (hundreds of meters to kilometers). As discussed previously, recharge tends to occur beneath wave peaks whereas discharge tends to occur away from wave peaks. Another factor involved that was not previously discussed is the movement of pressure waves horizontally through the Surficial aquifer, in addition to wave propagation in surface water. Pressure waves travel at different speeds through different layers of the aquifer, causing simultaneous upward discharge and downward recharge from the sand layer beneath the peat. That process was most clear at the E4 site, where vertical hydraulic gradients indicate that the sand layer acts as a source of water that simultaneously discharges to surface water and recharges to the underlying limestone aquifer at times of low water in WCA-2A (Harvey and others, 2000, p. 225).

Seepage-meter Results from WCA-2B and WCA-3A

Seepage meters at the one study site in WCA-2B indicated persistent recharge over time. At site WCA-3A15, neutral conditions or slight recharge was indicated. Only seepage-meter data were available from those sites; therefore, interpretations are made without the benefit of vertical head gradients to compare for consistency at other sites. Seepage-meter measurements were spaced far apart in space and time in those areas because of the remoteness of these study sites. Consequently, evidence for short-term reversals in vertical fluxes at those sites could not be thoroughly evaluated. Nevertheless, the results from those two



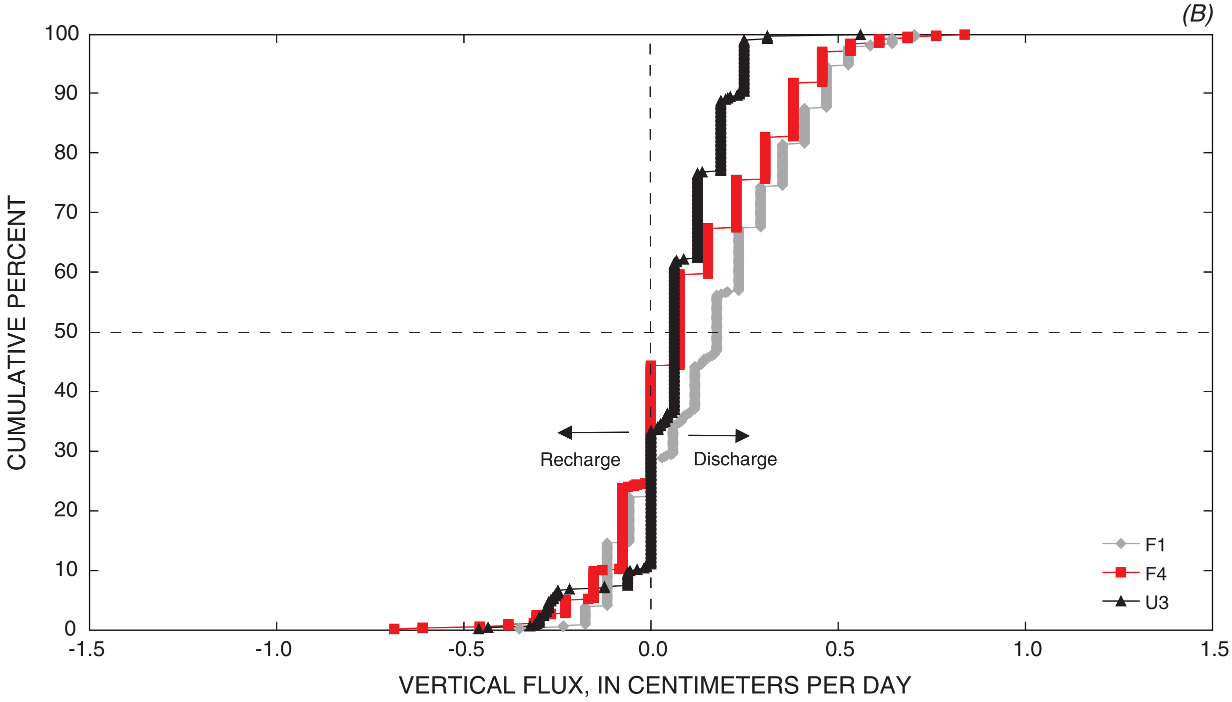


Figure 19. Cumulative distributions of vertical fluxes calculated by Darcy's law on Eastern transect *(A)*, and Western transect *(B)*, in Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida.

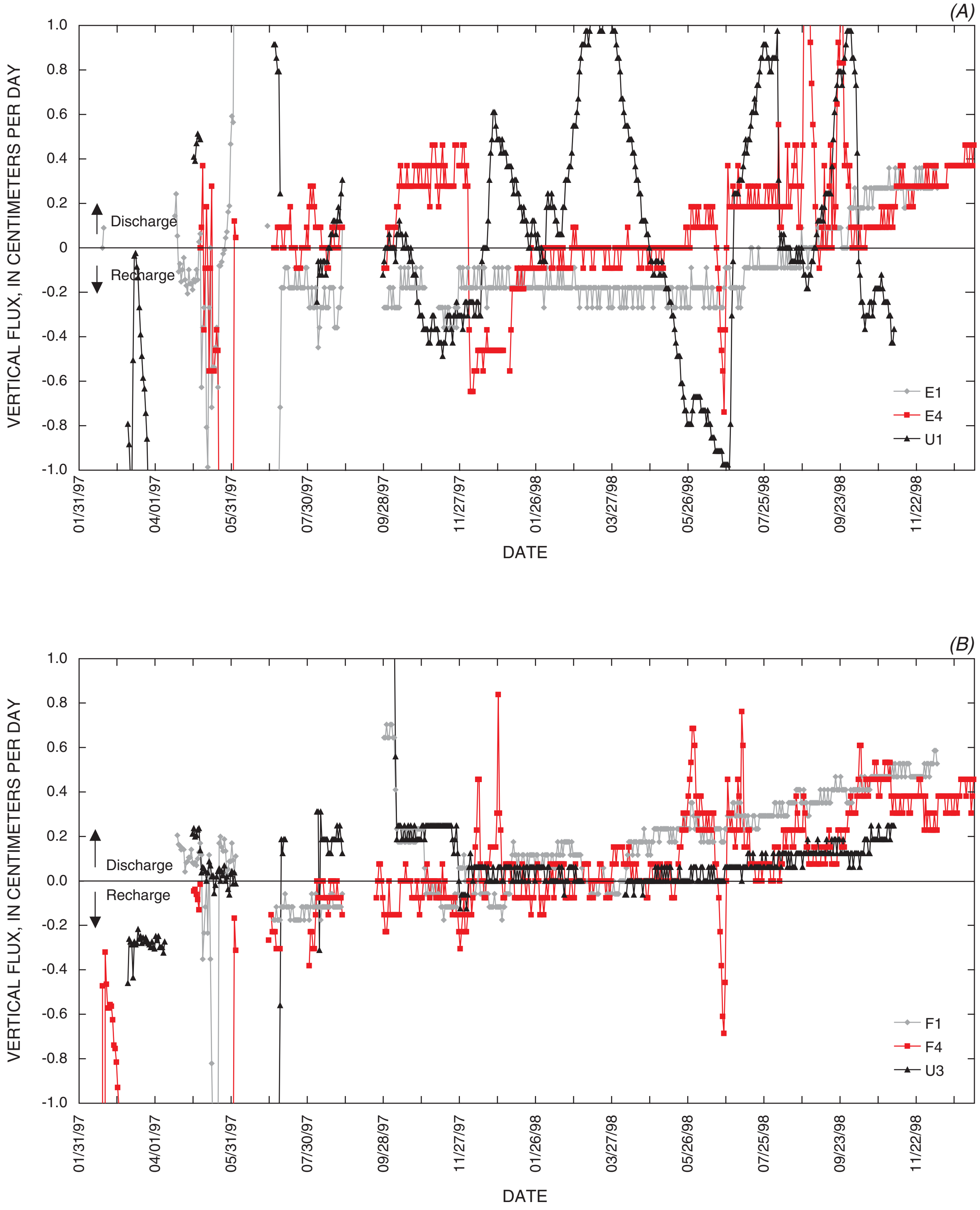


Figure 20. Vertical fluxes observed over a 2-year period on the Eastern transect *(A)*, and Western transect *(B)*, in WCA-2A, north-central Everglades, south Florida.

sites are valuable because they suggest a time-averaged trend of recharge at a site in WCA-2B referred to as 2BS, and fluxes that are below detection or slightly on the side of recharge at a site in WCA-3A referred to as 3A-15 (fig. 1).

Water Balance

An important extension of this study to estimate recharge and discharge was to average those measurements over space and time for inclusion in basin-wide water balances for ENR and WCA-2A. At ENR, it was relatively straightforward to develop those estimates (Choi and Harvey, 2000), in part because of the high density of measurements and partly because multiple independent approaches proved useful and could be compared. Developing basin-scale estimates of recharge and discharge at WCA-2A was much more difficult, mostly because the density and frequency of water-level and chemical measurements were much less than at ENR. To develop these estimates at WCA-2A, the results of a 30-year hydrologic budget for WCA-2A developed by South Florida Water Management District using the SFWMM were consulted (SFWMD, C&SF Restudy, http:\\www.sfwmd.gov). The present study uses new data as well as previous information to develop recharge and discharge estimates in ENR and WCA-2A (table 16). Discrepancies are noted between new information and previous work, such as new estimates of vertical fluxes in the interior of WCA-2A that exceed previous estimates of total recharge and discharge in WCA-2A. These discrepancies were expected because differing methods and different periods of data record were used in each study. Those discrepancies are discussed and, where possible, resolved, in the remainder of this section.

Recharge was the dominant interaction between the wetland and ground water at ENR when averaged over the entire basin and over the 4-year study period. Total recharge averaged 0.9 cm/d and discharge was 0.1 cm/d (Choi and Harvey, 2000). Expressed as a percentage of water inflows, those fluxes are 31 and 3 percent, respectively, of surface water pumped into ENR for treatment. Discharge at ENR is ignored in further discussion because recharge dominated vertical fluxes. Ground-water flow beneath levees accounted for approximately 94 percent of the total recharge flux in ENR. Choi and Harvey (2000) showed that approximately 73 percent of the total recharge was discharged to the seepage canal. The seepage canal collected a mixture of shallow ground-water flow beneath levees and deep ground water flowing vertically to the surface. At sites greater than 0.5 km from the western and northern levees, recharge also occurred but at much lower rates. The average recharge at interior sites was approximately 0.05 cm/d, which accounted for only about 6 percent of the total recharge in ENR (table 16). Having accounted for a total of 79 percent of all recharge in ENR, the remaining 21 percent was inferred to have bypassed the seepage canal, probably discharging instead in nearby agricultural land. Eventually, that water would have discharged to a canal at another location in the EAA, to be evapotranspired or pumped away through a different system of canals.

Recharge varied temporally in ENR. Whereas flow in the seepage canal was almost constant, total recharge varied over approximately a factor of 2, correlating positively with surface-water levels in ENR (Choi and Harvey, 2000). For that reason, Choi and Harvey (2000) concluded that recharge was controlled mainly by water management rather than other factors (such as seasonal or interannual variation in precipitation).

In WCA-2A, recharge also was the dominant interaction between the wetland and ground water. Averaged over 2 years throughout the entire basin, a recharge of 0.2 cm/d and discharge of 0.1 cm/d was estimated for the WCA-2A interior, which amount to 31 percent and 15 percent of average surface-water fluxes through WCA-2A, respectively (table 16). Using the SFWMM, researchers at SFWMD estimated recharge in WCA-2A to be 0.04 cm/d and discharge to be 0.02 cm/d, equal to 6 and 3 percent of surface-water inflow to WCA-2A, respectively. Lower values of recharge and discharge from SFWMD model simulations may be the result of the larger spatial scale and longer temporal scale of averaging inherent in their methods. The present research suggests that SFWMD estimates are minimum estimates, and that recharge and discharge in WCA-2A each are approximately a factor of 5 larger. It is important to keep in mind that the difference among various estimates of recharge and discharge is not a reflection on the relative value of different approaches—each has its merits. The detailed estimates of recharge and discharge developed by the present study are important to shorter term and smaller scale water-balance studies, and studies concerned with water quality. The estimates of recharge and discharge reported here are based on relatively short data sets and

Table 16. Basin-scale estimates of recharge and discharge in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida

[cm/d, centimeters per day; B.D., below detection; –, not applicable]

Site	Total Basin Flux (cm/d)		Interior Basin Flux[&] (cm/d)	
	Recharge	Discharge	Recharge	Discharge
ENR	0.9 [a] (31)[*]	0.1 [a] (3)	0.05 [c] (6)	B.D.[c] (–)
WCA-2A	0.04 [b] (6)	0.02 [b] (3)	0.2 [c] (31)	0.1[c] (15)

[a] Average for August 1994 to August 1998, from Choi and Harvey (2000).

[b] Average for 1965 to 1995, from South Florida Water Management District, http://www.sfwmd.gov.

[c] Average for February 1997 to October 1998, this study.

[*] Numbers in parentheses indicate percentage of surface-water inflow.

[&] Interior basin refers to all wetlands in basin farther than 0.5 kilometer from a levee

must be considered uncertain until a longer term data set is available. The larger scale water-balance work at SFWMD is well established and has primary importance to regional flow estimation. More detailed comparisons between the SFWMM and the measurements of the present report should be encouraged.

The main factor that caused recharge and discharge fluxes to increase at ENR relative to pre-drainage conditions was land subsidence, which was near its maximum in terms of the effects on the land slope in that vicinity. Another factor affecting recharge in ENR is the relatively large ratio of levee perimeter to wetland surface area (4 x 10^{-4} ft/ft^2) compared with WCAs. That ratio was a factor of 6 smaller in WCA-2A (6 x 10^{-5} ft/ft^2), suggesting a higher contribution of ground-water flow beneath levees per unit area of wetland. As discussed earlier, vertical fluxes within 0.5 km of levees usually were higher than 0.3 cm/d, whereas fluxes in the wetland interior typically were less. As a result, ground-water flow beneath levees accounted for 94 percent of recharge at ENR (whereas vertical fluxes in the wetland interior were thought to dominate in WCA-2A), and basin-averaged recharge was almost 5 times larger in ENR compared to WCA-2A (table 16).

The overall result of land subsidence and water-resources management in the north-central Everglades appears to be a general pattern of decreasing interactions between surface water and ground water, from areas where they are highest in the relatively small basins at the northern boundary (ENR and STAs), to the center of the Everglades' largest enclosed basin (WCA-3A). The greatest recharge and discharge fluxes were observed in ENR, and fluxes decreased toward the interior areas of WCA-3A (fig. 21). The increasing size of WCAs to the south is accompanied by a decreasing ratio of levee length to wetland surface area, which is an important reason why recharge and discharge decrease toward WCA-3A.

In contrast to basin-averaged recharge and discharge, fluxes in the wetland interior increased toward the south. Greater vertical fluxes in the wetland interior of WCA-2A (compared with ENR) are at least partly the result of greater driving forces associated with surface-water fluctuations in WCA-2A. Higher hydraulic conductivity of the peat in WCA-2A, compared with ENR, also contributed to higher vertical fluxes in the interior of WCA-2A.

USE OF GEOCHEMICAL TRACERS TO IDENTIFY SOURCES AND PATHWAYS OF WATER FLOW IN THE EVERGLADES

Attempts to manage water quality in the Everglades over the past 40 years generally have proceeded with little regard to the close hydrologic connection between surface water and ground water. Seepage of substantial quantities of Everglades surface water beneath levees was first quantified in the 1960s, and was shown to be an important factor depleting the water supply to Everglades National Park during dry periods. In contrast, the effect that seepage has on water quality has not been as widely considered. Although the variable sources of water inputs to the Everglades (for example, precipitation, agricultural runoff, Lake Okeechobee drainage) have been well documented, the chemical quality of those inflows is not always well known. In addition, the potential for ground water to function as a storage reservoir for surface-water contaminants, or as a site of biogeochemical reactions that affect contaminants, generally is not well understood. A thorough investigation will require study of the vast interior areas of the Everglades, in addition to the wetlands in close proximity to levee boundaries.

One reason that interactions between surface water and ground water are poorly understood in the Everglades is because the interactions are difficult to estimate or simulate. Measuring surface-subsurface interactions in wetlands is always a challenge, both because of the difficulties of deploying hydrological instrumentation in wetlands, and because the fluxes involved generally are small enough to challenge the precision of the readily available methods. For those reasons, hydraulic measurements alone may be inadequate to characterize interactions between surface water and ground water in the Everglades. The vast area of the Everglades, however, ensures that even small fluxes between wetland surface water and ground water potentially are of great importance to chemical budgets and water quality. Geochemical measurements, themselves, offer an alternative tool for researchers that potentially can supplement hydraulic measurements, revealing long-term patterns of interactions between surface water and ground water, and resulting effects on water quality.

