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Integrating Borehole Logs and Aquifer Tests in Aquifer Characterization

by Frederick L. Paillet[a] and Ronald S. Reese[b]

Abstract

Integration of lithologic logs, geophysical logs, and hydraulic tests is critical in characterizing heterogeneous aquifers. Typically only a limited number of aquifer tests can be performed, and these need to be designed to provide hydraulic properties for the principle aquifers in the system. This study describes the integration of logs and aquifer tests in the development of a hydrostratigraphic model for the surficial aquifer system in and around Big Cypress National Preserve in eastern Collier County, Florida. Borehole flowmeter tests provide qualitative permeability profiles in most of 26 boreholes drilled in the study area. Flow logs indicate the depth of transmissive units, which are correlated across the study area. Comparison to published studies in adjacent areas indicates that the main limestone aquifer of the Tamiami Formation in the study area corresponds with the gray limestone aquifer in western Dade County and the water table and lower Tamiami Aquifer in western Collier County. Four strategically located, multiwell aquifer tests are used to quantify the qualitative permeability profiles provided by the flowmeter log analysis. The hydrostratigraphic model based on these results defines the main aquifer in the central part of the study area as unconfined to semiconfined with a transmissivity as high as 30,000 m²/day. The aquifer decreases in transmissivity to less than 10,000 m²/day in some parts of western Collier County, and becomes confined to the east and northeast of the study area, where transmissivity decreases to below 5000 m²/day.

Introduction

Predicting the quantity and quality of ground water flowing in the subsurface requires accurate information on the geometry and hydraulic properties of aquifers. This information is commonly obtained by drilling, logging, and description of sediments obtained as cores or cuttings from boreholes. In heterogeneous formations, it is often difficult to identify individual aquifers, and to define the regionally averaged hydraulic properties of those units on the basis of logs and descriptions from a finite number of boreholes. Aquifer tests can provide useful estimates of such hydraulic properties. However, these tests require careful preparations, such as careful placement of production and observation wells and completion of these wells in specific intervals. The effectiveness of the aquifer tests is often contingent on the development of a preliminary hydrostratigraphic model that identifies aquifer and confining unit geometry. Thus, effective characterization of heterogeneous aquifers depends on efficient integration of borehole logs and aquifer testing. Then, carefully prepared aquifer tests are used to refine and quantify the hydraulic properties of the aquifers defined by the model.

One of the principle limitations of lithologic and geophysical logs is that neither gives a direct estimate of hydraulic properties of aquifer materials. Geophysical logs can be interpreted in terms of porosity and permeability on the basis of various formation models (Jorgensen 1991; Keys 1990). Such interpretation requires independent estimates of various constants that appear in the interpretation equations (Paillet and Crowder 1996; Doveton 1986). Reliable values for these constants may not be available for a given study, or estimates may be only approximate. Hydraulic tests can be run in the laboratory using recovered core samples. There are often questions about how a few hydraulic tests obtained from samples only a few centimeters in length relate to the properties of aquifers over scales of 100 m or more. Small core sections commonly do not provide a representative aquifer volume, and samples may have been disturbed by breakage, compaction, or desiccation in the coring and handling process. Core recovery may also bias sampling toward the most lithified and least permeable samples and fails to sample solution openings. All of these factors serve to highlight the difficulties encountered in formulating the effective hydrostratigraphic models that are needed to design and complete time-consuming and equipment-intensive aquifer tests in the characterization of heterogeneous aquifers.

The recent availability of high-resolution borehole flow logging equipment, such as the heat-pulse flowmeter (Hess 1986) and the electromagnetic flowmeter (Molz et al. 1994), represents a significant improvement in the ability to characterize aquifer permeability in situ. Flow logs can be obtained under ambient and low-flow pumping conditions in open boreholes with minimal drawdown. Flow logs can be used to identify the transmissive intervals and to estimate the relative transmissivity of the aquifer zones within such intervals. The relative transmissivity estimates apply to the area around the borehole, yielding data similar to that which could be obtained from conventional slug tests, except that the estimates are provided for all transmissive intervals from a single flow test. Ambient flow conditions, where water flows ver-

[a]U.S. Geological Survey, P.O. Box 25046, MS 403, Denver, CO 80225; (303) 236-5914; fax (303) 236-5968; fpaillet@usgs.gov

[b]U.S. Geological Survey, 9100 N.W. 36th St., Miami, FL 33178; (305) 717-5821; rsreese@usgs.gov

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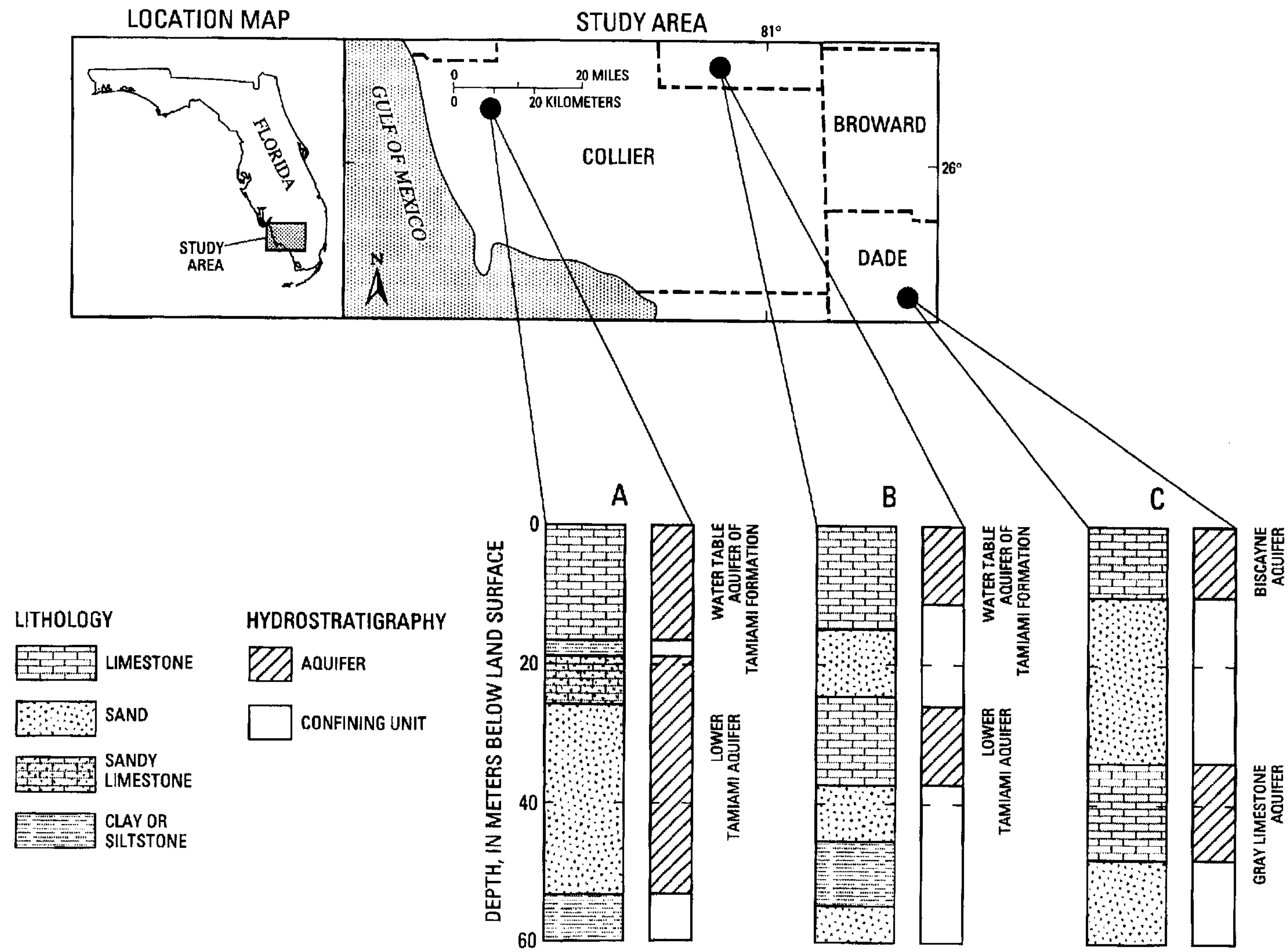

Figure 1. General location of the study area, showing lithologic columns and hydrostratigraphy at locations on the periphery of the study area given by: (a) Knapp et al. (1986) for western Collier County; (b) Smith and Adams (1988) for southeastern Hendry County; and (c) Fish and Stewart (1991) for northwestern Dade County.

tically along the open borehole from one aquifer unit to another, indicate separation of the aquifer zones by regionally continuous confining units. Equally important, the flow profiles indicate hydraulic properties continuously along the entire length of open or screened borehole, with no missing intervals, and where the contributions from fractures and solution openings are effectively accounted for. Thus, borehole flow logs have the capacity to significantly improve aquifer characterization and modeling when properly combined with lithologic and geophysical logs and carefully formulated aquifer tests.

In this study, core descriptions, geophysical well logs, borehole flow logs, and aquifer tests are integrated in the characterization of a previously poorly defined aquifer system in south Florida. The aquifer system in this area consists of a heterogeneous series of consolidated to unconsolidated carbonate, sand, siltstone, and clay sediments where the hydraulic properties of recovered samples are difficult to quantify on the basis of physical descriptions of sediments alone. Core descriptions and geophysical logs are used to define a preliminary hydrostratigraphic model. Borehole flow logs are used to identify the major transmissive units in each borehole, to estimate the relative permeability of each aquifer contributing flow to the borehole under test conditions, and to determine intervals serving as confining units in the area surrounding each borehole. Analysis of fluid column conductivity in open boreholes and the electrical conductivity of water samples recovered from specific intervals are used to confirm the identity of aquifer zones and confining units inferred from the log analysis. These data are used collectively to generate a model for aquifer units across the study area. Once this model was refined and verified, aquifer tests were used to quantify hydraulic properties at carefully selected locations, where the results of such tests are representative of the properties of major aquifers. These results serve to illustrate the utility of the integration of geophysical logs, flow profiles, and aquifer tests in the characterization of heterogeneous aquifers at locations where development of a preliminary hydrostratigraphic model is critical in the design of conventional aquifer tests.

The Study Area

The aquifer characterization study described in this report was motivated by the need to develop a better understanding of shallow subsurface ground water flow in the Big Cypress National Preserve and adjacent state and federal parkland in eastern Collier County, Florida. A ground water flow model will be developed and used to evaluate various remediation techniques proposed for

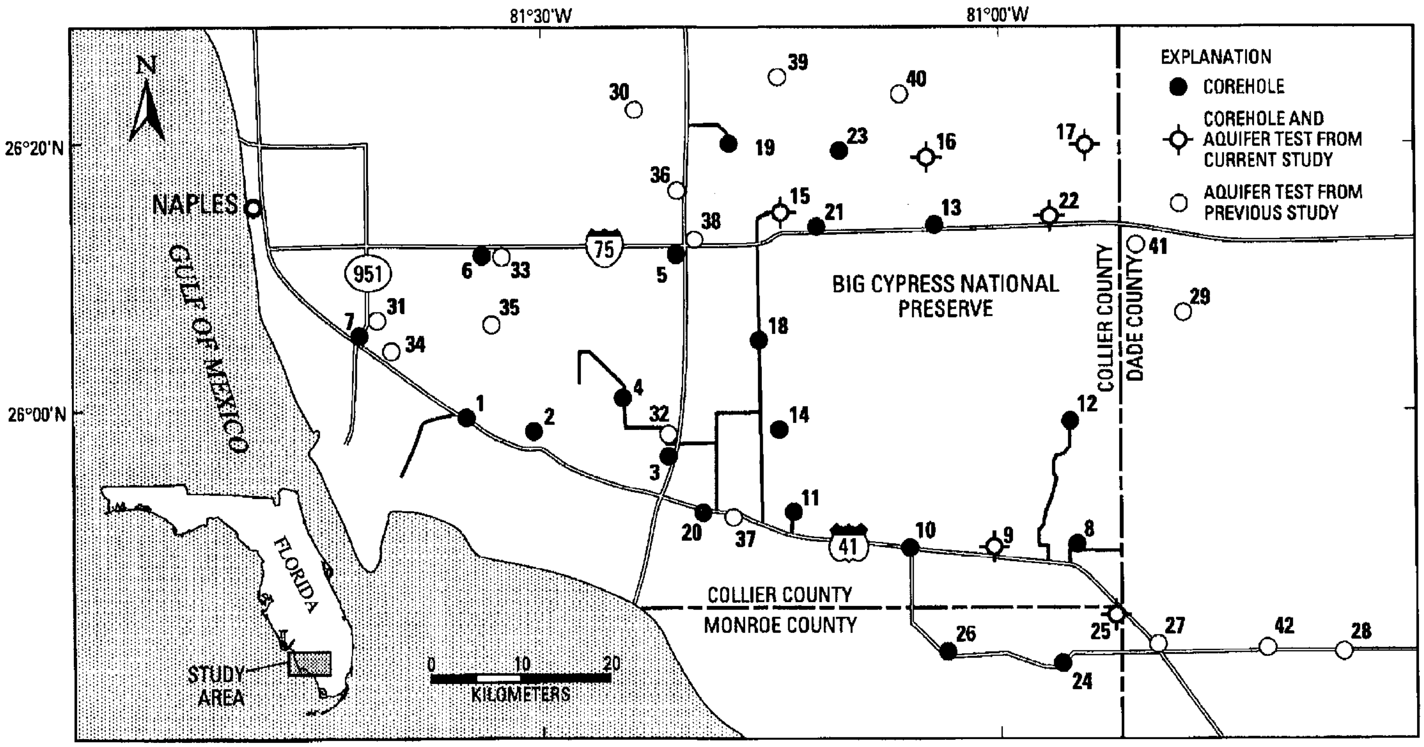

Figure 2. Locations of borehole, observation well, and aquifer test sites.

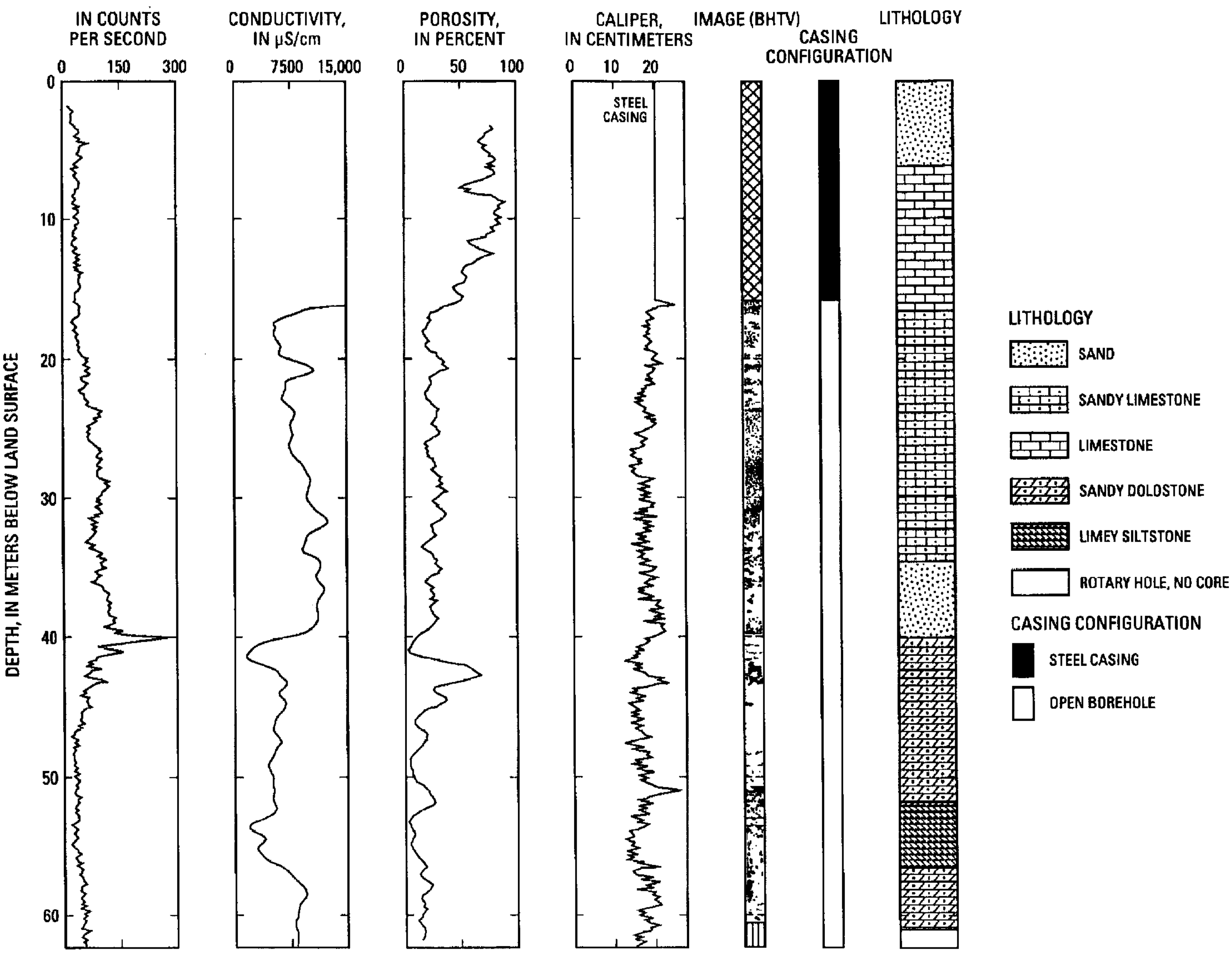

Figure 3. Composite of logs and core description for corehole 1, where the lithologic column is depth adjusted and filled in using the geophysical log information.