Approach

Variability in the geochemical composition of natural waters often can be used to identify distinct sources of water and mixing among those source waters. Dominant water sources and the extent of mixing are quantified on the basis of chemical similarity to various endmembers. Endmembers represent the unmixed source waters at a field site. Usually, the endmembers can be estimated from samples that show the extremes of variation in chemical composition. In the case of the Everglades, some important endmembers include deep ground water, wetland surface water, and

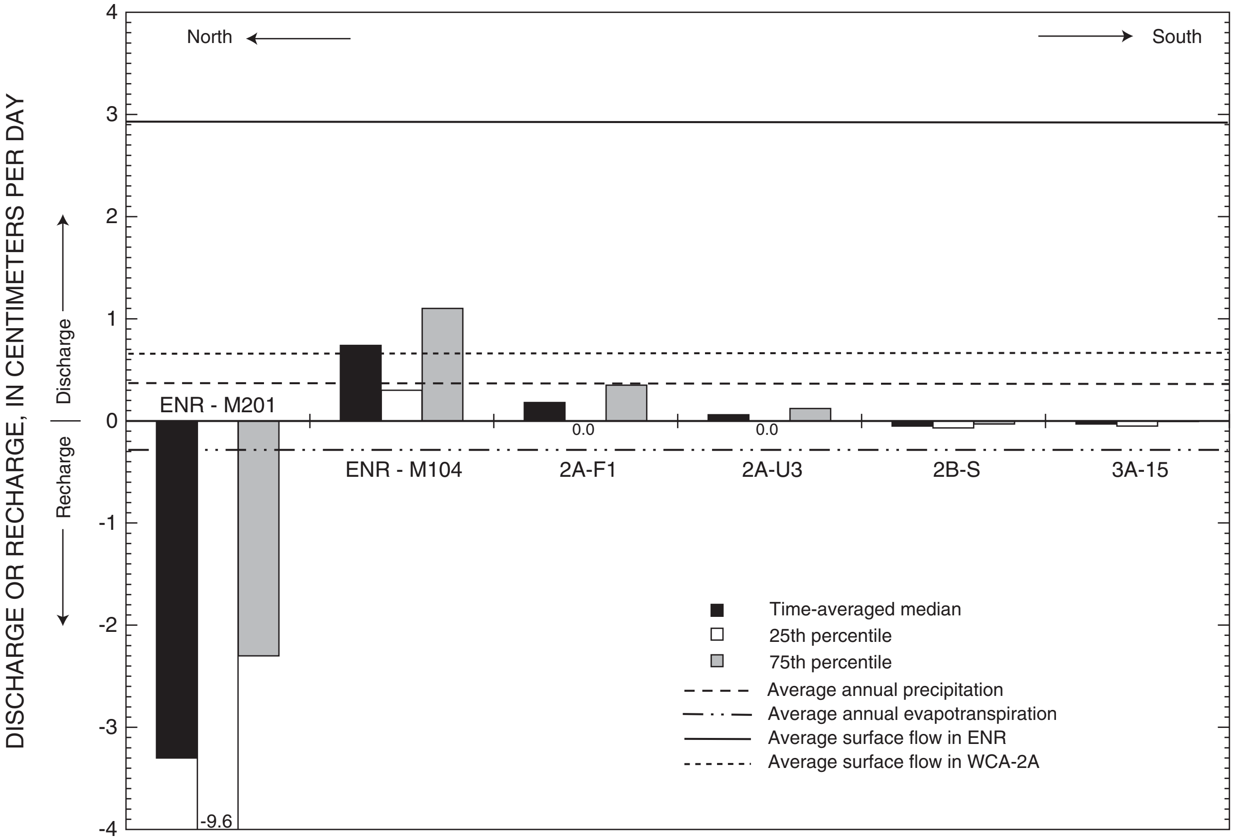


Figure 21. Spatial trends in discharge and recharge in north-central Everglades, south Florida. Time-averaged precipitation, evapotranspiration, and surface flows in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A) are plotted for comparison.

precipitation. Water samples with intermediate geochemical composition often reflect mixing between endmembers. The variability in geochemical composition of ground water also can represent differences in geochemical reactions between ground waters and the aquifer sediments that contain them, in addition to mixing of waters from different sources. In a given situation the ideal geochemical tracer provides information about flow paths and flow velocities, in addition to information about water source, mixing, and geochemical reactions. Depending on the aquifer system and the tracer, the relevant travel times that might be revealed include months, years, decades, centuries, or millennia.

Geochemical data from Everglades surface water and ground water are presented here to determine 1) the dominant sources of ground water and surface water in the north-central Everglades, and 2) locations of recharge and discharge and extent of vertical mixing between surface water and ground water. The present study used major ions and water-stable isotopes to delineate source waters and extent of mixing between surface water and ground water in the Everglades. A detailed description of the approaches used and methods is given in Harvey and others (2000).

Source of Ground-Water Recharge

Water-stable isotopes were one of the geochemical tracers used to determine the source of water to the Surficial aquifer beneath the north-central Everglades. The isotopes showed that recharge of surface water from the wetlands was the dominant source of ground water as opposed to infiltration of rainfall through the unsaturated zone of a nearby upland area or seasonal wetland. Most samples of Everglades surface and shallow ground water suggest a substantial effect of evaporation. The primary evidence for evaporation is isotopic ratios of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) in ground water that are most similar to Everglades surface water. Similar to Everglades surface water, these ground waters are isotopically "heavy" in comparison with precipitation, and enriched in $\delta^{18}O$ relative to $\delta^{2}H$ according to a ratio that indicates significant evaporation of water prior to recharge (fig. 22). Precipitation or recharge water that did not experience significant evaporation would be isotopically "lighter," without the strong evaporation signature. Only direct recharge of ground water from substantially evaporated surface water in the wetlands can explain the stable isotope geochemistry of Everglades ground water collected at most sites.

There are a few exceptions to the evaporative signature of Everglades surface and ground waters. In surface water, these exceptions occurred in WCA-2A after time periods of heavy rainfall when water levels were relatively low. For a brief period following those heavy rains, surface water was similar to precipitation in terms of having a relatively light water-stable isotopic composition.

Some shallow ground waters beneath central ENR also had the isotopically "light" stable isotopic composition. Wells M203-PZ, M103-PZ, M401-P, MP2-C and M203-P all had isotopic compositions that were closer to precipitation than to typical surface waters and ground water at nearby sampling locations. These shallow ground waters beneath central ENR appear to have been recharged by rapid infiltration of precipitation on farm fields of the Everglades Agricultural Area (EAA) prior to construction of the ENR wetland. Recharge through the unsaturated agricultural fields would have occurred quickly without sufficient time for evapotranspiration to occur. Because the ENR treatment wetland has been flooded continuously since late 1993, that recharge would need to have occurred prior to 1993, during the time of agricultural management in that location.

Distinguishing Sources of Recharge Using Major-ion Composition

Major-ion chemistry was useful to identify some of the more important sources of water to Everglades surface and ground water. Analyses from a sampling event in December 1997 are shown as points on a Piper diagram in figure 23. Piper diagrams show the effects of various factors, including major-ion composition of possible source waters, as well as the proportions of mixing between those source waters in samples. The effects of geochemical interactions between water and soil or aquifer material also may be indicated on a Piper diagram. Possible source waters, or endmembers, are identified on Piper diagrams by water samples that plot at the extreme edges of the sample distribution. Waters that are mixtures between two endmembers are identified as samples that plot on lines connecting the endmembers. Often, more than two endmembers are present, complicating what would otherwise be a simple mixing analysis. Even if only two endmembers are

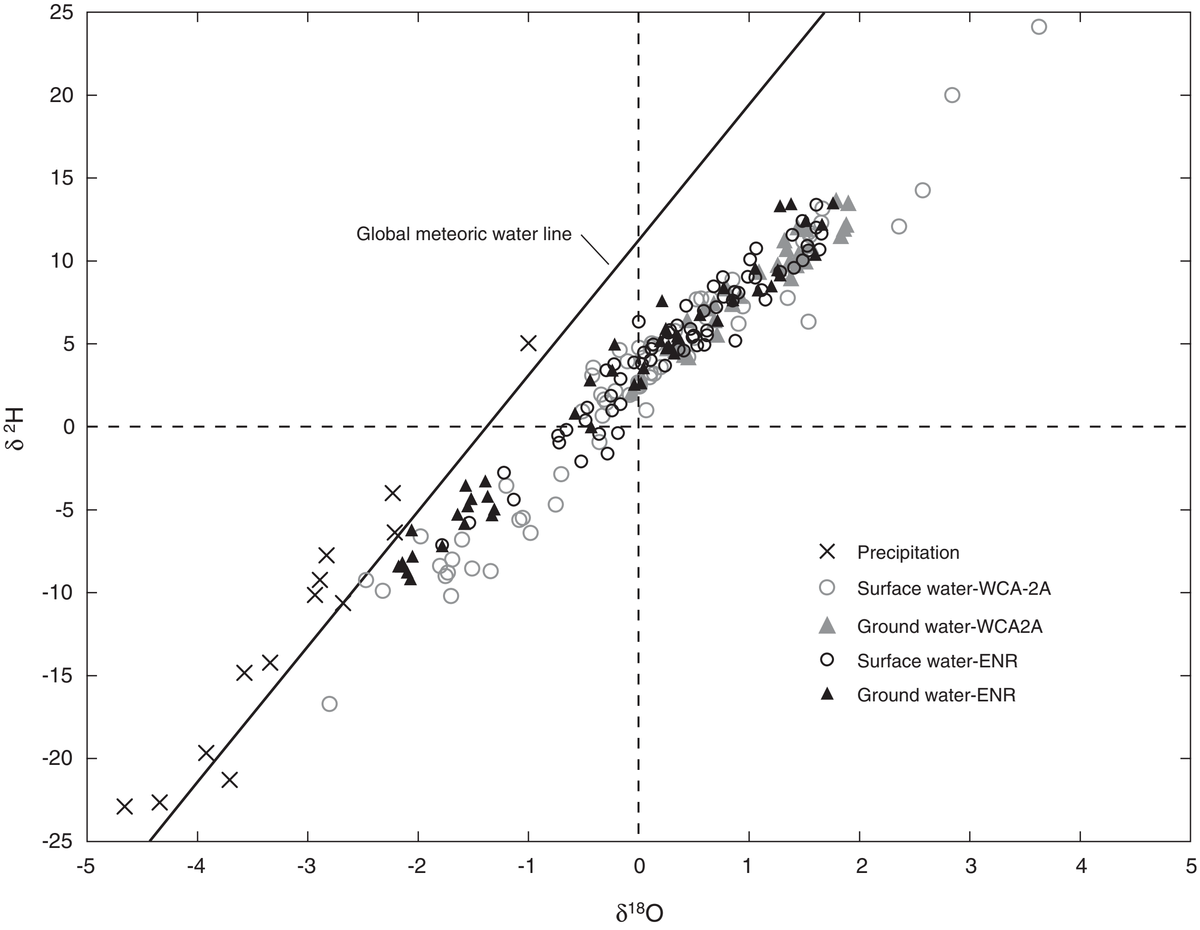


Figure 22. Water-stable isotopic ratios $\delta\,^2H$ and $\delta^{18}O$ from precipitation, surface water, and ground water in Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida. Most isotopic values from ground water are relatively heavy (positive) on a trend with lower slope than the global meteoric water line, suggesting that appreciable evaporation occurred from that water. In contrast, precipitation and many surface-water samples are relatively light in isotopic value. Only a small group of ground-water samples are relatively light in isotopic value (negative). See text for interpretation.

likely to be present, accurately classifying those end-members still may be difficult because of spatial and temporal variability of chemistry at a limited number of sampling sites.

There is no single widely accepted method of classifying water types by their major ion composition. For the present study, available classifications of water types in the Everglades were considered first. Howie (1987) used Stiff diagrams to classify ground waters in the southern part of the study area in Broward County. Upchurch (1992) suggested a descriptive classification of natural waters in Florida based on Piper diagrams, using the separate triangular graphs for cations and anions. Frazee (1982) developed a more specialized interpretive classification of south Florida waters using the combined cation and anion graph on Piper diagrams. In this study, the keys for both the Upchurch (1992) and Frazee (1982) classifications were used to prepare the Piper diagrams presented here (fig. 23).

Calcium and/or sodium generally dominate the cation composition of south Florida waters. The anion composition is dominated by bicarbonate and/or chloride ions. If a third cation (for example, magnesium) or anion (for example, sulfate) is important, the sample is referred to as "mixed" in its cation or anion composition. Using the descriptive classification scheme of Upchurch (1992), along with water-stable isotopic data, nine major water types relevant to the study area were delineated (fig. 23):

A1 – calcium bicarbonate water
F1 – calcium-sodium bicarbonate water
F6 – calcium-sodium bicarbonate-chloride water
E5 – sodium-chloride water
E6 – sodium chloride-bicarbonate water

B2 – calcium-magnesium bicarbonate-sulfate water
G1 – mixed-cation bicarbonate water
G1a – mixed-cation bicarbonate water with “light” stable isotopic signature
G6 – mixed-cation bicarbonate-chloride water

Background - Source and Transitional Waters

Interpretations of water sources to ENR and WCA-2A are summarized briefly here. Interpretations follow those of Frazee (1982) or are slight modifications thereof. Terms used to classify the waters for this study that were defined by Frazee (1982) are italicized.

Water types A1, F1, E5, and B2 are the relevant source waters in the north-central Everglades. Type A1 waters are *Fresh Recharge Waters* derived from rainfall and interaction with aquifer sediments, principally limestone. Type F1 waters are similar to A1 waters but are higher in ionic strength and have a greater importance of sodium either because of different aquifer sediments, greater reaction times, or mixing with different water. Type E5 waters are *Relict Seawater* derived from seawater intrusion into the fine sands of the bottom half of the Surficial aquifer during an earlier geologic time. The term *Relict Seawater,* therefore, has the same meaning as Frazee’s term *Lateral Inflow.* Type B2 waters are *Fresh Formation Waters* derived from *Fresh Recharge Waters* that have much longer contact times with soils and aquifer sediments. Consequently, B2 waters have a greater effect of magnesium and sulfate in their ion makeup.

Transitional Water is a general term used by Frazee (1982) to refer either to waters that are evolving by geochemical reactions with aquifer sediments, or waters that changed their geochemical character by mixing with other geochemically distinct waters.

The most frequent classification of water in ENR and WCA-2A were F6 waters, followed by G6, F1, E5, E6, and G1 waters. Many of those waters are the product of mixing among two or more endmembers. For example, the most common water type was F6, which is a mixture between *Fresh Recharge Waters* (F1) and older *Relict Seawater* from the base of the aquifer (E5). The progressively saltier mixtures along the mixing continuum are F1, F6, E6, and, finally, E5 waters. Another important mixed water type was G6, which shares a fresh-salt mixture in common with F6 and E6 waters, but also has inputs of magnesium and sulfate from mixing with B2 waters. A good example of *Transitional Waters* that evolved over centuries or millennia in contact with aquifer sediments, with little mixing with other waters, are B2 waters. B2 waters are otherwise known as *Fresh Formation Waters*.

Fresh Recharge Water

Water type A1 is freshwater that originated as rainfall-derived recharge to the aquifer. Type A1 water interacted with peat sediments and sand and carbonate layers of the Surficial aquifer over a relatively short period of geologic time (decades to centuries). Dissolution of limestone was the most important water-rock interaction affecting the chemistry of A1 waters. Type F1 waters are similar to A1 waters except that F1 waters have a higher ionic strength and more importance of sodium, which reflects either exposure to different aquifer sediments, more prolonged contact time, or a minor amount of mixing with *Relict Seawater.* Frazee (1982) refers to both A1 and F1 water types as *Fresh Recharge Water.*

A1 waters are represented at the study sites by shallow ground waters sampled from wells along the Atlantic Coastal Ridge. Surface water and shallow ground water from WCA-2A and ENR are F1 or F6 waters, because of a greater contribution from sodium and/or chloride ions. Whereas A1 waters probably represent waters recharged through unsaturated sediments of sandy coastal ridges, F1 waters are more likely derived from recharge of rainfall that fell directly onto the wetlands themselves. Because water-stable isotopes indicated that Everglades ground water principally was derived from recharge of wetland surface water, F1 waters appear to be a much more important source of *Fresh Recharge Water* to the Everglades than A1 waters.

A good model for the source of F1 waters to the study sites is water recharged within the rainfall-dominated wetlands of WCA-1. Wetlands outside of WCA-1 have other sources of water, such as deep ground-water discharge from the Surficial aquifer, drainage from Lake Okeechobee and from the Everglades Agricultural Area (EAA), with distinctly different geochemical signatures. The first of those other source waters discussed is discharge of *Relict Seawater* from the lower half of the Surficial aquifer.

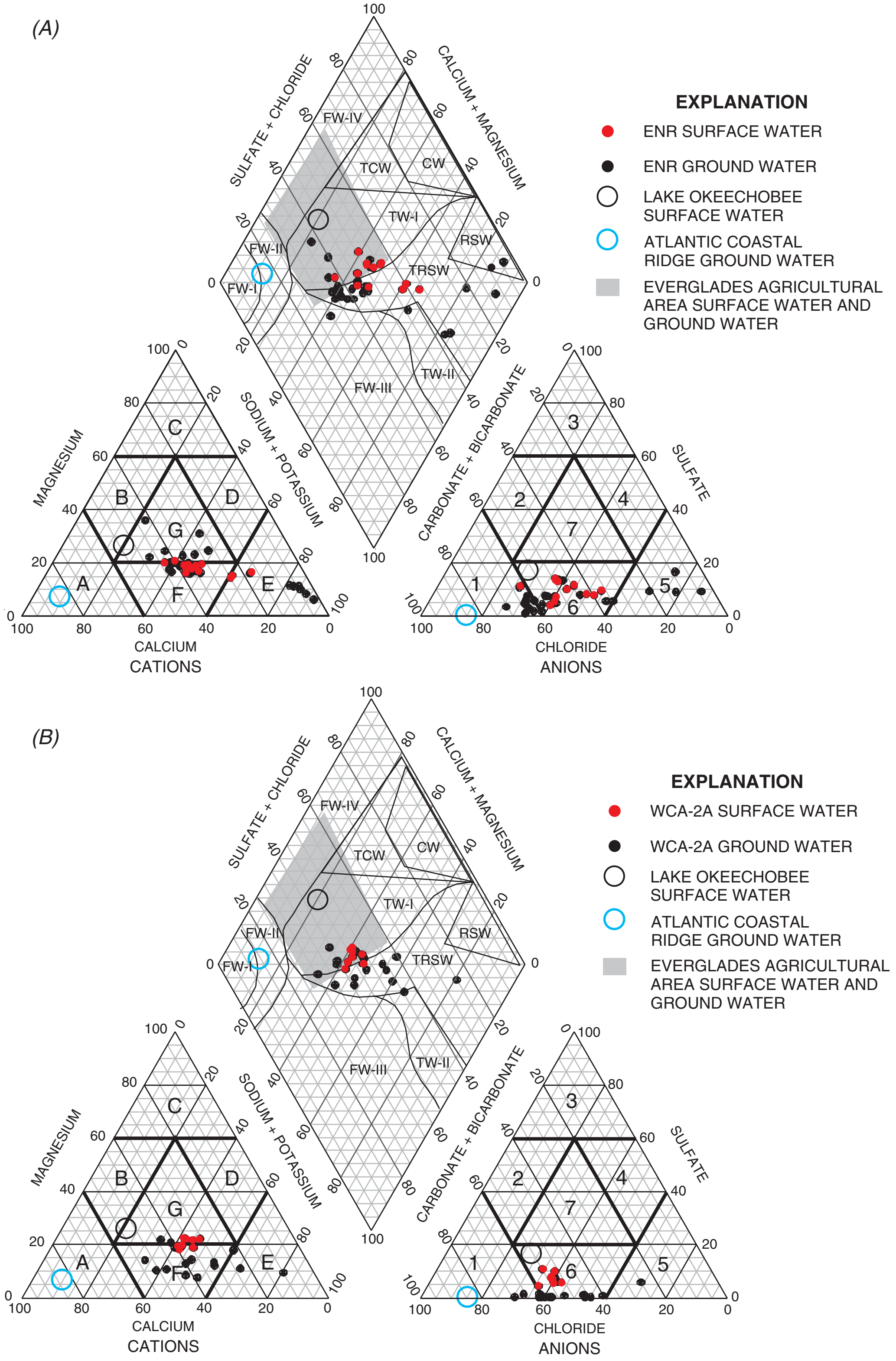


Figure 23. Piper diagrams illustrating variability in major ion composition of surface and ground waters from Everglades Nutrient Removal (ENR) project (*A*), and Water Conservation Area 2A (WCA-2A) (*B*), north-central Everglades, south Florida. See text for explanation of classifications.