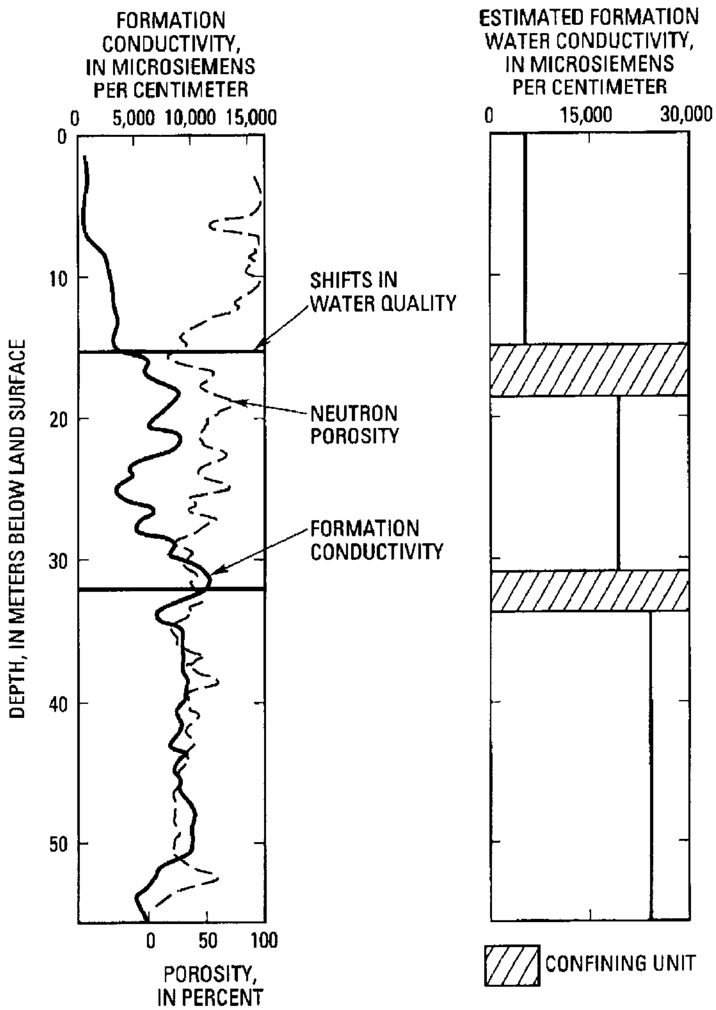

Figure 4. Overlay of induction and neutron porosity logs for corehole 2 indicating aquifer zones characterized by differences in water quality.

ecosystem restoration (Weedman et al. 1997, 1999). Major emphasis in proposed model applications relates to the effects of surface water diversion, interchange between surface and subsurface water, and salt water intrusion. The uppermost 60 m of sediments in the Big Cypress National Preserve area were investigated in this study. Lithologies in the study area consist of unconsolidated to consolidated carbonate, carbonate mud, sand, silt, and clay sediments. Limited information on the lithostratigraphy and hydrostratigraphy is available from a number of existing reports for sites near the study area (Figure 1). Knapp et al. (1986) describe two limestone aquifers (denoted as the water table and lower Tamiami aquifers in that report) separated by a semiconfining unit in west-central Collier County. Smith and Adams (1988) describe a similar limestone aquifer (denoted as the lower Tamiami Aquifer) beneath thin sand, silt, and clay deposits in northeast Collier County and adjacent eastern Hendry County. Fish and Stewart (1991) and Fish (1988) describe a single limestone aquifer (denoted as the gray limestone aquifer) beneath more than 20 m of sand, silt, and clay in northwest Dade and southwest Broward counties. Bennett (1992) used this information to construct a model for shallow ground water flow in western Collier County for the two limestone aquifers mapped by Knapp et al. (1986). However, the density of water level measurements and lithologic data in the Big Cypress Preserve region were too limited to validate this model in that area.

A total of 26 cores were drilled to a depth of about 60 m across the study area during the 1996 to 1998 period (Figure 2). Core recovery varied from less than 60% to more than 90%, generally improving as drilling experience accumulated. All cores were photographed, described, and archived. Boreholes were logged with geophysical probes not affected by the properties of borehole fluid while filled with drilling mud to maintain open boreholes. Continuously screened plastic casings were then temporarily installed in the boreholes, drilling mud evacuated from the borehole, and the borehole developed by circulation and surging with fresh water. Flow logs were then run under ambient and either pumped or injection conditions in the screened boreholes. After logging, the screen was removed and the boreholes plugged and abandoned, with the exception of a few boreholes completed as monitoring wells. Prompt plugging or completion of boreholes in a specific aquifer zone was important, because the regional upward hydraulic gradient would cause brackish or saline water detected in the zones near the bottom of most boreholes to contaminate the surficial aquifer through any boreholes left open for extended periods.

Hydrostratigraphy and Geophysical Log Analysis

Geologic descriptions of core and geophysical well logs were combined for each of the boreholes to produce a composite description of aquifer geology at each coring site (Figure 3). In this example, essentially all of the conventional geophysical logs available were run in this, the first cored borehole. Although core recovery was less than 70%, the stratigraphic contacts indicated on the logs could be used to "fill in" the core description and to adjust the exact depth of lithologic contacts. Subsequent analysis of geophysical logs demonstrated that the stratigraphy was effectively indicated by the combination of neutron porosity, natural gamma, and electromagnetic induction logs. This combination was used throughout the study, except in those few instances where logistical considerations related to the downhole use of radioactive sources precluded running the neutron log.

The cores and geophysical logs such as those in Figure 3 generally indicate a surficial limestone aquifer underlain by a fine sand. Below these units, sediments consisting of interbedded sand, silt, clay, and carbonate rock make up various additional confining units and aquifer zones. Comparison of log and cores from the western part of the study area at sites 6 and 7 with logs and sample descriptions given by Knapp et al. (1986) confirms that the lower portion of the Tamiami limestone with an underlying sand unit makes up the lower Tamiami Aquifer as described by those authors. Comparison of logs and cores from the eastern part of the study area confirms that the limestone aquifer coincides with the gray limestone aquifer described by Fish (1988) and Fish and Stewart (1991). For example, this limestone is present at about 15 m in depth in borehole 25, with sand below and various amounts of sand, silt, and carbonate sediments above. Thus, the series of cores and logs obtained in this study provides the means to map the gray limestone aquifer in the eastern part of the study area across the Big Cypress National Preserve area to the region east of the city of Naples where surficial sediments include the water table and lower Tamiami limestone aquifers.

The quantitative interpretation of geophysical logs was based on a three-parameter inversion. In this approach, aquifer and confining units are assumed to be characterized by three quantities: the permeability of water-filled pores, pore-water electrical conductivity, and clay mineral fraction. Although there were minor differences in the geophysical response of different mineral grains, these differences were assumed too small to be consistently identified from

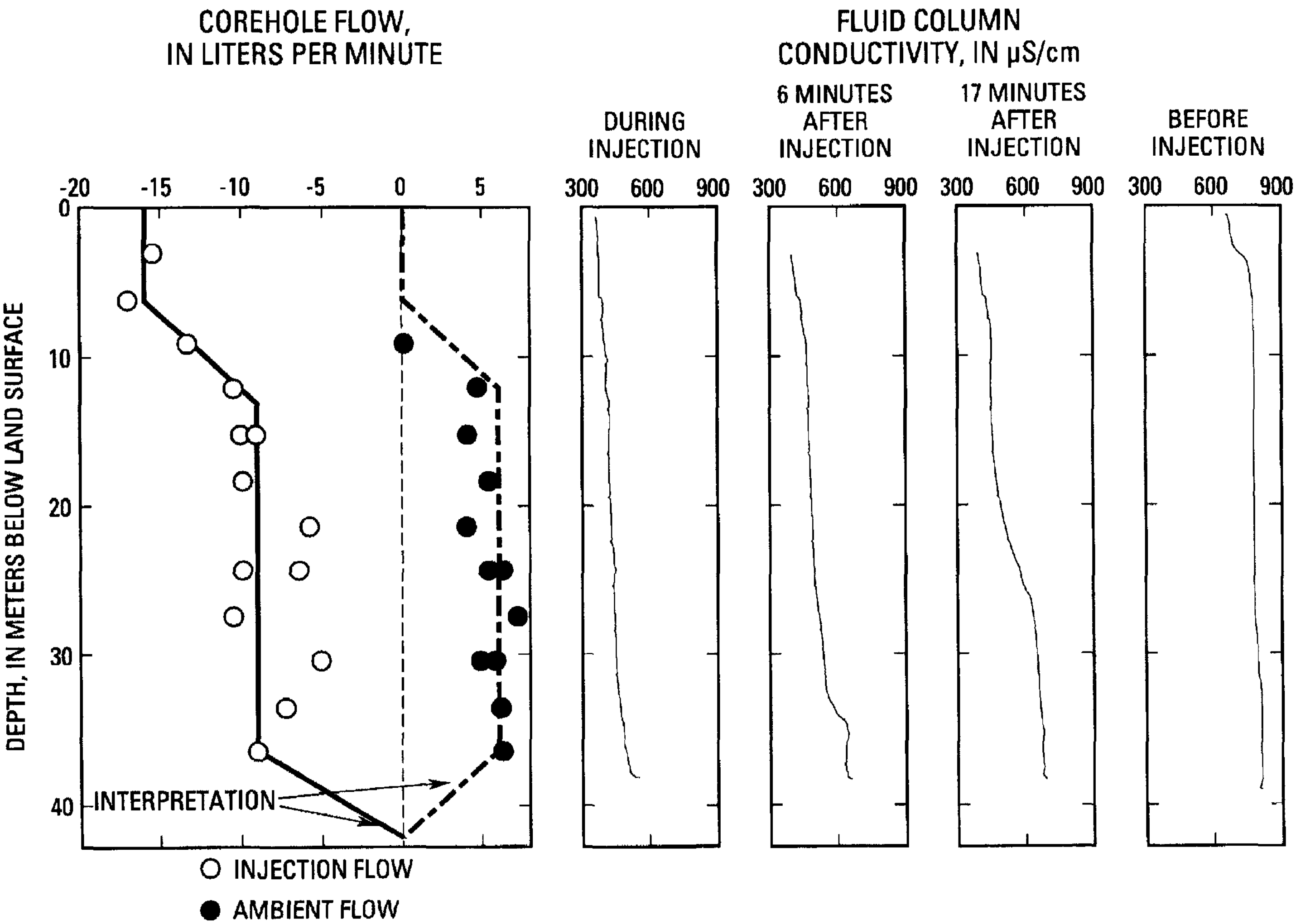

Figure 5. Borehole flow profiles obtained in corehole 13 under ambient and steady-state injection conditions, indicating transmissive zones and confining units; fluid column electrical conductivity profiles shown for verification of flow log interpretation.

log response alone. Instead, general lithologic descriptions from core samples were applied to beds identified from shifts in log response as indicated in Figure 3. The primary objective in log analysis was to uncouple the effects of permeability from those of water quality and clay fraction in induction log response. For example, the formation electrical conductivity given by the induction log is assumed to respond to these three quantities through the equation (Kwader 1985)

$$\sigma = \sigma_p + \sigma_m \qquad (1)$$

$$\sigma_p = \frac{\sigma_w}{F}; \quad \sigma_m = C_c\sigma_c; \quad \text{and} \quad F = F(K)$$

where σ is formation conductivity, σ_p is the conductivity of the pore space network, σ_m is the conductivity of the mineral framework, σ_w is the conductivity of the pore water, F is the formation factor (expressed as a function of formation permeability K), C_c is the clay mineral fraction, and σ_c is the electrical conductivity of the clay. In those intervals where the cores show no indications of clays, the log response can be attributed to the effects of permeability and pore water electrical conductivity. In the western part of the study area, clay beds were not found and the clay mineral fraction was negligible. Permeability and pore water salinity effects can be separated by comparing the values given by the porosity log, which is expected to respond to variations in permeability through the relationship between porosity and permeability given for granular solids (Jorgensen 1991), with those given by the induction log, which responds to both permeability and salinity (Figure 4). In this example, the neutron and induction logs follow similar trends whenever log response is determined by variations in permeability alone. The two logs show abrupt separations at depths where there is a change in pore water electrical conductivity. Overlays of neutron and induction logs such as that shown in Figure 4 were used to separate the sediment profiles in each corehole into zones of distinctly different water quality. In the western part of the study area, further analysis indicated that aquifer zones were separated by thin confining units composed of densely cemented sediments (Weedman et al. 1997). Further east in the study area, confining units consisted of thicker clay layers (Paillet et al. 1999; Reese and Cunningham, in press).

Although geophysical logs respond to aquifer properties within less than 1 m of the borehole, the differences in pore water electrical conductivity were assumed to serve as tracers indicative of the large-scale ground water flow system. The identification of regional-scale aquifer zones on the basis of contrasts in pore water salinity was verified by subsequent borehole flow profiles. Most of the boreholes completed with fully screened casing contained ambient upward flow between aquifer zones after mud was flushed from coreholes (Figure 5). Such ambient flow indicates differences in hydraulic head and suggests the identification of multiple aquifer zones, along with the confining units separating those zones in the uppermost 60 m

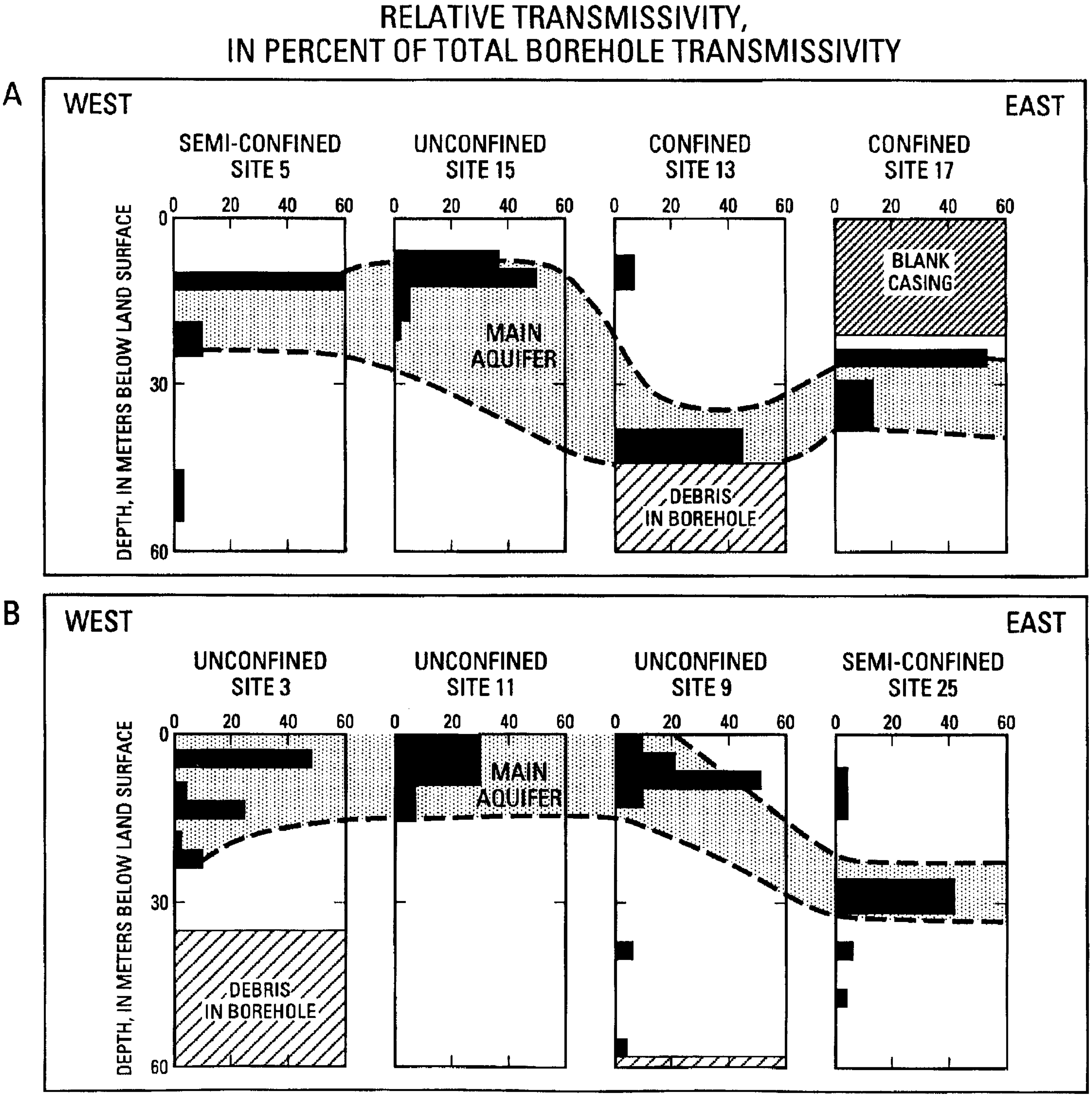

Figure 6. East-west profiles of relative transmissivity inferred from flowmeter and correlated with lithologic logs for representative coreholes: (a) profile along Alligator Alley in the northern part of the study area, and (b) profile along the Tamiami Trail in the southern part of the study area.

throughout the study area. The lateral continuity of the shallow confining units in the study area was later documented by surface electromagnetic soundings (Paillet et al. 1999) along profiles connecting some of the boreholes in Figure 2.