Relict Seawater

Type E5 water is high ionic strength water that is dominated by the ion signature of seawater; for example, sodium and chloride. In surface water and ground water of the north-central Everglades, this signature is acquired by mixing with a large component of *Relict Seawater* that originally intruded the fine sands in the lower half of the Surficial aquifer during a geologic time of a relatively higher sea-level stand. E5 waters mostly are represented by the deep ground waters of the Surficial aquifer (60-200 ft deep), but E5 waters also are found at shallow depths in the aquifer (less than 60 ft deep), and on the wetland surface, because of mixing caused by upward discharge of *Relict Seawater* from the aquifer to the wetland surface. The presence of E5 waters in surface water and shallow ground water attests to the importance of deep vertical mixing between surface water and ground water in some locations. Near levees, vertical mixing is especially deep, extending through at least the top half of the Surficial aquifer.

Fresh Formation Water

Water type B2 has greater effects of magnesium and sulfate in its ion composition, often because of longer periods of weathering in contact with soils and aquifer sediments (compared with other water types). Frazee (1982) refers to the water type as *Fresh Formation Water,* with long contact times being the main difference separating this water type from the *Fresh Recharge Water* dominated by calcium bicarbonate. Water type B2 is believed to be present in ground water beneath Lake Okeechobee and in areas surrounding Lake Okeechobee, including the Everglades Agricultural Area (EAA) (Frazee, 1982). Even longer contact times of B2 waters in the aquifer eventually would produce *Connate Water* (for example, classification C or D for cations and 3 or 4 for anions), a saltwater distinctly different from marine water in its ion balance. *Connate Water* also is believed to be present in ground water beneath Lake Okeechobee (Frazee, 1982).

Mixed Waters and Other Transitional Waters

Many of the ground waters from ENR and WCA-2A plotted on the Piper diagram on a mixing line between F1 and E5 waters. This mixing line represents the continuum between rainfall-driven recharge of wetlands in the Everglades (F1), and *Relict Seawater* (E5).

Another group of water samples, mostly surface waters and a few ground waters, had a mixed cation signature (for example, a G classification for cations), because of either mixing between water types or longer weathering times in the aquifer. For example, mixing of F6 type water with *Fresh Formation Water* or *Connate Water* probably accounts for classification of Lake Okeechobee water as G6 type water. The presence of *Fresh Formation Water* in ground water of the Lake Okeechobee and EAA is evident from water analyses reported in Parker and others (1955). Those water samples were collected in the 1940s from ditches, canals, and ground waters in the EAA. The range of those samples on the combined cation and anion portion of a Piper diagram is shown as a trapezoidal shaded area in figure 23.

A number of surface waters and shallow ground waters had the mixed cation signature of G6 or G1 waters. Because G6 waters only were found in surface water or shallow ground water, it was concluded that these waters are mixtures of various waters, such as A1, F1, E5, B2, and possibly *Connate Water.* Lake Okeechobee contains G6 type water, making it possible that some of the G6 waters from ENR and WCA-2A, most likely surface water, could be predominantly drainage water from Lake Okeechobee. In contrast, G1 waters were found both very shallow (15 ft) and relatively deep (60 ft or greater). The deeper G1 waters evolved by geochemical interactions with aquifer sediments. That geochemical change involved a transition from calcium-sodium bicarbonate water (F1) to calcium-sodium bicarbonate-chloride water (F6) and, finally, to G1 water with proportionately greater importance of magnesium (and sometimes sulfate) compared with G6 waters. The shift in anion composition usually is not as great as the cation shift, possibly because of bacterial sulfate reduction that removes sulfate from solution.

Most of the shallow G-1 ground waters have the unique “light” stable isotopic composition that was interpreted earlier in this section as a signature of rainfall-driven recharge through agricultural soil. The mixed ion classification of that water may, in part, be the result of chemical inputs associated with agricultural fertilizer (Bates and others, 2002). For that reason, a specialized classification was created for shallow G1 waters called G1a, which uniquely associates the water with rapid recharge of precipitation that fell on wetlands converted for agricultural use.

Geochemical Tracing of Surface-Water and Ground-Water Interactions

It was believed that geochemical data would help delineate ground-water discharge and recharge in the north-central Everglades. Geochemical tracers did support previous hydraulic analysis by identifying recharge in WCA-1 and flow beneath the levee as an important source of ground water to the aquifer beneath ENR and WCA-2A. Support for the above interpretation comes from cross-sectional plots of specific conductivity and water type (figs. 24 and 25). Those plots show that *Fresh Recharge Water* (Type-F1) has been recharged to substantial depths (60 ft or more) beneath the levees separating the study sites from WCA-1. This observation is consistent with hydraulic interpretations that water ponded at higher elevations on the WCA-1 side of the levee drives recharge and flow beneath the levee.

Geochemical data provide a long-term integrated view of levee underflow. Of particular value is the information about the depth of underflow that would be difficult to discern from hydraulic data alone. At greater depths beneath the levee (100 ft) is *Fresh Formation Water* (type G1) that also is derived from freshwater recharge, but which has had considerably longer contact time with aquifer sediments.

Ground-water geochemistry changes rapidly with distance away from the levee, with *Relict Seawater* present in the aquifer at elevations well above the fine sands in the bottom half of the Surficial aquifer (below 100 ft) where it was once thought to be restricted (fig. 25). Upward movement of *Relict Seawater* from the bottom half of the Surficial aquifer is caused by ground-water underflow beneath the levees. The potential energy that drives recharge also drives a corresponding discharge flux on the down gradient side of the levee. Those flow paths are referred to as "underflow" paths. The deepest of those underflow paths are deep enough to have contacted the fine sands that contain the relict saltwater, mixing with the saltwater and advecting some of the salts upward toward the wetland surface. As a result, the presence of *Relict Seawater* (type E5) or *Transitional Relict Seawater* (type E6) delineates zones of discharge. In WCA-2A, the zone of discharge extends for 2 mi on the down gradient side of the levee. In ENR, the zone of discharge that is delineated by relict seawater does not occur directly down gradient of the levee, but instead is more centralized beneath the 2.5-mi-wide ENR wetland.

Are sea salts from the deeper aquifer actually discharged to surface water? Two surface-water samples from ENR are classified as *Transitional Relict Seawater* (type E6), indicating that relict sea salts discharge to surface water. The best example may be discharge to the seepage canal on the western side of ENR. The purpose of the seepage canal is to collect ground water that recharges within the ENR treatment wetland and return it to the wetland. The seepage canal not only captures ground water recharged in ENR but also ground-water discharge from the deeper parts of the aquifer. In contrast to ENR, discharge of relict sea salts to the wetland surface is not indicated by analysis of surface-water samples in WCA-2A. However, the relatively high salinity and geochemical makeup (type E5 and E6) of the shallowest ground waters beneath site F1 in WCA-2A, as well as similar data from peat porewater (unpublished data), suggest that relict sea salts are discharging to surface water at low rates.

Shallow ground water indicated additional variability in geochemical type, in addition to *Fresh Recharge Water*, *Relict Seawater*, and *Transitional Relict Seawater*. A fourth common type in shallow ground water beneath ENR was the variation of *Fresh Formation Water* classified as type G1a. Although possessing the same overall geochemical signature as the water found at 100 ft beneath the levees at both ENR and WCA-2A, it is clear that the shallow ground water at approximately 15 ft beneath central ENR fundamentally is different in origin. This shallow ground water is the water with the very light water-stable isotopic signature that was discussed earlier in this section. This interpretation, also discussed earlier, is that this water is derived from precipitation that infiltrated rapidly on farm fields prior to construction of ENR.

Surface waters at ENR and WCA-2A always represented water mixtures rather than pure endmembers. The most common types were *Transitional*, *Relict Seawater*, and *Transitional Fresh Formation Water*. Surface waters always showed some effect of mixing with relict sea salts determined by the relative importance of chloride (type F6). The relict sea salts were derived from discharge of ground water from a deep source in the Surficial aquifer. A major component of drainage or runoff from Lake Okeechobee or the EAA was traceable by the increased relative importance of magnesium in water samples (type G6). Taken alone, however, major ions generally will not be sufficient to separate water predominantly derived from *Fresh Formation Water* from *Agricultural Recharge Water*. For

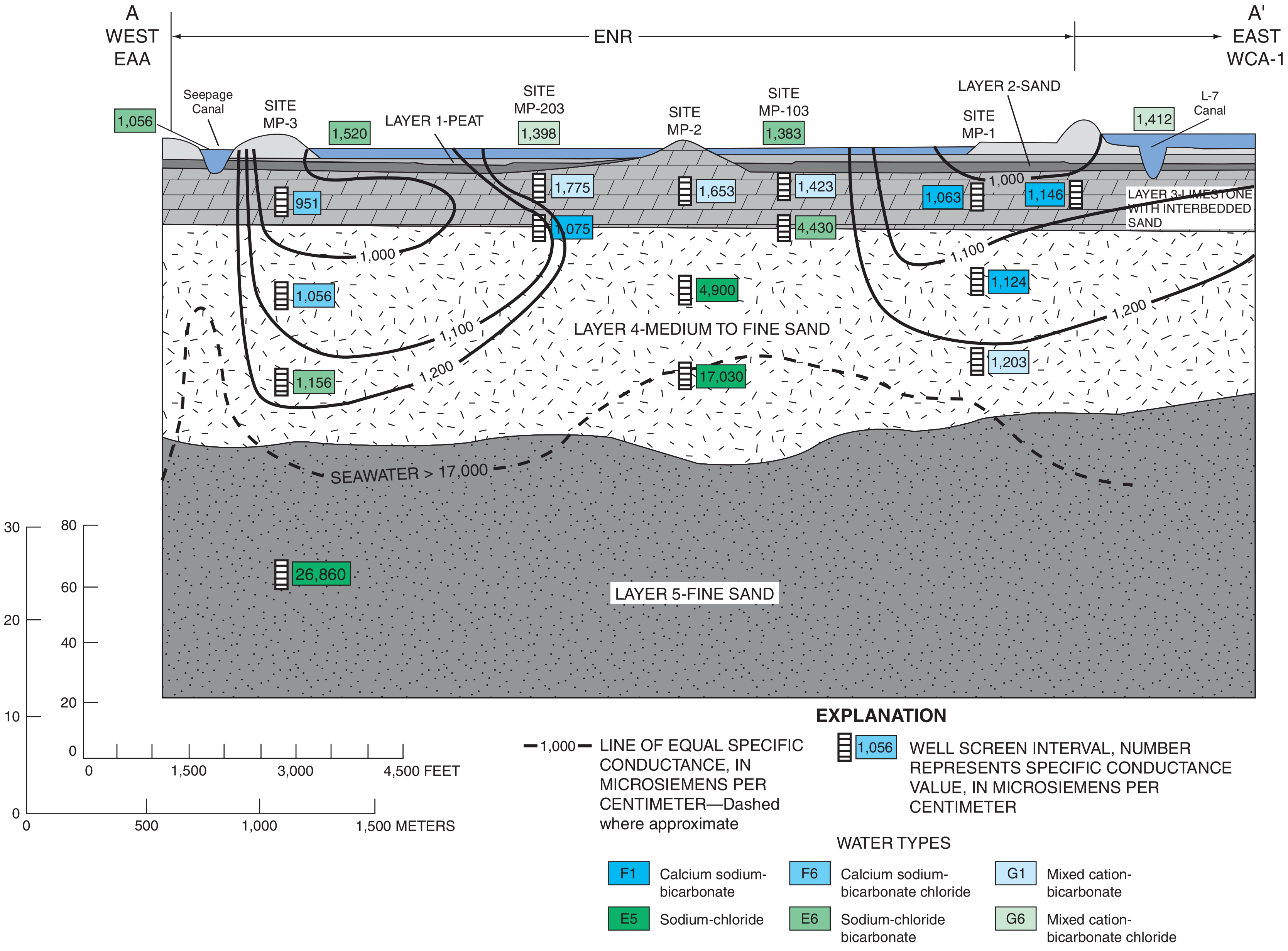


Figure 24. Ground-water flow paths delineated by specific conductivity (contours) and geochemical water type (color codes) at Everglades Nutrient Removal Area (ENR), north-central Everglades, south Florida.

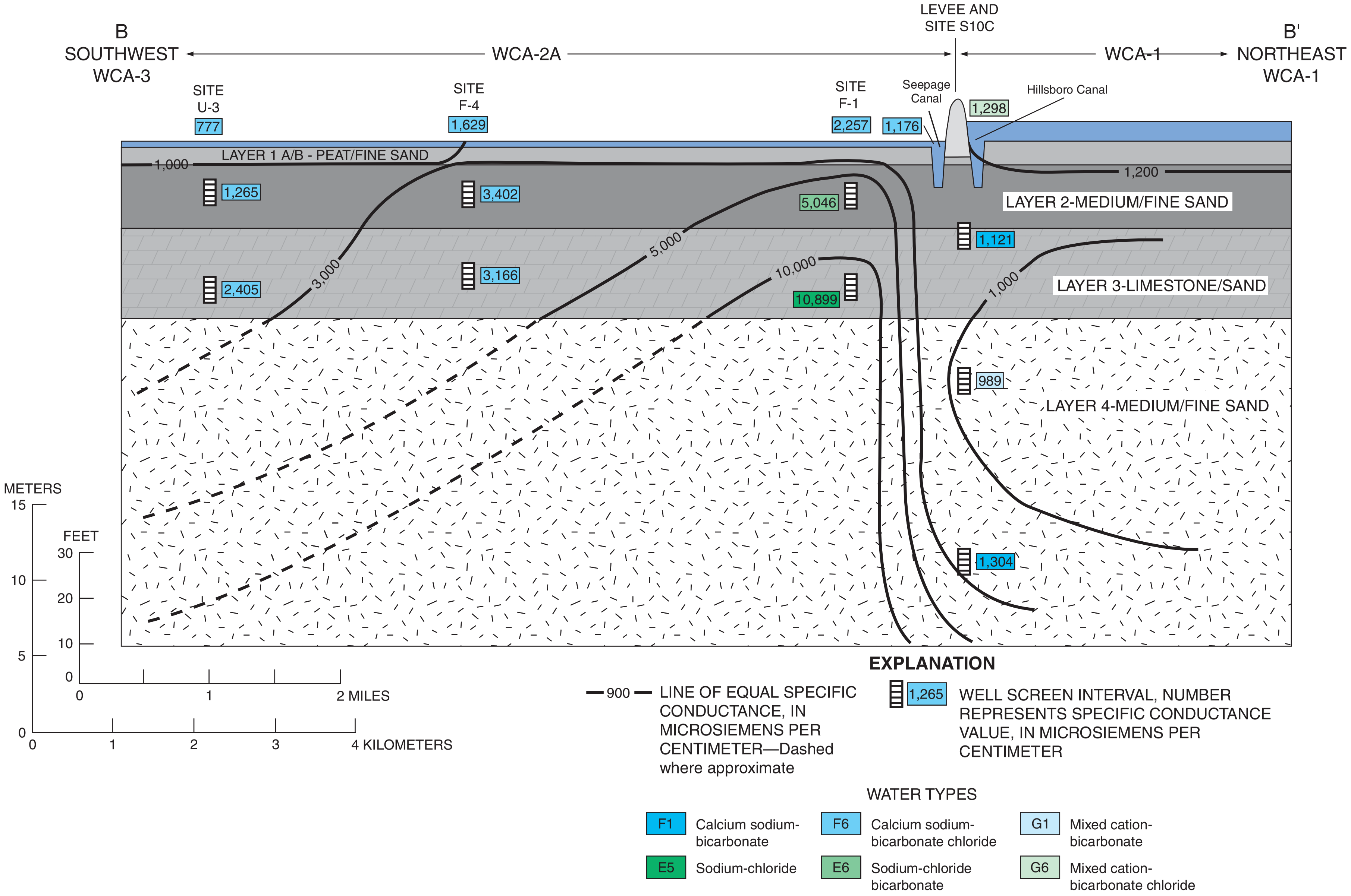


Figure 25. Ground-water flow paths delineated by specific conductivity (contours) and geochemical water type (color codes) at Water Conservation Area 2-A (WCA-2A), north-central Everglades, south Florida

example, using major ions alone, a ground water with long residence time in the aquifer cannot necessarily be distinguished from precipitation that recharged quickly in an agricultural field of the EAA (possibly because of the confusing signature introduced by chemical additives in fertilizer). Water-stable isotopes had considerable value in making that distinction, however, with lighter isotopes identifying waters recharged on agricultural fields without substantial evaporation.

Geochemical evidence provides a long-term integrated picture of hydraulic processes in the aquifer and exchange with surface water. Water-stable isotopes indicated that the major source of water in Everglades ground water is recharge of evaporated surface water from the wetlands rather than infiltration of rainfall through unsaturated sediments. This observation indicates that recharge always has occurred in the north-central Everglades. Ground-water recharge is balanced by discharge, which, although small in magnitude, is a persistent source of water to flow in the Everglades over the long term.

Major ion chemistry and water-stable isotopes identified eight major water types. Four of those were considered to be source waters (types F1, G1, G1a, and E5). The other four are mixtures of the source waters. The distribution of those water types identified long-term average flow pathways of recharge and discharge.

Particularly evident as a major factor driving recharge and discharge in the present-day Everglades were the effects of wetland compartmentalization by levees. Geochemical water typing provided information that was consistent with hydraulic information. The geochemical tracers, however, particularly were useful in showing the extent to which water management has caused vertical mixing throughout essentially the entire depth of the Surficial aquifer.

The effect of levees is indicated by the presence of *Fresh Recharge Water* recharged from the up gradient side of the wetland at a depth of 90 ft beneath the levee, whereas down gradient of the levee, relict sea salts have been entrained by the deepest underflow paths and transported upward to be discharged to surface water. The effect of levees on interactions between surface and ground water, therefore, extends vertically throughout at least the top three-fifths of the Surficial aquifer, and horizontally for at least 1 mi away from the levees. These observations support the hydraulic interpretation earlier in this report that water management has increased interactions between surface water and ground water in the north-central Everglades.