Analysis of Borehole Flow Profiles

Borehole flow logs can be used to construct vertical profiles of transmissivity near the borehole (Molz et al. 1989; Kabala 1994). A single profile during steady-state pumping or injection conditions can be used to infer transmissivity, but only under the assumption that there is no vertical gradient in hydraulic head. The ambient flow data as shown, for example, in Figure 5 indicate that there were significant upward hydraulic-head gradients in the study area at the time of logging. Flow profile analysis can be compensated for the effects of vertical-head gradients by subtracting two steady-state flow profiles according to the equation (Paillet 1998)

$$\frac{T_k}{\sum T_k} = \frac{Q_k^a - Q_k^b}{\sum (Q_k^a - Q_k^b)} \tag{2}$$

where T_k is the transmissivity of the transmissive interval denoted by index k, and Q_k^a and Q_k^b are the inflows to zone k under two steady-state conditions. In this study, one such steady-state condi-

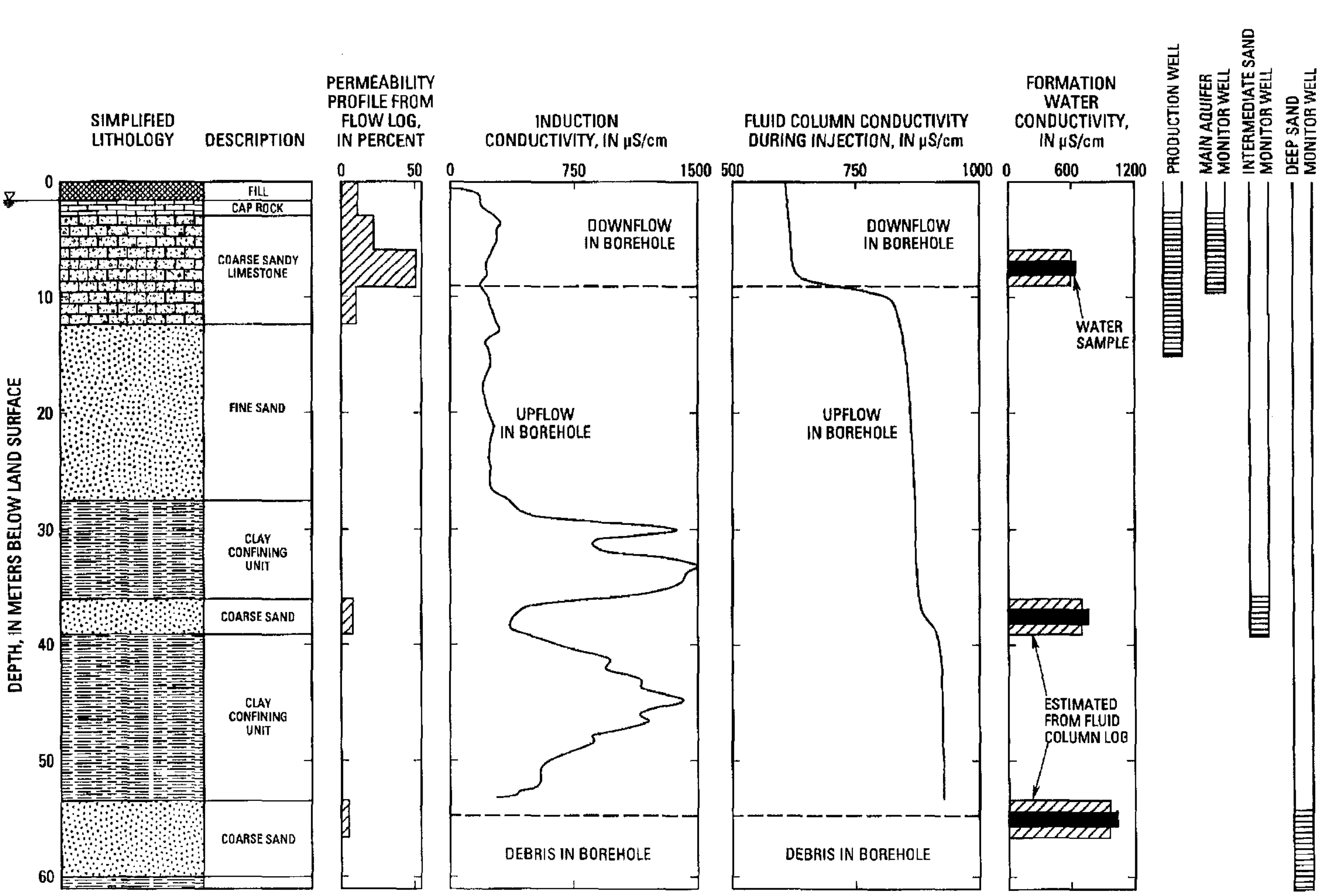

Figure 7. Lithostratigraphic section along the Tamiami Trail based on core descriptions and geophysical logs. See Figure 2 for location of wells by site number.

tion was ambient flow; the other was either steady-state injection or pumping at from 5 to 25 L/min. This analysis gives the transmissivity of each transmissive zone as the fraction of total borehole transmissivity. Paillet (1998) shows that these relative transmissivity values can be given a quantitative value if the net difference in open-borehole water levels is given for the two flow tests. In this study, aquifer zones were productive, and drawdown could not be measured under the flow conditions. Furthermore, screen slot size was designed to hold even the finest sediments, so that inlet losses were expected to dominate single-borehole aquifer tests run at higher production rates. Instead, the study was designed to give relative distribution of transmissivity by the analysis of borehole flow profiles, and then to quantify these relative profiles by obtaining absolute values for specific zones using carefully designed aquifer tests on representative intervals.

A typical pair of flow profiles obtained with the heat-pulse flowmeter (Hess 1986) in one of the coreholes is illustrated in Figure 5. The heat-pulse flowmeter determines the rate of vertical flow in a borehole by measuring the time required for a heated parcel of water to travel up or down 2 cm to a pair of thermistors installed in the cylindrical flow measurement section of the probe. This example was selected to illustrate the analysis under less than ideal conditions. In this instance, there is significant scatter to the flow data. This scatter is attributed to incomplete collapse of formation into the annulus on the outside of casing. Such scatter was typical when there were thick silt and clay intervals, which tended to resist deformation and collapse. The scatter is attributed to the widening of the flow profile in those regions where flow is allowed to move into the annulus. The flow profile interpretations are made by fitting continuous lines to the outer envelop of the flow measurements under the assumption that some flow data points represent depth stations where part of the flow bypassed the flowmeter

Table 1
Analysis of Borehole Flow Profile Data for the Corehole at Site 13

Depth Interval Top Bottom (m)	Ambient Inflow[1] (L/min)	Injection Inflow[1] (L/min)	Inflow Diff[2] (L/min)	Relative Transmissivity (percent)
0–3	0.0	0.0	0.0	0
3–6	0.0	0.0	0.0	0
6–9	–2.8	–3.8	1.0	6
9–12	–2.8	–3.8	1.0	6
12–15	0.0	0.0	0.0	0
15–18	0.0	0.0	0.0	0
18–21	0.0	0.0	0.0	0
21–24	0.0	0.0	0.0	0
24–27	0.0	0.0	0.0	0
27–30	0.0	0.0	0.0	0
30–33	0.0	0.0	0.0	0
33–36	2.8	–3.8	6.6	44
36–39	2.8	–3.8	6.6	44

[1]By convention, inflow from formation to borehole is positive and outflow to formation is negative.
[2]Difference given by subtracting inflow during injection from ambient inflow.

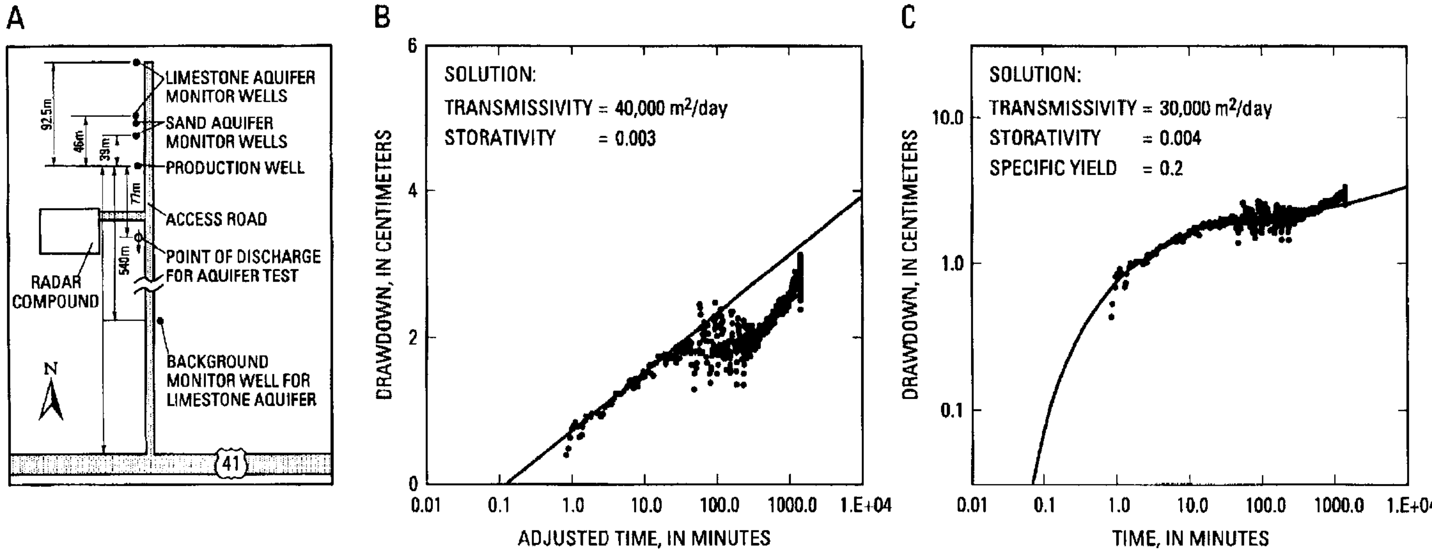

Figure 8. Geophysical and lithologic logs for corehole 9, indicating depths of completion of production well and piezometers used during aquifer testing.

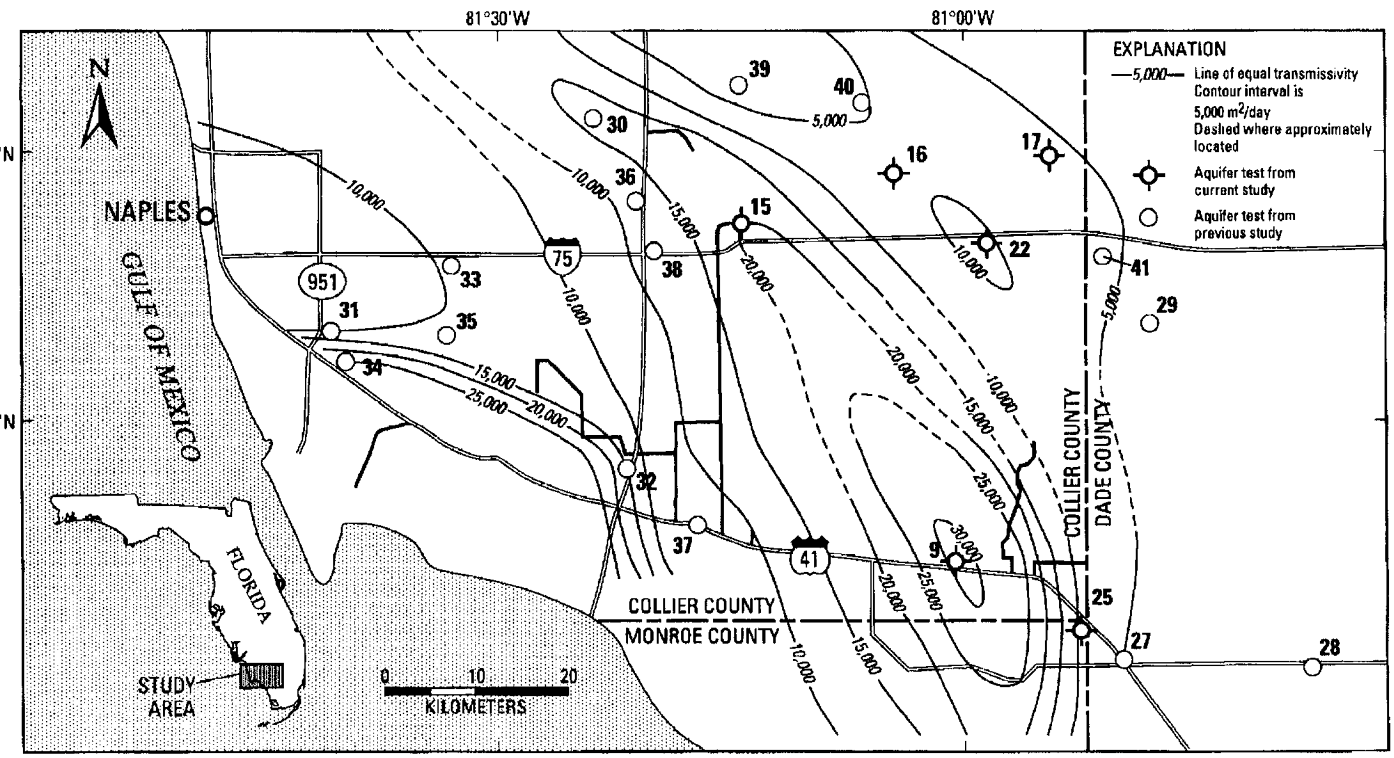

Figure 9. Aquifer test at the corehole 9 site: (a) layout of aquifer test site; (b) drawdown at the near monitoring well in the limestone aquifer and Cooper-Jacob confined solution for early time data; and (c) drawdown at the near monitoring well in the limestone aquifer and Neuman unconfined solution.

through the open annulus. These interpretation profiles are then differenced at 3 m intervals to estimate the amount of water entering the borehole (Table 1). Thus, the smooth interpretation curves in Figure 5 overcome the scatter, and the "steps" in each profile are used to estimate inflow or outflow in each of the two aquifer zones in Figure 5. Then, the inflows and outflows under each of the two flow conditions are used to estimate the relative transmissivity of each interval. Note that the correction for ambient head gradients is important. The injection profile in Figure 5, if taken alone, indicates approximately equal amounts of water exiting at upper and lower zones. Subtraction of the injection flows from the ambient flows indicates that the deeper zone is an order of magnitude more transmissive than the upper zone. Also note that the fluid column electrical conductivity logs shown in Figure 5 independently support the flow-log analysis. For example, the upward rate of movement of the "step" in the profile during reestablishment of the ambient upward flow in the period after injection stopped (about 8 m in 11 minutes) confirms the approximately 5 L/min ambient upflow indicated by the flowmeter profile.

Qualitative Description of Aquifer Properties

The profiles of relative transmissivity for a representative set of boreholes distributed across the study area are illustrated in Figure 6. Each profile indicates the relative amount of transmissivity in each 3 m interval, but the absolute magnitude of transmissivity probably varies among boreholes. All boreholes were transmissive enough at the time of flow logging that no significant water level drawdown or buildup could be measured during pumping or injection at rates of 25 L/min or less. Also note that not all of the 60 m of cored depth were available for flow logging in some of the boreholes because of unconsolidated debris heaving up through the bottom of the open-ended casing, or the presence of blank surface casing in the upper part of some boreholes. In addition, there are uncertainties about the exact depth interval where water entered the borehole under ambient and pumping conditions because of possible intervals of unfilled annulus. For this reason, the relative transmissivity values in Figure 6 are averaged over 3 m intervals. With these qualifications, the analysis of the flowmeter logs is assumed to give a valid representation of the vertical distribution of permeability along each of the coreholes where flow logs were obtained.