EFFECT OF GROUND-WATER AND SURFACE-WATER INTERACTIONS ON MERCURY TRANSPORT IN THE NORTH-CENTRAL EVERGLADES

A major part of research on aquatic cycling of mercury concerns chemical reactions in the subsurface (Gilmour and others, 1998). For example, the conversion of inorganic forms of mercury to methylmercury is a critical step that makes mercury more bioavailable in aquatic ecosystems. This reaction is thought to occur predominantly in the subsurface; for example, in porewater of the wetland peat (Gilmour and others, 1991). In order to understand the biogeochemical controls on mercury methylation, it also is necessary to understand physical transport processes that affect movement of mercury between surface water and peat porewater. Diffusion often has been investigated as an important mechanism that releases methylmercury from porewater into surface water, whereas advective transport (with discharging or recharging water) less often has been considered (Krabbenhoft and Babiarz, 1992).

Mercury mobility with recharging and discharging ground water in the Everglades is evaluated in this section. Discharge is the upward flow of ground water through peat into surface water, whereas recharge is the downward flow of surface water through peat into the aquifer. In addition to potentially transporting mercury, discharge and recharge also may affect mercury cycling by transporting other constituents that could affect chemical transformations of mercury. An example is transport of sulfate, which potentially affects mercury cycling through the effect on sulfate-reducing bacteria and sulfide levels, and their effects on methylation rates. The specific objectives of this part of the study are listed below:

1.) Characterize the distribution of dissolved total mercury and methylmercury (Hg_T and MeHg) in the Everglades Nutrient Removal (ENR) project and Water Conservation Area 2A (WCA-2A) in surface water, peat porewater, and ground water.
2.) Relate patterns in mercury distribution to factors such as aquifer lithology, ancillary geochemistry, and source of recharge water.

3.) Quantify ground-water exchange fluxes of mercury to improve the overall mercury mass budget at the ENR.

ENR is a relatively large constructed wetland (3,815 ac) in the north-central Everglades built as a prototype for testing the effectiveness of a larger set of constructed wetlands called Stormwater Treatment Areas (STAs) designed to remove excess nutrients from agricultural runoff. A concern developed among water-resources managers that STAs might release large amounts of inorganic mercury to dissolved phases that subsequently would be exported in surface-water outflow. Much attention was focused on the ENR project because it represented an area of the Everglades where that concern could be tested by developing a reliable mercury balance. Previous hydrological work in ENR (for example, Choi and Harvey, 2000) demonstrated clearly that recharge and discharge of ground water had to be considered, in order to develop a reliable budget for mercury (or any chemical constituent that differs in its average concentration in surface water). The general approach used here was to combine recent estimates of recharge and discharge in ENR (Choi and Harvey, 2000) with mercury data from ground water and surface water to compute wetland to ground-water fluxes.

Although ENR is relatively large for a constructed wetland, it is small in comparison with hundreds of thousands of acres that make up the larger basins in the north-central Everglades. A disadvantage of working primarily at ENR is that it does not represent spatial variability across diverse Everglades landscapes. For that reason, the mercury distribution in WCA-2A also was investigated. Data from WCA-2A are not as comprehensive as from ENR, but, nonetheless, serve to broaden the relevance and applicability of conclusions given here.

Approach

Mercury data were used in the present investigation in two major ways: to assess spatial patterns in concentrations and to refine mercury mass balances. Two data sets were used for those purposes. Each data set is described below.

Data set I

Data were combined from various collaborating research projects to address the mercury distribution. Data sources from ground water are described first. A team of USGS and SFWMD researchers collected filtered samples for total mercury (Hg_T) and methylmercury (MeHg) analyses from a total of 19 sites in ENR and WCA-2A. A total of 39 wells were sampled along with the surface water at each site. Research sites and sampling procedures are summarized briefly here. Sampling wells encompassed various depths throughout the top half (100 ft) of the Surficial aquifer. A total of 24 shallow wells (approximately 25 ft deep) were sampled, 8 intermediate-depth wells (approximately 60 ft deep), 6 deeper wells (approximately 90 ft deep), and one 180-ft-deep well. All wells and accompanying surface waters were sampled on five site visits between June 1997 and June 1998. Detailed sampling procedures and all mercury data from the ground-water sampling effort are reported in Harvey and others (2000).

Mercury analyses from porewater were made available by the ACME (Aquatic Cycling in Mercury in the Everglades) research group, a group consisting primarily of USGS scientists but also other cooperating investigators. Those porewater samples had been acquired and analyzed separately from the ground-water samples and were analyzed in a different laboratory (USGS, Middleton, Wis.), following the procedures described in King (2000). The procedures used to collect those samples are described briefly here. Filtered peat porewater samples were acquired approximately three times per year between May 1995 and January 1999. Porewater was collected from discrete depths in the peat (approximately 5-cm vertical resolution) over total depths ranging from 20 to 50 cm below the peat surface. Fewer sites were sampled for peat porewater than for ground water, but sampling of peat porewater extended over a longer time period (David Krabbenhoft, U.S. Geological Survey, oral commun., 2001).

Data set II

For the purpose of improving the ground-water component of the ENR mercury budget, a second data set was obtained from the SFWMD mercury program (South Florida Water Management District, 1999). SFWMD conducted detailed sampling of mercury in surface water and ground water at ENR between 1995 and 1999. The data discussed here are a subset of a very large database produced through their efforts (Miles and Fink, 1998; South Florida Water Management District, 1999). All available SFWMD data from monitoring wells and from the seepage canal were used in this study. The seepage canal receives ground-water discharge on the western side of ENR and returns it to the project inflow on the northern side. Also, SFWMD data collected from one surface-water site representative of the volume-averaged concentration of mercury in recharging surface water was used in this study. The SFWMD data used here is referred to as data set II.

Data set II included approximately 155 surface-water analyses (including filtered and unfiltered splits) collected biweekly at surface-water site M203 (fig. 2). The rationale for choosing that site was that it provided a good estimate of volume-averaged concentration of mercury in recharging ground water. Ground-water analyses in data set II are represented by 82 filtered samples collected from 14 wells emplaced beneath the eastern and western perimeter levees (Rohrer, 1999; Harvey and others, 2000). The shallow wells used for collection of data set II were approximately 25 ft below land surface, with screens emplaced in a sandy limestone layer. These are the ground waters most involved in recharge and discharges fluxes (Choi and Harvey, 2000), and were, therefore, a priority for sampling. In addition, 15 samples from the seepage canal, some filtered and some unfiltered, were used. Sampling procedures for mercury data that are part of data set II are given by South Florida Water Management District (1999).

Laboratory Analyses

All of the mercury data from Harvey and others (2000), as well as the additional analyses from data set II, were collected and analyzed according to SFWMD protocols as part of their mercury program (South Florida Water Management District, 1999). Samples for Hg_T were analyzed by the Florida Department of Environmental Protection prior to September 1997, and for the remainder of the project by Frontier Geosciences (Seattle, Wa.), a contract laboratory specializing in mercury analyses. MeHg analyses were conducted by Frontier Geosciences for the duration of the project. Approximate detection limits were 0.2 and 0.02 ng/L for Hg_T and MeHg, respectively. All mercury data analyzed by contract laboratories and corresponding information are kept by the SFWMD as part of their mercury research program (Darren Rumbold, South Florida Water Management District, written commun., 1999).

An important consideration for interpreting data from the SFWMD mercury program is a problem with filter contamination. Extensive testing by SFWMD during the summer of 1998 revealed that the capsule filters used until that time randomly contaminated some Hg_T analyses, typically by increasing concentrations by 20 to 50 percent (Darren Rumbold, South Florida Water Management District, written commun., 1999). Testing indicated that the percentage of the filtered samples affected was low, less than 20 percent. Unfortunately, the contamination problem was discovered late in the sampling program. As a result of the contamination, all of the Hg_T analyses prior to August 1998 potentially are affected. Fortunately, because samples are affected at random and because the proportion of samples affected is relatively small, the contamination problem is not large enough to invalidate the major trends identified in this investigation. Interpretations that are based on relatively large data sets are valid because all samples have an equal probability of being affected. However, sample contamination is expected to have introduced noise to the data set that may obscure subtle trends that otherwise may have been observable.

It is important to note that no MeHg analyses were affected by the contamination problem, nor were any Hg_T analyses from peat porewater affected. Also, a different type of filter was used for peat porewater collections, and that filter type passed extensive tests for contamination (David Krabbenhoft, U.S. Geological Survey, oral commun., 2001).

Distribution of Mercury in Ground Water, Surface Water, and Peat Porewater

Concentrations of filterable mercury species in the Everglades reflect many processes, including sources, affinity for the local substrate and resulting distribution coefficient, and rates of transformation by biogeochemical processes. A simple comparison of mercury concentrations among sites provides initial indications about the most important processes affecting spatial variation. Hypotheses are explored further through relations with ancillary geochemical or hydrological factors.

Hg_T concentration was highest in peat porewater and lowest in ground water (fig. 26a). Median concentrations of Hg_T in peat porewater were 5 ng/L at ENR and 2 ng/L at WCA-2A. Surface-water concentrations of total mercury were approximately 1 ng/L at both sites. Median concentrations of Hg_T in ground water generally were between 0.5 and 0.7 ng/L. The exception was one deep well (180 ft) representing a layer of fine sand near the bottom of the Surficial aquifer at ENR. Samples from this well had a slightly higher Hg_T concentration than other well samples, with a median concentration of 0.9 ng/L determined for four sampling events.

MeHg concentration also tended to be higher in peat porewater and surface water compared with ground water (fig. 26b). The median concentration in peat porewater was about 0.05 ng/L in both ENR and WCA-2A. Median concentrations in surface water were 0.04 and 0.07 ng/L in ENR and WCA-2A, respectively. In ground water, median concentrations of MeHg generally were at or very near to the detection limit (between 0.02 and 0.03 ng/L)

Site-specific studies in the Everglades normally show that dissolved MeHg concentrations are highest in porewater from the top 5 cm of peat (Gilmour and others, 1998). Similar median concentrations of MeHg in porewater and surface water in the box plots of figure 26 may be misleading. Depth-averaging of MeHg in the peat lumps together relatively high porewater concentrations of MeHg in upper layers of peat with undetectable levels of dissolved MeHg from lower layers.

Ratios of MeHg to Hg_T are potential indicators of the extent that the available mercury has been methylated. A formal analysis would require corrections for the relative affinities of Hg_T and MeHg for solids, as well as the production and removal rates of different mercury species by specific biogeochemical reactions. This analysis is beyond the present study scope and only concentration ratios are discussed. The ratio MeHg/Hg_T was highest in surface water (0.04-0.07), intermediate in shallow ground water (0.03–0.05), and lowest in peat porewater (0.01–0.02) (fig. 26c). A low ratio in peat porewater likely was the result of depth-averaging in peat because most porewater samples are below the layer of active methylation. Ratios in surface water were relatively high as compared with porewater because MeHg diffuses into surface water from the top 5 cm of peat where active methylation occurs. Median ratios of MeHg /Hg_T in most ground waters generally were lower than surface water (less than 0.04), which does not strongly suggest active

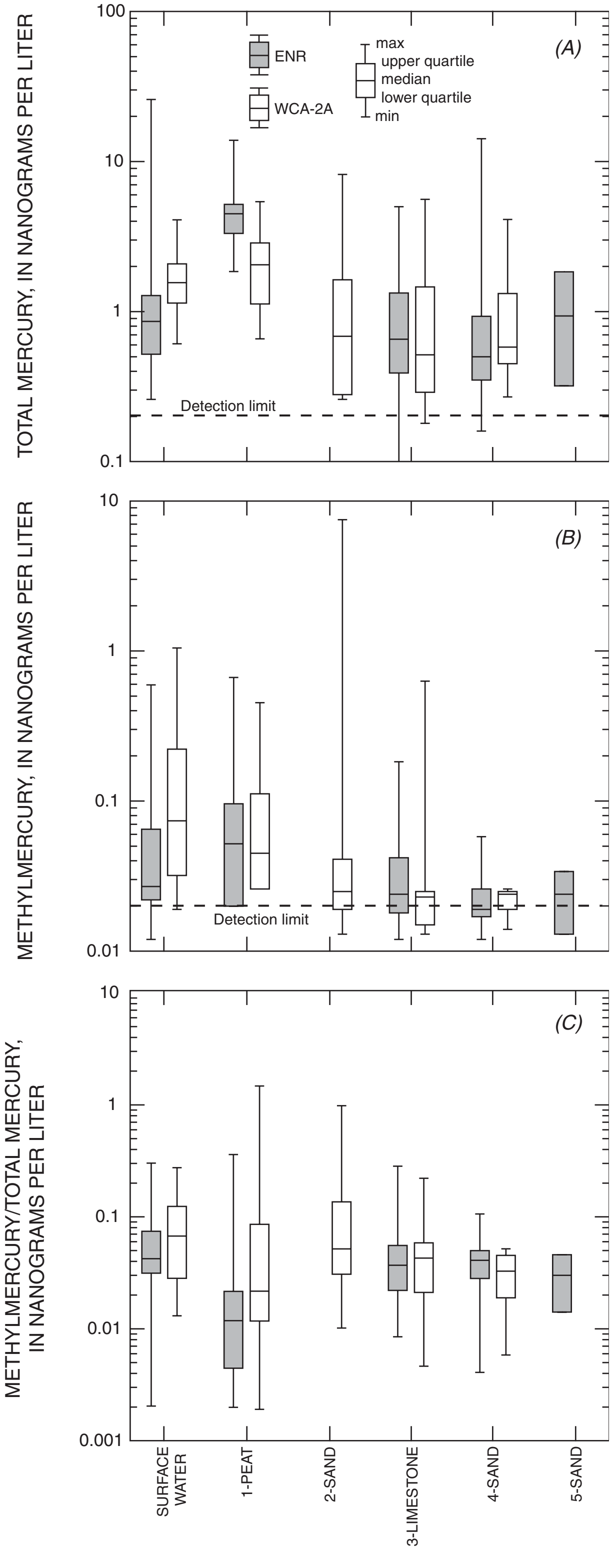


Figure 26. Distribution of dissolved total mercury *(A)*, methylmercury *(B)*, and ratio of methylmercury to total mercury *(C)* in surface water and ground water of the Everglades Nutrient Removal (ENR) project and Water Conservation Area 2 (WCA-2), north-central Everglades, south Florida.

methylation in ground water. The exception was the upper sand layer of the aquifer at WCA-2A (geologic layer 2), where the median ratio was slightly higher and similar to surface water (0.05).

Median concentrations of both Hg_T and MeHg showed trends of decreasing concentrations with depth in the aquifer to near detection levels (fig. 26). Ground water, therefore, appears not to be an appreciable source of dissolved mercury to the peat or surface water (compared to other sources such as atmospheric deposition). Instead, it appears more likely that surface water and peat are potential sources of mercury to the Surficial aquifer.

Relation to Ground-Water Geochemical Type and Source of Recharge

Simple variables, such as location, or geologic characteristics of aquifer layers, generally were unable to explain substantial variability in mercury distribution. For that reason, other potentially important variables were examined, including sulfate concentrations, geochemical water type, and source of recharging ground water.

Relation to Sulfate

Many investigations of mercury cycling in aquatic environments have identified a close linkage with sulfur cycling (Gilmour and others, 1991; Branfireun and others, 1996). For that reason, mercury and sulfate (SO_4^{2-}) concentrations were plotted and analyzed. Other investigators acknowledge that sulfide, rather than sulfate, usually is a better indicator of the methylation rates in the Everglades (Gilmour and others, 1998). Unfortunately, sulfide in ground water was not measured during this study.

MeHg was almost always detectable in surface water, where SO_4^{2-} concentrations ranged from tens to hundreds of mg/L SO_4^{2-}. There was obvious correlation between MeHg and SO_4^{2-} in surface water (fig. 27). MeHg was only infrequently detected in ground water at ENR and concentrations were not related to SO_4^{2-} in any obvious way. Discounting wells U1-GW4 and U3-GW3 (considered as outliers), the only detectable MeHg in WCA-2A ground water (up to 0.06 ng/L) was measured in wells with undetectable (less than 1 mg/L) SO_4^{2-}. Extremely high values of MeHg in repeat measurements from U1-GW4 (up to 8 ng/L) appear to be the result of a contaminated well. A single very high observation of MeHg measured on one visit to well U3-GW3, although not necessarily indicative of a contaminated well, was also treated as an outlier in the data set.

Source of Recharge Water

At ENR many of the ground-water samples with highest concentrations of MeHg tended to belong to the geochemical subtype referred to as “agricultural recharge water.” The source of agricultural recharge water was rainfall onto agricultural soils that infiltrated downward through the unsaturated zone to the water table. Agricultural recharge water is identified mainly through the much lower (more negative) values of $\delta^{18}O$ and $\delta^{2}H$ that are characteristic of rainfall that infiltrates quickly into soils before extensive evaporation occurs. Recharge of this type could have occurred only while the ENR site was managed as farmland. Agricultural recharge water was rare in ground-water samples from the Everglades, which most often have the positive values of $\delta^{18}O$ and $\delta^{2}H$ associated with the evaporation that occurs in wetland surface water. The other indicator of agricultural recharge water is major ion chemistry that reflects greater representation of calcium, magnesium, and sulfate relative to sodium, potassium, and chloride in ground-water chemistry, compared to other ground waters that underlie the Everglades.

Although not as unique an association with the agricultural recharge water type, there was a tendency for Hg_T concentrations to be higher in agricultural recharge water compared to other ground waters and surface waters at ENR (fig. 28). For example, of the measurements of Hg_T that were relatively high at ENR (greater than 2 ng/L), almost all were associated with agricultural recharge water. However, 50 percent of the wells where Hg_T concentration was above 0.5 ng/L were not associated with agricultural recharge water. Although the highest values of Hg_T were associated with agricultural recharge water, water type did not explain the distribution of Hg_T in ground water, because 50 percent of the detectable Hg_T measurements were associated with non-agricultural recharge water. Therefore, unlike MeHg, Hg_T appears to be present in all shallow ground water beneath the north-central Everglades, regardless of source.

The difference in concentrations between ground water recharged in agricultural and wetland settings were more pronounced for MeHg than Hg_T. For example, samples from wells that had the highest concentrations of MeHg (up to 0.2 ng/L) and the highest ratios of

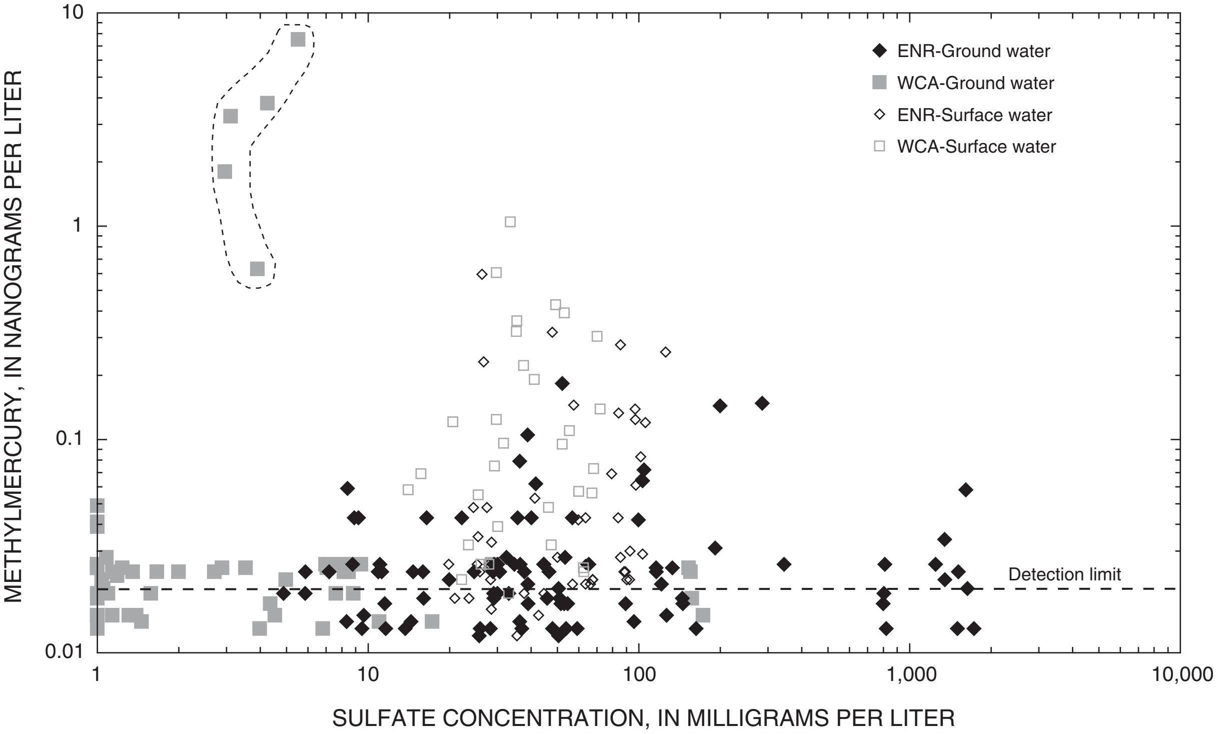


Figure 27. Dissolved methylmercury and sulfate concentrations in surface water and ground water of Everglades Nutrient Removal Area (ENR) and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida. Dotted lines surround potentially unreliable data from well U1-GW-4 and U3-GW3. See text for explanation.

MeHg/Hg_T (up to 0.4), almost were all agricultural recharge waters (fig. 28b). MeHg essentially only was detectable in ENR ground water that had been recharged under agricultural-management conditions (fig. 28b). Eight of 17 measurements in wells with that water type had MeHg concentrations between 0.03 and 0.2 ng/L. None of the other samples from wells recharged from wetland surface water contained MeHg concentrations greater than 0.03 ng/L.

The data suggest that the source of MeHg is present only in ground water recharged in certain areas of the Everglades previously converted to agriculture. Why should the presence of MeHg be associated uniquely with agricultural recharge water, whereas Hg_T is present in all types of ground water beneath the Everglades? Either agricultural management increased recharge of MeHg, or created ground-water conditions under which methylation was more efficient. Plots of MeHg compared with Hg_T indicate variable ratios of MeHg/Hg_T (fig. 29), and, therefore, do not help answer remaining questions. These questions cannot be answered with the results from the present study but deserve further attention as part of possible future studies.

A few qualifications are appropriate about the extent to which agricultural recharge water beneath ENR is representative of agricultural management throughout the Everglades Agricultural Area (EAA). The ENR site was farmed for many years prior to the construction of the treatment wetland. Agriculture management of the ENR site began after the initial conversions of wetlands to agricultural fields in the early 1900s. WCA-1 was constructed during the period 1949–1950. Because of its position adjacent to WCA-1, the ENR vicinity was difficult to drain and, therefore, probably was wetter than many other parts of the EAA. Also, re-flooding of the ENR in 1993 that began operation of the treatment wetland was not a typical agricultural practice in the EAA. Based on the work of other investigators, an increase in surface-water MeHg concentration is expected after re-flooding of a wetland following a period of extended "dry down" of the peat (Kelly and others, 1997). It is possible that re-flooding at ENR affected the transport of MeHg out of the peat; however, that episodic recharge cannot explain the high values of MeHg observed in agricultural recharge water beneath ENR because water-stable isotope and ion tracers demon-

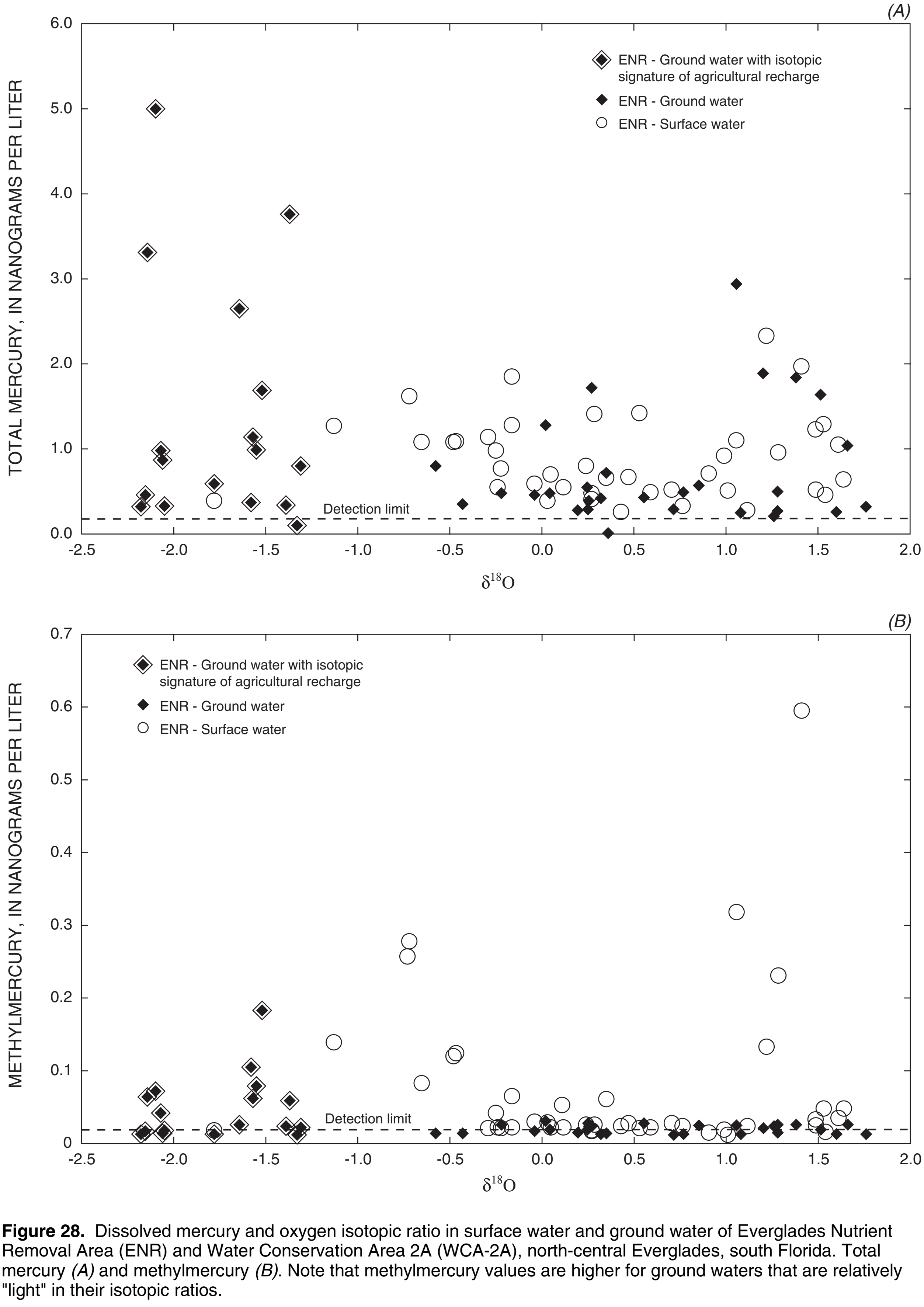


Figure 28. Dissolved mercury and oxygen isotopic ratio in surface water and ground water of Everglades Nutrient Removal Area (ENR) and Water Conservation Area 2A (WCA-2A), north-central Everglades, south Florida. Total mercury *(A)* and methylmercury *(B)*. Note that methylmercury values are higher for ground waters that are relatively "light" in their isotopic ratios.

strate that high MeHg ground water was recharged prior to flooding of ENR. Therefore, a preliminary conclusion that high values of MeHg in agricultural recharge water beneath ENR may be representative of all EAA ground water is warranted. More observation and analysis of ground-water mercury in the EAA will be required to determine a final conclusion.

Ground-water Component of the Mercury Budget at ENR

The South Florida Water Management District recently (1999) developed a budget for mercury inputs and outputs for ENR. This budget includes atmospheric inputs of mercury by wet deposition, inputs with surface water pumped into the ENR, export by surface-water pumping at the outflow point, and gaseous evasion from surface water and plants. The data and procedures for developing the overall budget are discussed in detail in South Florida Water Management District (1999). However, the District was unable to close the mercury budget between surface water, wetland soil, and the Surficial aquifer (L. Fink, South Florida Water Management District, oral commun., 1998). The present work extends the previous budget by improving the estimate of ground-water recharge of mercury. In addition, preliminary determinations regarding the mobility of mercury in ground water were made by comparing budget estimates with the mercury load in a canal that collects ground water from beneath ENR.

Computation of Mercury Fluxes

The approach used here was to combine time-averaged recharge and discharge fluxes at ENR developed by Choi and Harvey (2000) with time-averaged mercury concentrations to compute mercury fluxes. Discharge of mercury to the ENR was computed by multiplying the average ground-water mercury concentrations in eastern-side wells by the ground-water discharge flux. Recharge was computed similarly using concentrations from wells on the western side of ENR. The average surface-water concentrations of Hg_T and MeHg (at site M203) were 1 ng/L and 0.1 ng/L, respectively (table 17). Wells on the eastern side of ENR, where ground-water discharge occurs, had an average Hg_T concentration of 0.7 ng/L and undetectable MeHg (less than 0.02 ng/L). In contrast to the eastern side, ground water on the western side had the highest average concentration of Hg_T (1.4 ng/L). MeHg also was undetectable in the western wells. The difference in mercury concentrations between recharging and discharging sides of ENR are shown graphically in figure 30.

The steady-state approach to calculating a mercury budget assumes that flow and concentration either do not vary substantially with time or are well described by average values. Both recharge and mercury concentrations vary over time in ENR. Recharge fluctuated by approximately a factor of 2 about the mean value. Those fluctuations were smooth, however, occurring on timescales of weeks to months, which were well described by the biweekly estimation procedure for recharge used by Choi and Harvey (2000). Mercury sampling was less frequent than hydrologic measurements (approximately monthly), and various gaps of 2 months are present in the data. Mercury concentrations in surface water varied more than an order of magnitude if occasional spikes in concentration are included (fig. 31). Concentration spikes resulted for both filtered and unfiltered Hg_T data, reflecting the effects of particle re-suspension on surface-water concentrations. Hg_T concentration values that were filtered sometimes were higher than unfiltered values for the same day, which may reflect the contamination problem discussed earlier.

Data collection was too sparse to establish definitively whether ground-water Hg_T in the western wells increased over the 4-year study period. Observing breakthrough of Hg_T in those wells is the expected result of the increased recharge of Hg_T that began after the ENR wetland became operational. Determining the time of Hg_T breakthrough is important because it would help characterize interactions between mercury and aquifer sediments, and resulting retardation during transport. Unfortunately, the number of sampling events is too sparse, particularly near the beginning of the measurement period, to determine breakthrough time (fig. 31). MeHg in ground water showed no obvious differences over time or between locations (fig. 30). Because no other major long-term trends were apparent in recharge or in mercury concentrations, time-averaging both recharge and mercury concentrations data was judged to be a reasonable first-order approach to budgeting ground-water fluxes at ENR.

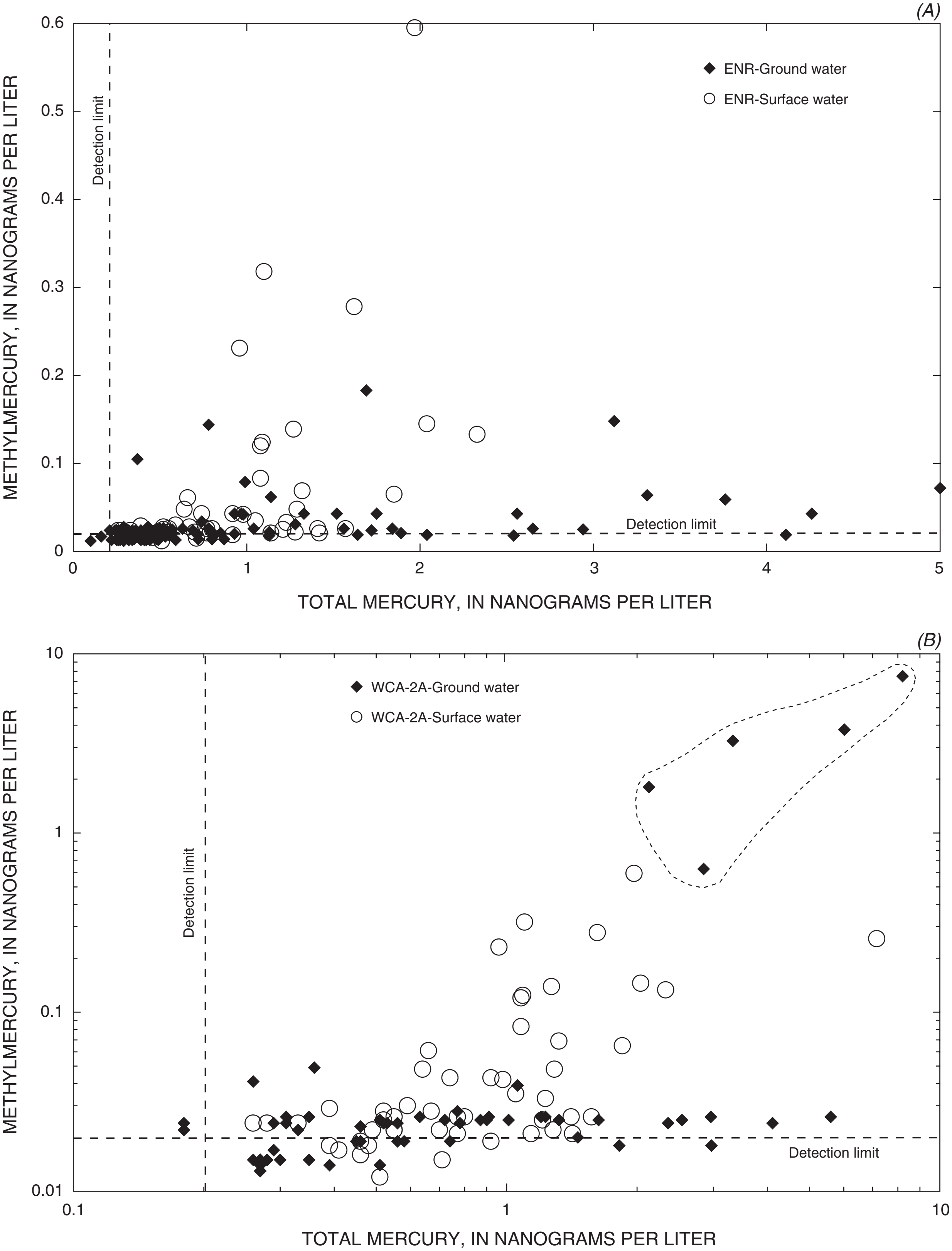


Figure 29. Dissolved methylmercury and total mercury, Everglades Nutrient Removal Area (ENR) *(A)* and Water Conservation Area 2A (WCA-2A) *(B)*, north-central Everglades, south Florida. Dotted lines surround potentially unreliable data from well U1-GW4 and U3-GW3. See text for explanation.

Table 17. Mercury concentrations in shallow ground water and surface water at Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida

[Hg_T, total mercury; MeHg, methylmercury]

Sites	Years sampled	Total number of observations	Mean Hg concentrations[1]		Standard deviations	
		n	Hg_T (ng/L)	MeHg (ng/L)	Hg_T (ng/L)	MeHg (ng/L)
Westside wells						
MP3-D	97-98	4	0.8	0.02	0.6	0.005
P02A	96-98	18	1.1	0.02	0.7	0.005
P03A	96-98	9	1.4	0.02	0.7	0.005
P04A	96-98	11	1.5	0.02	0.8	0.005
P05A	96-98	13	2.7	0.02	3.5	0.005
P06A	96-98	13	1.8	0.02	1.1	0.006
P07A	96-98	14	1.0	0.02	0.6	0.007
Average between sites			1.4	0.02	1.1	0.006
Eastside wells						
MP1-C	97-98	4	0.5	0.02	0.3	0.005
MP1-D	97-98	4	0.9	0.02	0.8	0.005
P10A	95-96	4	0.7	0.02	0.3	0.004
P12A	95-96	4	0.6	0.02	0.1	0.004
P13A	95-96	10	1.0	0.02	0.9	0.01
Average between sites			0.7	0.02	0.5	0.006
Seepage canal	97-98	5	0.8	0.02	0.5	0.006
Seepage canal - Unfiltered	94-99	10	0.4	0.05	0.1	0.05
Seepage canal - All data	94-99	15	0.6	0.04	0.3	0.004
Surface water - ENR-203	95-99	155	1.0	0.01	0.7	0.14

[1] All concentrations are for filtered samples unless otherwise noted.

The seepage canal on the western and northern sides of ENR collects ground water that was recharged in ENR. Average Hg_T concentrations are based on a small number of samples (15) from the seepage canal. The 5 filtered samples actually had a higher mean concentration of Hg_T (0.8 ng/L) than the 10 unfiltered samples (0.4 ng/L). The higher concentrations may have resulted from two sources: 1) contamination of the filtered Hg_T analyses, or 2) lower Hg_T concentrations in the seepage canal earlier in the study (1994 and 1995), before breakthrough of Hg_T in ground-water discharge occurred. The present analysis used all Hg_T analyses available in the seepage canal, whether filtered or unfiltered, which resulted in an average value of Hg_T of 0.6 ng/L for the seepage canal. Dissolved MeHg was undetectable (less than 0.02 ng/L) in the seepage canal.