The qualitative transmissivity profiles in Figure 6 indicate that in the western part of the study area aquifer permeability is concentrated in a shallow, unconfined to semiconfined aquifer composed of limestone to unconsolidated carbonate sediments in the uppermost 10 m. The hydrostratigraphy indicated by the flowmeter data analysis is compared with a simplified stratigraphic section generated from cores and logs obtained along the Tamiami Trail in Figure 7. The main aquifer in Figure 6 mostly coincides with the water-table aquifer of the Tamiami Formation on the lithologic columns given by Knapp et al. (1986) on the western edge of the study area, and with the lower Tamiami Aquifer of Smith and Adams (1988) on the northern edge of the study area. The lower Tamiami Aquifer (carbonate rock and underlying sand) is also present on the western edge of the study area and could be the interval from 25 to 38 m in borehole 1; however, the degree of confinement between this aquifer and the water-table aquifer at this site is indicated to be poor. The main limestone aquifer descends on the eastern edge of the study area from above 10 m at borehole 9 to below 15 m at borehole 25 and correlates with the gray limestone aquifer of the Tamiami Formation described in western Dade County by Fish and Stewart (1991). The shallow main limestone aquifer in the center of the study area is underlain by a much less transmissive sand layer, and separated from deeper and probably discontinuous sand aquifers by one or more confining units. The stratigraphic section appears to thicken toward the north and east. In this direction, the shallow (main) limestone aquifer descends to 30 m in depth and has clay confining units present both above and below.

Quantitative Determination of Aquifer Properties

The flow profiles (Figure 6) indicate the main limestone aquifer of the Tamiami Formation, which is correlated with the water-table and lower Tamiami aquifers in the west and the gray limestone aquifer in the east is continuous across the study area. Therefore, aquifer tests conducted to measure the transmissivity of this aquifer would serve to determine the absolute transmissivity scale of this interval near boreholes when the tests are conducted. However, aquifer tests designed to characterize this highly transmissive aquifer require extensive preparation. Production rates of 1000 or more L/min, and large diameters and gravel packed production wells designed to ensure negligible inlet losses at such large discharges are needed to produce measurable drawdown in observation wells. The aquifer test layouts in this study involved at least two observation wells in the main aquifer and others in underlying or overlying aquifers. Four representative sites were selected to conduct such aquifer tests (sites 9, 15, 17, and 25; Figure 2). The results of an earlier aquifer test were available from the Everglades City municipal well design project, a test that was conducted at a site within 100 m of borehole 3 in the western part of the study area (Missimer and Associates 1981). The distribution of hydraulic conductivity in the limestone aquifer could be extrapolated to other boreholes on the basis of the results from these five aquifer tests. This extrapolated hydraulic conductivity could then be used to fix an absolute scale to the qualitative transmissivity profiles on the basis of the lithology and thickness of aquifer units given in Figure 6.

The aquifer and confining units determined from the corehole and flow logs at the site of corehole 9 are illustrated in Figure 8. The multiwell aquifer test conducted at this site is representative of the results from all four tests run for this study and of the test described by Missimer and Associates (1981). The production well at this location was completed in the limestone aquifer over the interval from 3 to 15 m. Two observation wells were completed in this same interval, and two additional observation wells were completed in two underlying sand aquifers (Figure 9a). An additional background monitoring well was installed in the carbonate aquifer at a distance of about 540 m. The aquifer test was run over a 24-hour period at an average pumping rate of about 1100 L/min. Over that period, drawdown of about 3 cm was measured at a distance of about 92 m. Analysis of the measured limestone aquifer response indicates a transmissivity of at least 30,000 m^2/day. An early-time fit of the drawdown data to a confined aquifer type curve gives a transmissivity of about 40,000 m^2/day (Figure 9b). However, drawdown at later times suggests delayed release due to gravity drainage representative of an unconfined aquifer with a transmissivity of 30,000 m^2/day (Figure 9c). No drawdown was measured in either of the underlying sand aquifers during the test. The transmissivity of these two sand aquifers was estimated by conducting single-well drawdown-recovery tests in the piezometers completed in the 37 to 40 m and 55 to 61 m intervals. These tests yielded transmissivity estimates of about 20 m^2/day and 140 m^2/day, respectively, confirming the qualitative flowmeter estimates that these deeper aquifers were much less transmissive than the overlying limestone aquifer. This is demonstrated by comparing the qualitative transmissivity profile for borehole 9 in Figure 8 with the transmissivity values given by the aquifer test in Figure 9. The qualitative profile gives a ratio of about 20 to 1, compared with a ratio of more than 200 to 1 from the aquifer tests. These results are typical of other such comparisons reported by Paillet (1998) in that the qualitative transmissivity values are accurate to within only a few percent of the sum of transmissivities for all aquifer zones in the borehole.

The complete set of aquifer test results conducted by the U.S. Geological Survey (USGS) are summarized in Table 2. The table includes results from the eight aquifer tests completed as part of this study, results from other USGS aquifer tests in the study area, and aquifer tests reported by non-USGS references. Additional information concerning the methods and results of aquifer tests in this study are given by Reese and Cunningham (in press). Sites 30 through 38 in Table 2 give values for the water table aquifer of the Tamiami Formation and are taken from Knapp et al. (1986; Table 20). The aquifer test results indicate that the limestone aquifer of the Tamiami Formation is much more transmissive than any of the sand aquifers in the study area (Table 2).

A map showing the distribution of transmissivity in the limestone aquifer is based on values given in Table 2 (Figure 10). This map indicates there is an area where aquifer transmissivity is greater than 20,000 m^2/day that trends northwest-southeast in the central part of the study area. In this area, the limestone unit that includes the aquifer is shallow, exposed or nearly exposed at the surface, and still

Table 2
Summary of Aquifer Test Results for the Limestone Aquifer of the Tamiami Formation and Underlying Unnamed Sand Aquifers

Site ID	Interval Open (m)	Type of Test[1]	Transmissivity (m^2/day)	Storativity Unitless	Leakance[2] (day^{-1})	Interpreted Behavior	Source
A. Limestone Aquifer							
9	3-15	1	30,000	0.004	—	Semiunconfined	Current study
15	7-17	1	20,000	0.0005	—	Semiunconfined	Current study
16	18-31	2	7000	S/S′=0.44	—	Confined	Current study
17	23-41	1	6000	0.0006	—	Confined	Current study
22	23-38	2	10,000	S/S′=1.1	—	Confined	Current study
25	27-35	1	8000	0.0004	0.007	Semiconfined	Current study
27	31-45	1	3600	NR[3]	NR	Semiconfined	Fish and Stewart (1991)
28	37-46	1	1200	NR	NR	Semiconfined	Fish and Stewart (1991)
29	31-48	1	4600	0.00001	NR	Confined	Fish (1988)
B. Sand Aquifer							
9	37-40	2	20	S/S′=1.111	—	Confined	Current study
9	55-61	2	140	S/S′=1.000	—	Confined	Current study
15	27-33	3	80	0.00008	—	Semiconfined	Current study
C. Tests Done Outside of the U.S. Geological Survey							
30	?-15	1	19,000	0.003	0.00015	Semiunconfined	Missimer and Assoc. (1983)
31	3-15	1	10,000	0.02	—	Unconfined	Missimer and Assoc. (1980)
32	5-8	1	15,000	0.12	—	Unconfined	Missimer and Assoc. (1981)
33	6-21	1	12,000	0.0003	—	Semiunconfined	Knapp et al. (1986)
34	6-13	1	25,000	0.01	—	Unconfined	Knapp et al. (1986)
35	3-15	1	11,000	0.07	—	Unconfined	Knapp et al. (1986)
36	3-12	4	11,000	—	—	Unconfined	Knapp et al. (1986)
37	4-12	4	8900	—	—	Unconfined	Knapp et al. (1986)
38	0-16	4	12,000	—	—	Unconfined	Knapp et al. (1986)
39	30-38	1	1800	0.0002	NR[3]	Confined	Leggette et al. (1983)
40	24-37	1	4600	0.0001	0.00013	Confined	Smith and Adams (1988)
41	26-49	1	7200	0.00004	0.00003	Confined	Murray-Milleson (1989)

[1]Type of test:
1. Multiwell test with solutions by Theis (1935), Cooper and Jacob (1946), Hantush and Jacob (1955), Neuman (1972), and others.
2. Single-well test with Theis (1935) recovery solution. Gives ratio of storativity during drawdown to that of recovery.
3. Numerical analysis using drawdown data in limestone and sand aquifers during the same test.
4. Estimated from specific capacity data (Theis et al. 1963).