Mercury Fluxes with Recharging and Discharging Water in ENR

The resulting mercury flux computations are reported in table 18 with reference to the overall mercury balance at ENR (South Florida Water Management District, 1999). Ground-water discharge to ENR from the eastern side (WCA-1) was not appreciable, contributing approximately 0.5 and 0.3 percent of Hg_T and MeHg to ENR, respectively. However, recharge on the western side of the ENR is a major pathway for output of Hg_T from ENR. Recharge of Hg_T accounted for an output of 70 g/yr, or 10 percent of all inputs to ENR. Recharge of MeHg was negligible, either below detection, or, if values of MeHg close to detection levels are used, accounting for no more than export of 1 g/yr (3 percent of inputs).

The finding that Hg_T mercury is recharged in substantial quantities to the sand and limestone aquifer

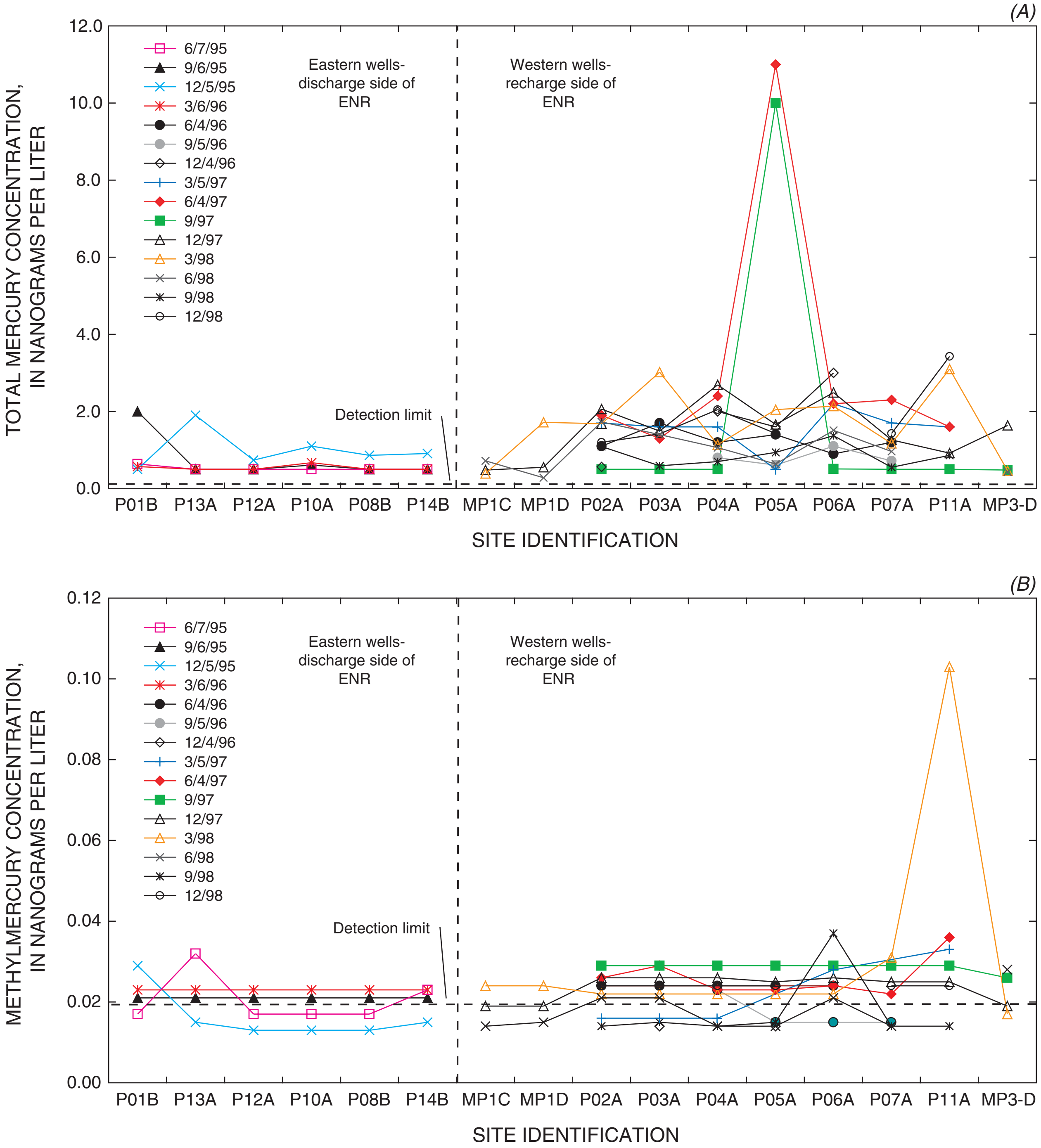


Figure 30. Dissolved total mercury *(A)* and methylmercury *(B)* in shallow wells at Everglades Nutrient Removal project (ENR), north-central Everglades, south Florida. Wells are grouped by eastern and western sides of the wetland, where ground-water discharge and recharge occur, respectively.

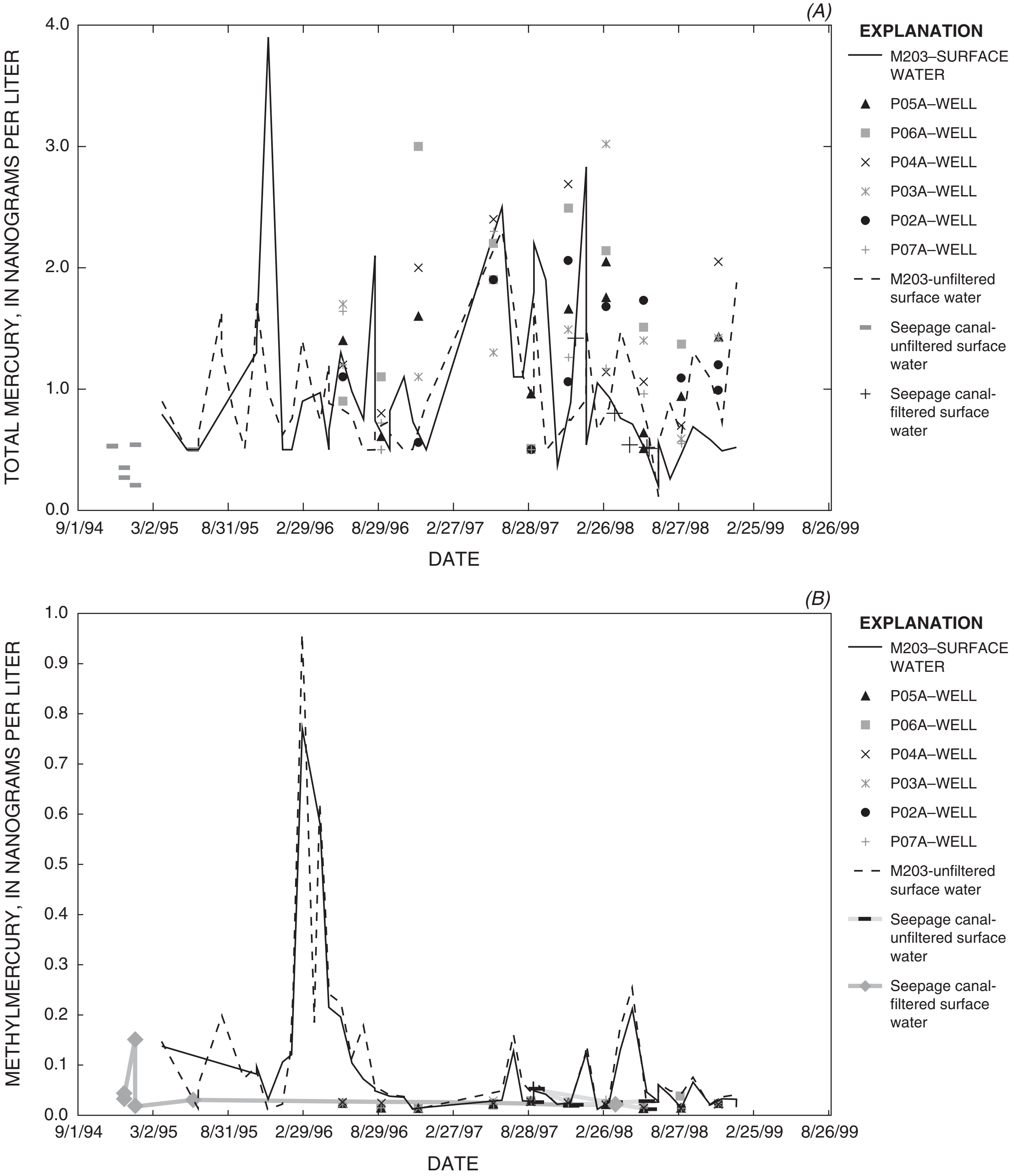


Figure 31. Time course of total mercury *(A)* and methylmercury *(B)* concentrations in Everglades Nutrient Removal project (ENR), north-central Everglades, south Florida.

is consistent with vertical profiles of Hg_T concentrations in peat. A vertical profile in peat shows relatively equivalent concentrations of Hg_T through the entire depth of peat, which supports the conclusion that Hg_T is recharged to the aquifer (fig. 32). In contrast, MeHg does not appear to be recharged through the peat. The steep decline in MeHg concentration with depth in peat is presumed to result from the increasing importance of demethylation over methylation, compared to downward advection of MeHg through peat. A peat profile from western ENR where MeHg only was detected in the top 5 cm of the peat is consistent with the negligible recharge flux of MeHg (table 18 and fig. 33).

In addition to calculating ground-water exchange fluxes, it also was possible to estimate the change in mercury storage in peat. For the purposes of this study, change in mercury storage in peat is estimated as the difference in advection of mercury downward across the peat surface and recharge of mercury out of the base of the peat into the aquifer. Downward advection of surface-water mercury into peat is computed similarly to ground-water recharge, except surface-water concentrations are multiplied by the recharge flux instead of ground-water concentrations. Downward advection accounted for movement of 50 g/yr, or 8 percent of total inputs, of Hg_T from ENR surface water to peat porewater. For MeHg, downward advection into peat accounted for 5 g/yr, or 20 percent of inputs of MeHg, respectively (table 18). After computing storage estimates, it was apparent that Hg_T was released from peat at a rate of 20 g/yr and MeHg was stored at a rate of 4 g/yr, which are equal to rates of 3 and 10 percent of the inputs to ENR, respectively.

Caution is required in evaluating rates of mercury storage in peat calculated during this study. These calculated rates do not consider the effects of sedimentation of particulate matter with solid phase mercury onto the peat surface, or the effects of upward diffusion of mercury back to surface water. For example, King (2000) showed that upward diffusive fluxes probably exceed downward advective fluxes of mercury at ENR. Nonetheless, storage estimates calculated here can be used as a preliminary interpretation of the changes in mercury processing in the peat. The rate of release of total mercury from solid phases on peat was calculated as the difference in the flux from the peat to the aquifer and the flux from surface water to the peat. Partitioning components indicate that approximately 70 percent of the Hg_T recharged to the aquifer was derived from downward advection of surface water into peat, whereas the remainder (30 percent) came from release of Hg from solid phases in peat. Release of particulate mercury from peat into recharging water was not expected, because of the high affinity of mercury for sorption sites on peat. On the other hand, release of Hg_T from organic sediments has been observed in littoral zones of lakes that receive sedimentation of labile organic matter with bound mercury (Krabbenhoft and

Table 18. Annual budget for recharge, discharge, and subsurface storage of dissolved mercury in Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida, 1994-98.

[Concentrations and fluxes were averaged for the period 1994-98; concentrations are the average of filtered samples unless otherwise noted; Hg_T, total mercury; MeHg, methylmercury; a, average concentration in eastside wells x average ground-water discharge; b_1, average concentration at M203 x average ground-water recharge; b_2, average concentration in westside wells x average ground-water recharge; c, calculated as (b_1 - b_2 + a); d, average concentration in westside wells x average flow in seepage canal; e, calculated as (b_2 - d - a)]

RECHARGE AND DISCHARGE FLUXES OF MERCURY[1] AND SUBSURFACE STORAGE CHANGES	FLUX (grams/year)		PERCENTAGE OF INPUT TO ENR[2]	
	Hg_T	MeHg	Hg_T	MeHg
a - Discharge from ground water to peat, eastside	3	0.1	0.5	0.3
b - Recharge from ENR surface water, westside				
b_1 - ENR surface water to peat	50	5	8	20
b_2 - ENR peat to ground water	70	1	10	3
c - Apparent storage change in peat[3]	-20	4	3	10
d - Seepage canal flux[4]	20	1	3	3
e - Apparent storage change in Surficial aquifer[3]	50	0	8	0

[1] Ground-water recharge and discharge fluxes are from Choi and Harvey (2000).

[2] Sum of mercury inputs by atmospheric wet deposition and surface-water pumping.

[3] Positive and negative numbers indicate gains or losses of dissolved mercury from storage because of chemical association with sediment.

[4] Computed by using all filtered and unfiltered mercury data because of the relatively small number of samples.

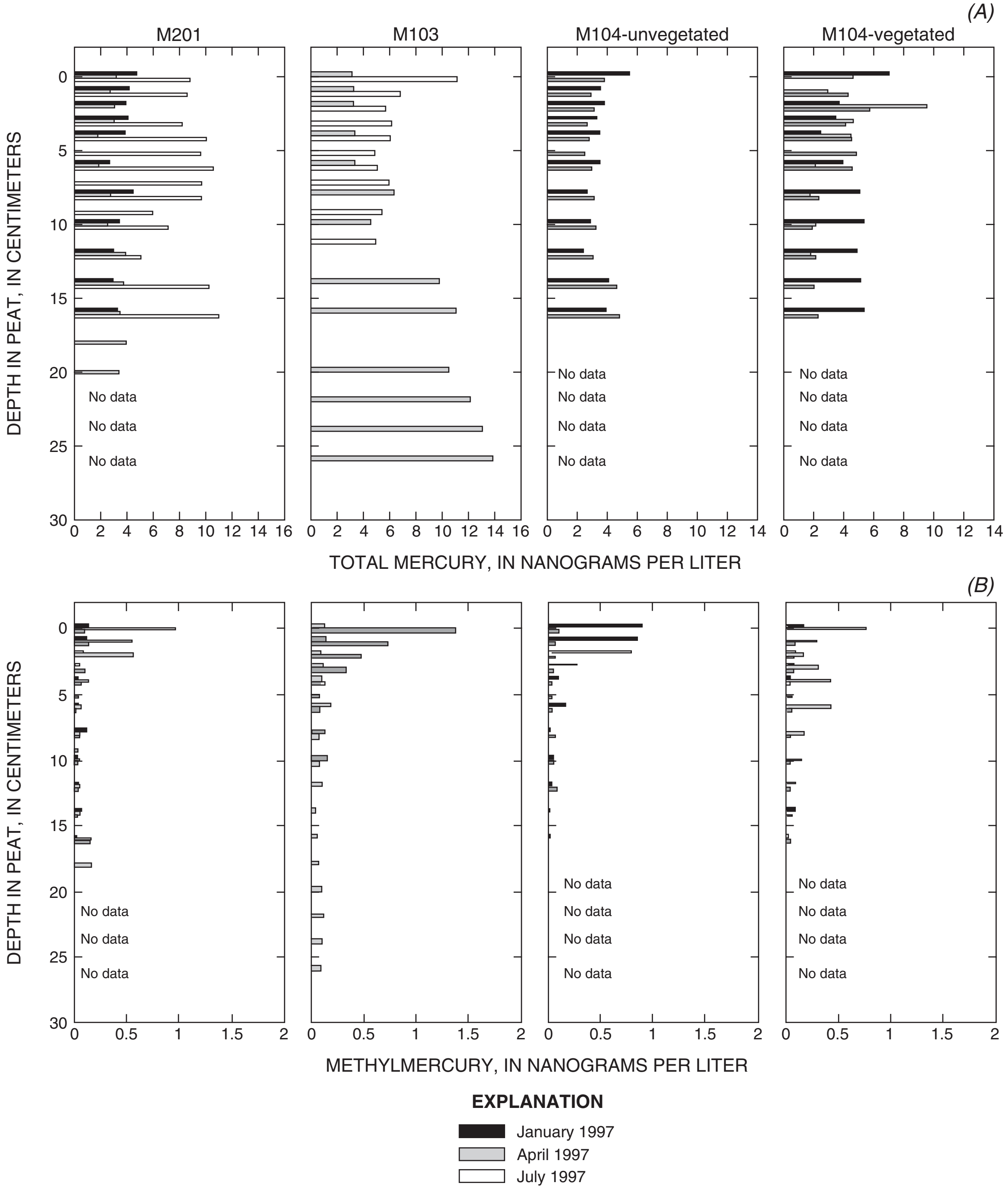


Figure 32. Profiles of estimated concentrations of dissolved total mercury *(A)* and methylmercury *(B)* in peat porewater at Everglades Nutrient Removal (ENR) project, north-central Everglades, south Florida. Dissolved concentrations were estimated by King (2000), who used measurements of solid phase mercury concentrations and sediment bulk density, along with estimates of the liquid-solid distribution coefficient at selected depths from the study sites.

Babiarz, 1992). Other factors may be important in causing Hg_T release in ENR peat. First, the storage of mercury may have been exceptionally high, building up during many years of agricultural farming in oxic soils that then became anoxic following re-flooding (Kelly and others, 1997). Second, ancillary constituents recharged with surface water or released by sediment diagenesis after re-flooding may affect the binding constants for mercury. For example, King (2000) found that both dissolved inorganic sulfur compounds and sulfur-bearing dissolved organic carbon compounds may compete with mercury for surface-binding sites in peat, effectively decreasing the partitioning coefficient for mercury on peat.

MeHg appears to be either strongly retained in the peat or rapidly degraded, judging from both storage calculations and profiles of MeHg in peat. Much of the retention in peat porewater may be temporary, because of biodegradation and the steep diffusion gradient that may transport MeHg back to surface water. King (2000) found that upward diffusion of MeHg back to surface water probably exceeds the downward recharge flux of MeHg into the peat.

Evidence for Reactivity of Mercury in Peat and in the Surficial Aquifer

What is the fate of Hg_T recharged to the aquifer? It is possible that some of the Hg_T was retained in ground-water flow paths beneath the western boundary levee. The average concentration of total mercury in the seepage canal (0.6 ng/L) was less than half of the average for wells beneath the western and northern levees (1.4 ng/L) (table 17), suggesting the possibility that mercury is retained by geochemical reactions in ground water. If shallow recharge in ENR were the only source of water to the seepage canal (and if the concentrations were no longer changing with time), it

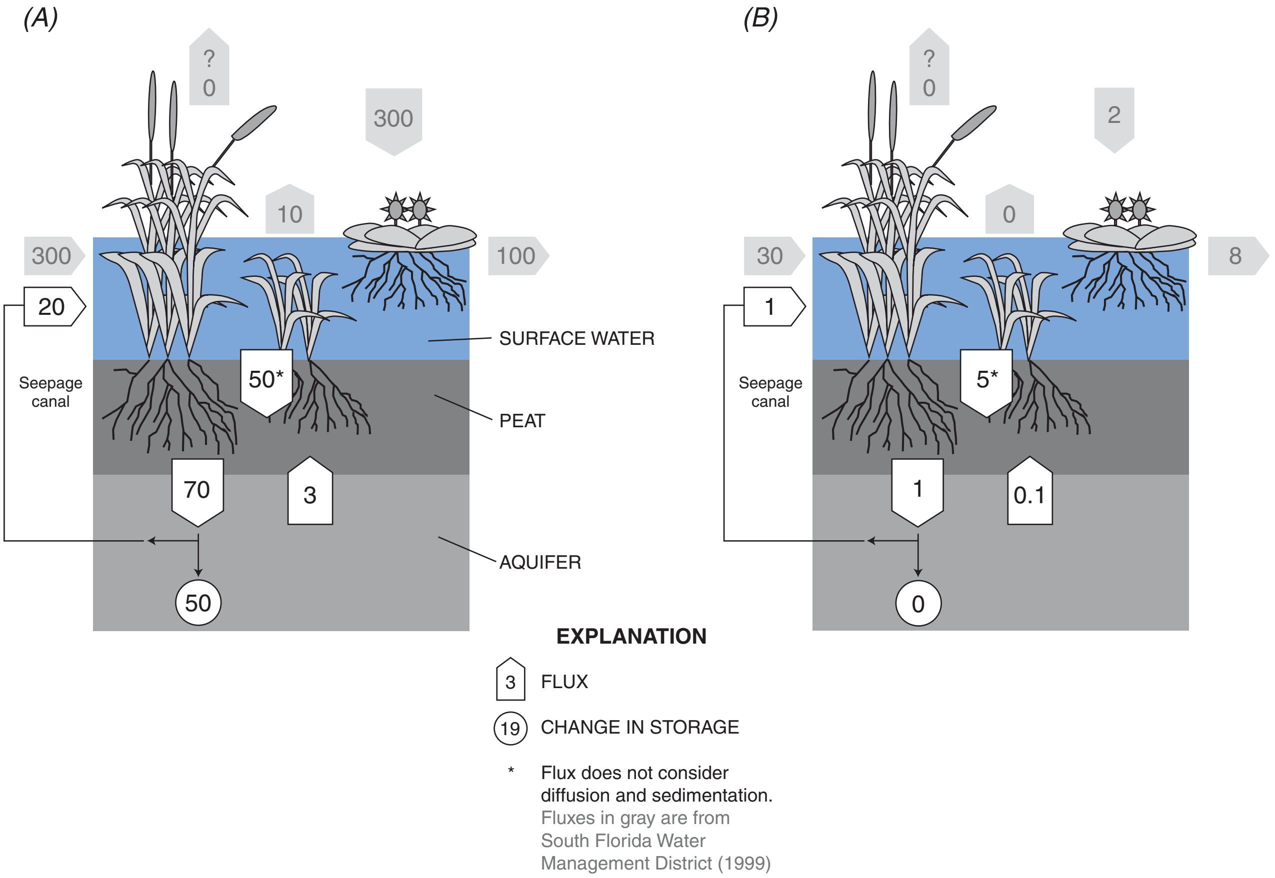


Figure 33. Average ground-water fluxes and storage rates (grams per year) of total mercury (A) and methylmercury (B) compared with surface-water and atmospheric fluxes in Everglades Nutrient Removal Area (ENR), north-central Everglades, south Florida. Surface-water and atmospheric wet deposition fluxes are from South Florida Water Management District (1999). Budget represents a 4-year average, 1994-98.

only would be necessary to divide the seepage canal concentration by the concentration detected in western wells to determine the extent of mercury retention. A preliminary conclusion from these data could be drawn by assuming that mixing between shallow ground-water recharge and deeper ground water from another source was minimal. However, it would be more prudent to attempt to account for mixing with deeper ground water.

Choi and Harvey (2000) found that, on average, the seepage canal captures most of the recharging ground water in ENR (approximately 73 percent). During periods with of low water levels in ENR, recharge of ENR water closely matched flows in the seepage canal. During periods of high water levels in ENR, there is an additional component of recharge in ENR to deep flow paths not captured by the seepage canal. There is increased flow in the seepage canal at those times (approximately 20 percent increase), and chemical data from the seepage canal shows that the additional flow represents discharge from deeper ground water with higher chloride and lower mercury concentrations. The task of accounting for mixing between shallow and deeper ground water was accomplished using a combined water and chloride balance for the seepage canal. The water balance suggests that, on average, discharge from deeper ground water to the seepage canal makes up approximately 10 percent of the flow in the seepage canal. The deeper ground water that discharges to the seepage canal has a chloride concentration approximately equal to 370 mg/L (the highest measured chloride concentration in the seepage canal; Harvey and others, 2000). The resulting mass balance on chloride in the seepage canal simulated an average concentration of 170 mg/L. This concentration is similar to the measured average concentration (Harvey and others, 2000). Based on this average chloride concentration, an Hg_T concentration of 1.3 ng/L was computed in the seepage canal for the situation where discharge of deep ground water (with undetectable Hg_T) is the only important factor affecting Hg_T concentrations (that is, chemical mercury reactions were ignored). Comparing the computed concentration with the average measured concentration of Hg_T in the seepage canal (0.6 ng/L) indicates that approximately 50 percent of the Hg_T was removed by chemical reactions in the shallow part of the Surficial aquifer or in the bottom sediments of the seepage canal.

Therefore, based on the computed budget, it was determined that total mercury is stored by geochemical retention during passage through the aquifer sediments. The simplest type of chemical reaction that would explain storage in the aquifer is sorption of mercury to peat or aquifer sediments (sand and limestone). Sorption would cause retardation in the transport of Hg_T; however, complete breakthrough of mercury eventually would be expected if sorption were completely reversible. Breakthrough of Hg_T in western levee wells at ENR appeared to have occurred relatively quickly (2 years or less), because a steady plateau concentration of Hg_T had been reached by the time those wells were sampled routinely. Based on these data, breakthrough of Hg_T also would have been expected to be detected in the seepage canal during the 4-year study period, but that was not the case. An interpretation that is consistent with these observations is that retention of Hg_T is non-reversible on aquifer solids. Another interpretation is that non-reversible retention of Hg_T occurred on organic sediments as ground water discharged across the bottom of the seepage canal. The present data are not sufficient to draw a final conclusion. Detailed examination of core material and bench-top experimentation would be needed to make further evaluations.

Improving future ground-water budgets for mercury should be investigated. The present investigation used a time-averaged approach to develop the mass budget. This approach was simple and considered a first step. Also, this approach had the advantage of consistency with other budget estimates that are reported as annual estimates. Calculating time-averaged fluxes was also the most straightforward means to deal with problems such as gaps in mercury data and random contamination of a small percentage of filterable Hg_T concentrations (South Florida Water Management District, 1999). Future work may determine that a time-dependent analysis is justified. In any case, the annually averaged approach is a good first step to refine specific questions, develop preliminary conclusions, and establish alternatives for further research.

Additional work also is needed to estimate diffusive fluxes of mercury from peat to surface water, and sedimentation of mercury to the wetland surface, because those fluxes could be significant compared to recharge fluxes. For example, estimates of mercury diffusion from ENR sediments suggest that upward diffusive fluxes of mercury from peat to surface water probably exceed the downward recharge fluxes (King, 2000). More work is needed to determine how diffusion and sedimentation will interact with ground-water fluxes to affect the mercury balance in peat.

SUMMARY AND CONCLUSIONS

Water-resources management in the Everglades has evolved from the original purpose to protect against floods and to conserve water during dry periods, to also include protecting and restoring natural functions and characteristics. The main effect that digging canals and draining wetlands had was to reduce the water-storage capacity of this subtropical peatland. Over time, the decreased water storage contributed to the degradation of a natural balance between highly seasonal water flows, pristine low-nutrient freshwaters, and a unique assemblage of specially adapted plants and wildlife. The first half of the twentieth century saw the many adjustments to the changing hydrology that caused a general drying out of the Everglades system. The second half of the twentieth century began with the completion of a system of levees that enclosed Water Conservation Areas (WCAs). For a number of years following completion of WCAs, water tended to be stored at levels that were too high for the ecosystem during wet periods, resulting in problems such as the drowning of tree islands. Equally undesirable was an approach to managing floods that involved conveying vast amounts of freshwater (that the pre-drainage Everglades previously could have stored) through canals to be flushed to the Atlantic Ocean. During excessively dry periods control structures were shut to keep water levels at minimum acceptable levels in WCAs, which had the effect of curtailing the southerly flow of water to the Everglades National Park (ENP). Even during times between storms and droughts, problems persisted with water management in the Everglades. Some of these problems included shallow seepage beneath levees that occurred at all times and deeper ground-water flows increased from the Everglades to outside areas after an extended period of ground-water pumping in well fields to the east. Thus, southerly flows to ENP were depleted even during times of typical water-level conditions. The Comprehensive Everglades Restoration Plan, authorized by Congress in 2000, sought to address the large, complex, and expensive to remediate water-management problems.

Except for seepage studies beneath the eastern boundary levees, interactions between surface water and ground water have not been extensively investigated in the Everglades. More work is needed on accurately estimating recharge and discharge, and the effects on the water balance and water quality of the Everglades. Investigations of the factors that control recharge and discharge also are important. A problem of special concern in the Everglades is characterizing recharge and discharge in the vast wetland interior areas, where few studies have been completed. Interactions between surface water and ground water in interior areas, and their modification because of water-resources management, are relevant to the protection of fresh ground-water resources beneath the vast interior of the Everglades.

In an effort to learn more about surface-water and ground-water interactions in the Everglades, the U.S. Geological Survey (USGS) and South Florida Water Management District (SFWMD) developed an agreement to undertake a detailed study of those interactions in selected areas of the north-central Everglades. The present study focused its efforts on the most highly manipulated part of the Everglades system—areas of the north-central Everglades that had been converted to farming during the past century and now returned to management as constructed wetlands, called Stormwater Treatment Areas (STAs).

The present investigation determined the extent to which interactions between surface water and ground water have increased in the north-central Everglades as a result of water-resources management. On the western side of the WCAs, and in the Stormwater Treatment Areas, or STAs, there has been a dramatic shift since pre-drainage times in the direction of horizontal ground-water flow and in the magnitude of recharge. The direction of ground-water flow shifted southwest to northwest as a consequence of the steepening of land and water-table slopes that followed extensive land subsidence in the Everglades Agricultural Area, or EAA. Another factor that was important in changing interactions between surface water and ground water was the abrupt change in water level (typically 2.5 ft or more) across levees that increased driving forces for recharge and discharge. Rapid releases of large quantities of surface water between basins also had the effect of increasing recharge and discharge by propagating surface waves (and subsurface pressure waves through the aquifer), causing temporary periods of increased recharge often followed by temporary periods of increased discharge.

Recharge is the dominant interaction between surface water and ground water in the northern Everglades when averaged over space and time. Net recharge is the result of increased hydraulic gradients caused by land subsidence and decreasing water-table elevations outside of the WCAs. Basin-averaged recharge at the Everglades Nutrient Removal (ENR) project (0.9 cm/d) exceeded recharge at Water Conservation Area 2A (WCA-2A) (0.2 cm/d) by more than a factor of 4. Recharge exceeded discharge in both ENR and WCA-2A, by a factor of 10 at ENR, and by a factor of 2 in WCA-2A. Recharge in both ENR and WCA-2A accounted for a volumetric flux of water equal to approximately 30 percent of surface water pumped into each basin.

Recharge and discharge increased since pre-drainage conditions in the vicinity of ENR as a result of water-management conditions. The estimated change was from approximately no net flux under pre-drainage conditions to 0.9 cm/d net recharge under present water-management conditions. Changes in net recharge and discharge probably were not as dramatic in WCA-2A, from no net flux under pre-drainage conditions to approximately 0.08 cm/d net recharge under present conditions. An increase in net recharge since pre-drainage conditions mainly has been controlled by large-scale and long-term changes, such as subsidence in the agricultural areas and increasing ground-water pumping from well fields to the east of the Everglades.

Site-specific estimates of recharge and discharge in ENR and WCA-2A ranged between detection limits (0.04 cm/d) and 20 cm/d. The general pattern of recharge and discharge measurements showed that interactions between surface water and ground water decrease from the north Everglades toward the north-central Everglades. The largest recharge and discharge fluxes were observed in ENR. From ENR, recharge and discharge decreased consistently toward the wetland interior of WCA-3A. What explains the pattern of decrease from north to south? Recharge and discharge fluxes were highest within 0.5 km of levees (always greater than 0.3 cm/d), whereas vertical fluxes in the wetland interior rarely exceeded 0.3 cm/d. The order of magnitude difference in vertical fluxes near and far from levees suggests that basin-averaged fluxes are predictable from the ratio of the length of levee perimeter to the surface area of each basin, which decreases from the northern extent of the Everglades (ENR and STAs) towards the WCA-3. Greater hydraulic conductivity in WCA-2A peat compared with ENR also affected recharge and discharge. Differences in hydraulic properties of peat appear to be explained by peat compaction in wetlands managed for agriculture for appreciable time (decades).

Vertical fluxes in the interior areas of the wetland basins were relatively small and varied over time, frequently changing direction. To put these fluxes in the perspective of other water balance fluxes, recharge and discharge in interior areas were usually less than 50 percent of average precipitation and evapotranspiration (0.4 cm/d and 0.35 cm/d, respectively). Nevertheless, recharge and discharge in the wetland interior still are quite important. For example, recharge in the interior of WCA-2A accounted for a volumetric flux equal to 30 percent of surface flow through that basin.

Little is known about the factors that control vertical exchange in the wetland interior. Hydrogeologic model simulation showed that recharge and discharge in the wetland interior are not explained by water-level differences across levees. Instead, it is more likely that the local and regional water-surface slopes, controlled by topography and water releases between basins, have a greater effect on recharge and discharge in the wetland interior. The factor discussed in great detail in this report was the effect of large releases of water in WCA-2A that transmit waves of surface water through the wetlands, and induce pressure gradients that cause cycles of recharge and discharge. Another important factor is the layering of different aquifer sediments in the aquifer, which transmits surface-pressure perturbations at different rates. The relation between water releases and hydraulic properties of aquifer sediments and peat drives vertical exchange in ways that are not yet fully understood. It is clear, however, that recharge and discharge are related closely with fluctuating surface-water levels. Reversal between recharge and discharge in the wetland interior may not affect the long-term average water balance; however, those vertical fluxes could contribute to net exchange of solutes, including contaminants, between wetlands and ground water. Future investigations will require better field measurements and more sophisticated modeling to test the importance of such factors in controlling surface-water and ground-water interactions.

Geochemical evidence provides a long-term integrated picture of hydraulic processes in the aquifer and exchange with surface water. Water-stable isotopes indicated that the major source of fresh water in Everglades ground water is recharge of evaporated surface water from the wetlands rather than infiltration of rainfall through unsaturated sediments. This observation is consistent with the interpretation that both recharge and discharge have always occurred in the Everglades, with recharge occurring at time periods of relatively high surface-water levels and discharge occurring when surface-water levels were low.

Major ion chemistry and water-stable isotopes identified eight major water types in the north-central Everglades. Four of those types were considered to be source waters. The other four are mixtures of the source waters. The distribution of those water types identified long-term average flow pathways of recharge and discharge. Particularly evident as a major factor driving recharge and discharge in the present-day Everglades was the effect of wetland compartmentalization by levees. Geochemical water typing provided information that was consistent with hydraulic information. The geochemical tracers, however, particularly were useful in showing the extent to which water management has caused vertical mixing throughout essentially the entire depth of the Surficial aquifer. The effect of levees is indicated by the presence of *Fresh Recharge Water* recharged to a depth of at least 90 ft on the up-gradient (headwater) side of the levee, and *Relict Seawater* discharged on the down-gradient (tailwater) side of the levee. The effect of levees on interactions between surface and ground water, therefore, extends vertically throughout at least the top half of the Surficial aquifer (100 ft), and horizontally for at least 1 mi away from the levees. These observations support the hydraulic interpretation that water management has increased interactions between surface water and ground water in the north-central Everglades.

A wide-ranging assessment of the distribution of mercury in surface water, peat porewater, and ground water found no evidence that ground water was a significant source of mercury to surface water. Rather, peat and surface water appear to be a source of mercury to ground water, transported with recharging ground water. Maximum values of total mercury (Hg_T) in shallow ground water were approximately equal to corresponding measurements in surface water at both ENR and WCA-2A. Methylmercury (MeHg) was detectable only in certain shallow wells at ENR and WCA-2A. Those wells had MeHg concentrations that were 50 percent and 10 percent of the highest MeHg concentrations in surface water at ENR and WCA-2A, respectively. Whereas Hg_T was detectable throughout the Surficial aquifer, MeHg was mainly present at detectable concentrations only in ground water recharged at the ENR site when that area was managed for agriculture.

Variable SO_4 concentrations do not co-vary with MeHg concentrations at either ENR or WCA-2A. Source of recharge water generally is thought to cause variability in mercury concentrations. For example, MeHg only was detectable in shallow ground water beneath ENR in wells where major ion chemistry and water-stable isotopic ratios indicated that agricultural recharge water was the source. Eight of 17 samples from wells with agricultural recharge water had detectable MeHg, with values as high as 0.2 ng/L. In contrast, well samples with wetland recharge water all had very low values of MeHg (less than 0.04 ng/L). Type of recharge water was not as important for $Hg_{T,}$ because measurements greater than 0.5 ng/L were distributed equally between the agricultural recharge water and wetland recharge water.

Ground-water fluxes of mercury were determined as part of a steady-state hydrologic and mercury balance in ENR. The resulting mercury flux computations indicated that ground-water discharge to ENR from the eastern side (WCA-1) was not appreciable, contributing approximately 0.4 and 0.3 percent of Hg_T and MeHg to ENR, respectively. However, recharge on the western side of the ENR was a major pathway for export of Hg_T from ENR. Recharge of Hg_T accounted for an export of 68 g/yr, or 10 percent of all inputs to ENR. Recharge of MeHg was negligible, either below detection, or, if values of MeHg close to detection levels are used, accounting for no more than export of 1 g/yr (3 percent of inputs).

Based on the mass budget for Hg and other evidence, it was concluded that recharge of Hg_T was augmented with release of more Hg_T during downward transport through the peat. The primary evidence for this conclusion is that average concentrations of Hg_T measured in shallow ground water were higher than average values measured in surface water. Independently measured profiles of Hg_T in peat porewater corroborate that conclusion, showing that Hg_T concentrations are high throughout the entire depth of peat. Therefore, it appears that solid-phase mercury stored in the peat is being mobilized and recharged to the aquifer. Mass-balance estimates suggest that 70 percent of the recharged Hg_T comes from surface water, whereas 30 percent comes from release from the peat. In contrast to results for Hg_T, it was found that MeHg was not recharged to the aquifer. Support for this conclusion comes from measurements of MeHg in shallow ground water that are below detection, and from porewater profiles in peat that show relatively high concentrations of MeHg are restricted to very near the peat surface.

Chemical data and water-stable isotopic ratios indicate that most surface water recharged in ENR is discharged to a seepage canal on the western and northern side of ENR. Transport of recharged water through the aquifer to the seepage canal appears to take place in a matter of weeks to months, with only relatively minor mixing with deeper ground water. Measurements of Hg_T in the seepage canal suggested that Hg_T had not yet discharged to the canal at the end of the 4-yr study period (1994-98). Because the travel time between points of recharge in ENR and discharge in the seepage canal was relatively short (weeks to months), it was concluded that mercury was retained or delayed in its transport through the aquifer by interaction with aquifer sand or limestone or fine organic materials at the base of the seepage canal.

REFERENCES CITED

Abtew, W. and Mullen, V., 1997, Water budget analysis for the Everglades Nutrient Removal Project: Technical Memorandum, South Florida Water Management District, WRE #354, 21 p.

American Society of Testing and Materials, 1991, Standard test method for particle-size analysis of soils, D-422: Philadelphia, Pa., 6 p.

Barlow, P.M. and Moench, A.F., 1998, Analytical solutions and computer programs for hydraulic interaction of stream-aquifer systems: U.S. Geological Survey Open-File Report 98-415A, 85 p.

Bates, A.L., Orem, W.H., Harvey, J.W., and Spikier, E.C., 2002, Tracing sources of sulfate in the Florida Everglades: Journal of Environmental Quality, v. 31, p. 287-299.

Beach, D.K., 1982, Depositional and diagenetic history of Pliocene-Pleistocene carbonates, northwestern Great Bahama Bank: evolution of a carbonate platform: University of Miami, Miami, Fla., 600 p.

Bolster, C.H., Genereux, D.P., and Saiers, J.E., 2001, Determination of specific yield for the Biscayne aquifer with a canal-drawdown test: Ground Water, v. 39, no. 5, p. 768-777.

Boggs, Jr. Sam., 1995, Principles of sedimentation and stratigraphy: Prentice Hall, Upper Saddle River, N.J., 774 p.

Bloom, N.S., 1995, Cleaning of sampling equipment and bottles (FGS-007): Frontier Geosciences Inc., Seattle, Wash., 4 p.

Bouwer, H., 1989, The Bouwer and Rice Slug Test – An update: Ground Water, v. 27, no. 3, p. 304-309.

Bouwer, H. and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423-428.

Broecker, W.S. and Thurber, D.L., 1965, Uranium-series dating of corals and oolites from Bahaman and Florida Key limestones: Science, no. 149, p. 58-60.

Branfireun, B.A., Hayes, A., and Roulet, N.T., 1996, The hydrology and methylmercury dynamics of a Precambrian Shield headwater wetland: Water Resources Research, v. 32, p. 1785-1794.

Brooks, H.K., 1968, The Plio-Pleistocene of Florida, with special reference to the strata outcropping on the Caloosahatchee River, *in* Perkins, R.D. (ed.), Late cenozoic stratigraphy of southern Florida—a reappraisal: Miami, Fla., p. 3-42.

Burns and McDonnell, 1991, Design memorandum perimeter levee system, Contract C89-0041, A.4, Technical Memorandum, South Florida Water Management District, West Palm Beach, Fla., variously paged.

Chin, D.A., 1990, A method to estimate canal leakage to the Biscayne aquifer, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4135, 32 p.

Choi, J. and Harvey, J.W., 2000, Quantifying time-varying groundwater discharge and recharge in wetlands: a comparison of methods in the Florida Everglades: Wetlands, v. 20, no. 3, p. 500-511.

Core Laboratories, Inc., 1999, Report - Core Analysis of Report for South Florida Water Management District of Various Wells in Florida., Midland, Texas.

Cunnigham, K.J., 1998, Regional Stratigraphic Correlation of a Pliocene Mixed Siliclastic Carbonate Ramp (Tamiami Formation): Presented at the 1998 Annual Meeting of the Geological Society of America, October 26-29, 1998, Toronto, Canada.

Dames and Moore, 1988, Final Report- Phase III Studies (Tasks I and II) Foundation Exploration and Design Consultation Proposed Southern Region Wastewater Treatment Plant, Palm Beach County, Florida., Boca Raton, Fla., variously paged.

Danish Hydraulic Institute, 1999, Small scale integrated surface water and ground water model development: model application report to the SFWMD, Hørsholm, Denmark, 33 p.

Enos, P., 1977, Holocene sediment accumulations of the south Florida shelf margin, *in* Enos, P., and Perkins, R.D. (eds.), Quaternary Sedimentation in South Florida: Geological Society of America Memoir, v. 147, 130 p.

Fish, J.E., 1988, Hydrogeology, aquifer characteristics, and ground-water flow of the Surficial Aquifer system, Broward County, Florida: U.S. Geological Survey Water-Resources Investigations Report 87-4034, 92 p.

Fish, J.E. and Stewart, M., 1991, Hydrogeology of the surficial aquifer system, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90-4108, 50 p.

Frazee, Jr., J.M., 1982, Geochemical pattern analysis: method of describing the Southeastern Limestone regional aquifer system, *in* B.F., Beck (ed.), Studies of the hydrogeology of the southeastern United States. Americus, Special Publications: No.1, Georgia Southwestern College, p. 46-58.

Genereux, D. and Slater, E., 1999, Water exchange between canals and surrounding aquifer and wetlands in the Southern Everglades, U.S.A.: Journal of Hydrology, v. 219, p. 153-168.

Genereux, D. and Guardiario, J., 1998, A canal drawdown experiment for determination of aquifer parameters: Journal of Hydrogeologic Engineering, v. 3, no. 4, p. 294-302.

Gerould, S., and Higer, A., 1995, South Florida ecosystem program of the U.S. Geological Survey: U.S. Geological Survey Fact Sheet FS-134-95, 2 p.

Giddings, J.B., 1999, Deposition and chronostratigraphic subdivision of the Quaternary sediments, Broward County, Florida: Unpublished Master's Thesis, Florida Atlantic University, Boca Raton, Fla., 155 p.

Gilmour, C.C., Henry, E.A., and Mitchell, R., 1991, Sulfate stimulation of mercury methylation in freshwater sediments: Environmental Science and Technology. v. 26, p. 2281-2287.

Gilmour, C.C., Riedel, G.S., Ederington, M.C., Bell, J.T., Benoit, J.M., Gill, G.A., and Stordahl, M.C., 1998, Methylmercury concentrations and production rates across a trophic gradient in the northern Everglades: Biogeochemistry, v. 40, p. 327-345.

Gleason, P.J., and Stone, P., 1994, Age, origin, and landscape evolution of the Everglades peatland, *in* Davis, S.M., and Ogden, J.C., eds., Everglades—The ecosystem and its restoration: St. Lucie Press, Fla., p. 149-198.

Guardo, M. and Tomasello, R.S., 1995, Hydrodynamic simulations of a constructed wetland in south Florida: Water Resources Bulletin, v. 81, no. 4, p. 687-701.

Guardo, M., 1999, Hydrologic balance for a subtropical treatment wetland constructed for nutrient removal: Ecological Engineering, v. 12, p. 315-337.

Harvey, J.W., 1996, Vertical exchange of ground water and surface water in the Florida Everglades: U.S. Geological Survey Fact Sheet FS-169-96, 2 p.

Harvey, J.W., Krupa, S.L., Gefvert, C.G., Choi, J., Mooney, R.H., and Giddings, J.B., 2000, Interaction between ground water and surface water in the northern Everglades and relation to water budget and mercury cycling: study methods and appendixes: U.S. Geological Survey Open-File Report 00-168, 411 p.

Hoffmeister, J.E., 1974, Land from the sea—the geologic story of south Florida: Miami, Fla., Univ. of Miami Press, 143 p.

Holtz, R.D. and Kovacs, W.D., 1981, An introduction to geotechnical engineering: Englewood Cliffs, N.J., Prentice-Hall, 733 p.

Howie, B., 1987, Chemical characteristics of water in the surficial aquifer system, Broward County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4330, 2 p.

Hutcheon Engineers, 1996, Everglades construction project stormwater treatment area No. 1-W Works-Contract No. C-E101 Amendment No. 1: Supplement to the detailed design report, Hutcheon Engineers, Florida, 34 p.

Jensen, J. R., Rutchey, K., Koch, M.S., and Narumalani, S., 1995, Inland wetland change detection in the Everglades Water Conservation Area 2A using a time series of normalized remotely sensed data: Photogrammetric Engineering and Remote Sensing, v. 61, no. 2, p. 199-209.

Kasenow, Michael, 1994, Introduction to aquifer analysis: Dubuque, Iowa, Wm. C. Brown Publishers, 471 p.

Kelly, C.A., Rudd, J.W.M., Bodaly, R.A., Roulet, N.P., St. Louis, V.L., Heyes, A., Moore, R.R., Schiff, S., Aravena, R., Scott, K.J., Dyck, B., Harris, R., Warner, B., and Edwards, G., 1997, Increases in fluxes of greenhouse gases and methylmercury following flooding of an experimental reservoir: Environmental Science and Technology, v. 31, p. 1334-1344.

Keys, W.S., 1990, Borehole geophysics applied to groundwater investigations: Dublin, Ohio, National Water Well Association, 313 p.

Klein, H., and Sherwood, C.B., 1961, Hydrologic conditions in the vicinity of Levee 30, northern Dade County, Florida: Florida Bureau of Geology Report of Investigations No. 24, 24 p.

Krabbenhoft, D.P. and Babiarz, C.L., 1992, The role of groundwater transport in aquatic mercury cycling: Water Resources Research, v. 28, no. 12, p. 3119-3128.

King, S.A., 2000, Mercury distribution, speciation and transport in the Everglades Nutrient Removal Treatment wetland: Madison, University of Wisconsin, Ph.D. dissertation, 130 p.

Krupa, S.L., 1999, Recognition and analysis of secondary depositional crusts in the surficial aquifer system of southeast Florida: Boca Raton, Florida Atlantic University, unpublished Masters thesis, 273 p.

Land, L.F., Rides, H.G., and Schneider, J.J., 1973, Appraisal of the Water Resources of Eastern Palm Beach County, Florida: Florida Geological Survey, Report of Investigation Number 67, 64 p.

Lovejoy, D.W., 1983, The Anastasia Formation in Palm Beach and Martin Counties, Florida: Miami Geological Society Memoir, v. 3, p. 58-72.

MacVicar, T., Van Lent, T., and Castro, A., 1994, South Florida Water Management Model Documentation Report: Technical Publication 84-3, South Florida Water Management District, West Palm Beach, Florida.

MacIntyre, I. G., 1975, A diver-operated hydraulic drill for coring submerged sub-strates: Atoll Research Bulletin, v. 185. p. 21-25.

McPherson, B.F., and Halley, R., 1996, The South Florida environment—A region under stress: U.S. Geological Survey Circular 1134, 61 p.

Merritt, M.L., 1996, Simulation of the water-table altitude in the Biscayne Aquifer, Southern Dade County, Florida, Water years 1945-89: U.S. Geological Survey Water-Supply Paper 2458, 148 p., 9 pls.

Miles, C.J. and Fink, L.E., 1998, Monitoring and mass budget for mercury in the Everglades Nutrient Removal Project: Archives of Environmental Contamination and Toxicology, v. 35, p. 549-557.

Miller, W.L., 1978, Effect of bottom sediments on infiltration from the Miami and tributary canals to the Biscayne aquifer, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 78-36, 63 p.

Miller, W.L., 1988, Description and evaluation of the effects of urban and agricultural development on the surficial aquifer system, Palm Beach County, Florida: U.S. Geological Survey Water-Resources Investigations Report 88-4056, 58 p.

Miller, W., 1987, Lithology and base of the surficial aquifer system, Palm Beach County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4067, 1 pl.

Mitterer, R.M., 1974, Pleistocene stratigraphy in southern Florida based upon amino acid diagenesis of fossil *Mercenaria:* Geology, v. 2, p. 425-428.

Mitterer, R.M., 1975, Ages and diagenetic temperatures of Pleistocene deposits of Florida based upon isoleucine epimerization in *Mercenaria*: Earth and Planetary Science Letters, v. 28, p. 275-282.

Nemeth, M.S., Wilcox, W.M., and Solo-Gabriele, H.M., 2000, Evaluation of the use of reach transmissivity to quantify leakage beneath Levee 31N, Miami-Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 00-4066, 80 p.

Osmond, J.K.; Carpenter, J.R., and Windom, H.L., 1965, Th^{230}/U^{234} age of Pleistocene corals and oolites of Florida: Journal of Geophysical Research, v. 70, p. 1843-1847.

Parker, G. G. and Cooke, W.C., 1944, Late Cenozoic geology of southern Florida, with a discussion on ground water: Florida Geological Survey, Bulletin 27, Tallahassee, Fla., 119 p.

Parker, G.G., Ferguson, G.E., Love, S.K., and others, 1955, Water Resources of Southeastern Florida, with special reference to the geology and ground water of the Miami area: U.S. Geological Survey Water-Supply Paper 1255, 965 p.

Perkins, R.D., 1977, Depositional framework of Pleistocene rocks in south Florida, *in* Enos, P., and Perkins, R.D., Quaternary sedimentation in south Florida: Geological Society of America Memoir, v. 147, p. 131-196.

Reese, R. and Cunningham, K., 2000, Hydrogeology of the Gray Limestone aquifer in southern Florida: U. S. Geological Survey Water-Resources Investigations Report 99-4213, 244 p.

Rohrer, K.P., 1999, Hydrogeological characterization and estimation of ground water seepage in the Everglades nutrient removal project: South Florida Water Management District, WRE- 372, 147 p.

Romanowicz, E., and Richardson, C.J., 2000, Modelling hydroperiods and flooding depths in the northern Everglades, Water conservation Area 2A. INTECOL: Millennium Wetland Event and Annual Meeting of the Society of Wetland Scientists, August 6-12, 2000, p. 324 in Program with Abstracts.

Russell, G. and Wexler, E., 1993, Hydrogeology and simulation of groundwater flow near the Lantana landfill, Palm Beach County, Florida: U. S. Geological Survey Water-Resources Investigations Report 92-4107, 55 p.

Schroeder, M., Klein, H., and Hoy, N., 1958, Biscayne Aquifer of Dade and Broward Counties, Florida: Florida Geological Survey Report of Investigation No. 17, Tallahassee, Florida, 56 p.

Scott, T.M., 1988, The lithostratigraphy of the Hawthorn Group (Miocene) of Florida: Florida Bureau of Geology Bulletin No. 59, Tallahassee, Fla., 148 p.

Scott, T.M., 1992, A geological overview of Florida: Florida Geological Survey Open File Report 50, Tallahassee, Fla., 78 p.

Scott, W.B., 1977, Hydraulic conductivity and water quality of the shallow aquifer, Palm Beach County, Florida: U.S. Geological Survey Water-Resources Investigations Report 76-119, 22 p.

Sonenshein, R. S., 2001, Methods to quantify seepage beneath Levee 30, Miami-Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 01-4074, 36 p.

South Florida Water Management District, 1995, Everglades 1995 Annual Report: West Palm Beach, Fla., 40 p.

South Florida Water Management District, 1998, Comprehensive quality assurance plan (#870166G) WRE 370: West Palm Beach, Fla., 130 p.

South Florida Water Management District, 1999, The effect of best management practices on the loading of mercury species to the ENR project: monitoring program (project C-1): West Palm Beach, Fla., 70 p.

St. Louis, V.L., Rudd, J.W.M., Kelly, C.A., Beatty, K.G., Bloom, N.S., and Flett, R.J., 1994, Importance of wetlands as sources of methyl mercury to boreal forest ecosystems: Canadian Journal of Fisheries and Aquatic Sciences, v. 51, p. 1065-1076.

Stober, J., Scheidt, D., Jones, R., Thornton, K., Ambrose, R., and France, D., 1996, South Florida ecosystem management—monitoring for adaptive management: implications for ecosystem restoration (Interim Report): Environmental Protection Agency Report EPA 904-R-96-008.

Swayze, L.J., 1988, Ground-water flow beneath Levee 35A from Conservation Area 2B, Broward County, Florida: U.S. Geological Survey Water-Resources Investigations Report 87-4280, 22 p.

U.S. Army Corps of Engineers, 1952, Part I, Agricultural and conservation areas – supplement 5 – Test levee investigations: Partial definite report, North-central and South Florida Project for Flood Control and Other Purposes, 28 p., 14 pls.

Upchurch, S.B., 1992, Quality of water in Florida's aquifer systems, *in* Florida's ground water quality monitoring program: Background hydrogeochemistry, Maddox, G.L. and others (eds.), Florida Geological Survey, Talahassee, Fla., 364 p.

Urban, N.M., Davis, S.M., and Aumen, N.G., 1993, Fluctuations in saw grass and cattail densities in Everglades Water Conservation Area 2A under varying nutrient, hydrologic and fire regimes: Aquatic Botany, v. 46, p. 203-233.

Vukovic, M. and Soro, A., 1992, Determination of hydraulic conductivity of porous media from grain-size composition: Littleton, Colo., Water Resources Publications, 83 p.

Walton, W.C., 1987, Groundwater pumping tests—Design and analysis: Chelsea, Mich., Lewis Publishers, 201 p.