[2]— indicates not applicable given the aquifer behavior or type of test.
[3]NR indicates not reported.

relatively thick as shown by the east-west geologic cross section (Figure 7). Aquifer tests indicate that the aquifer is semiunconfined or unconfined (sites 9 and 15; Table 2) in this area. To the east and northeast of this area, transmissivity decreases to less than 10,000 or 5000 m^2/day as the aquifer becomes deeper (as deep as 30 m), confined or semiconfined, and thinner in some areas. In this eastern area, the aquifer has leakance values of 1×10^{-4} day^{-1} or lower (sites 40 and 41; Table 3). To the west of the central area, the aquifer has transmissivity values of less than 10,000 m^2/day in some areas, but could be higher than 20,000 m^2/day in an area along the coast to the southwest (Figure 10). In this western area, the aquifer is indicated to be unconfined or semiunconfined (Table 2) and generally has been referred to as the water-table aquifer (Knapp et al. 1986).

However, in the area farthest to the west (sites 6 and 7) the lower portion of the limestone unit of the Tamiami Formation is

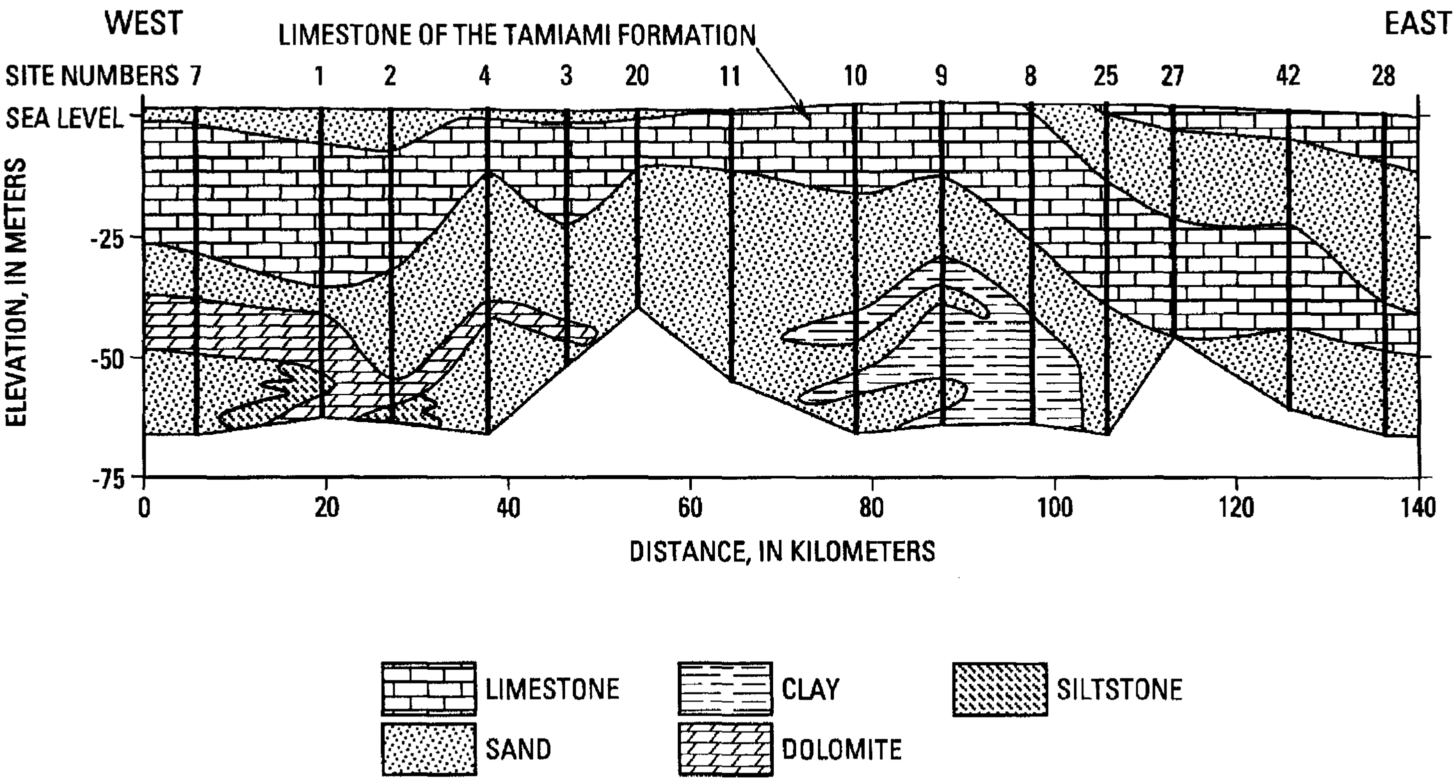

Figure 10. Distribution of transmissivity in the main aquifer (limestone aquifer of the Tamiami Formation) in the study area.

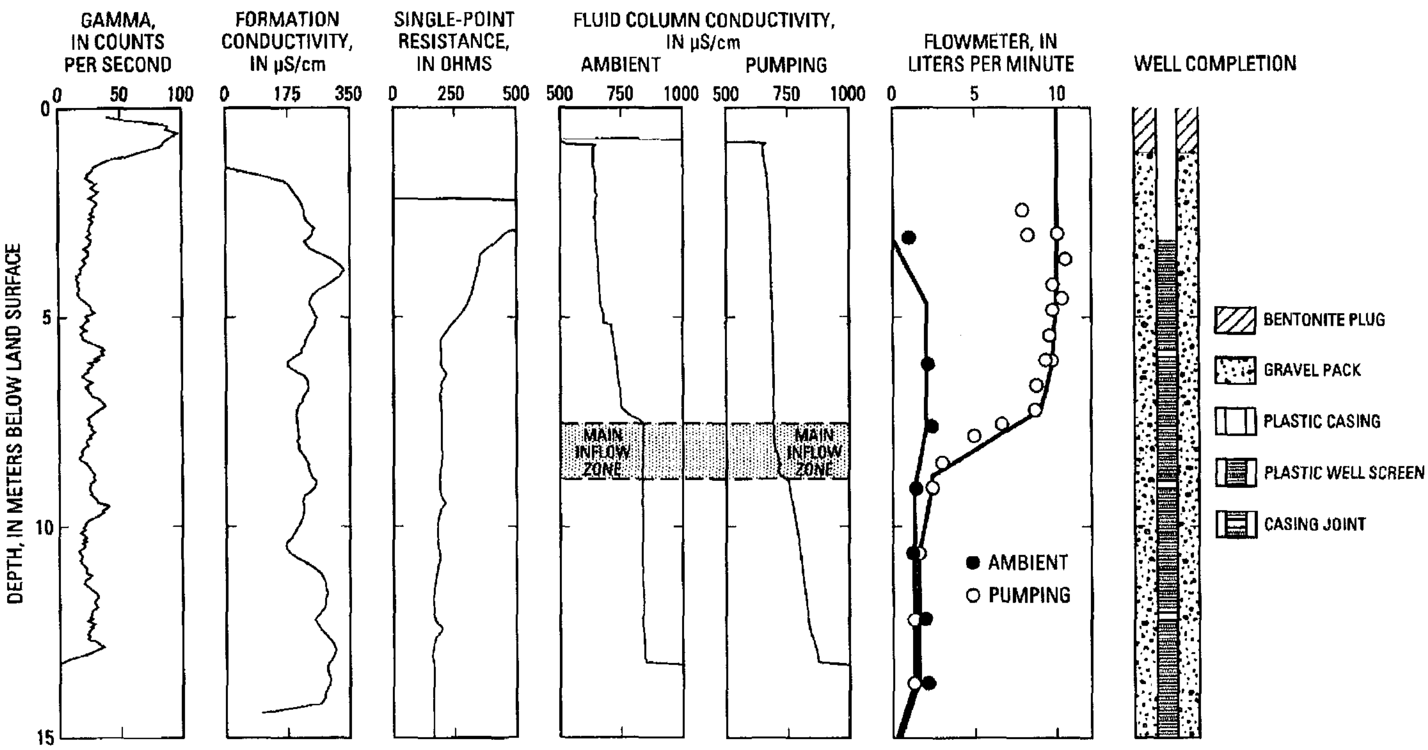

Figure 11. Flow profile during ambient and steady pumping conditions in the screened and gravel packed production well at the corehole 9 site, indicating distribution of inflow during production from the main limestone aquifer.

included in the lower Tamiami Aquifer. Based on mapping done by Knapp et al. (1986), the depth below land surface of the water-table aquifer at site 7 is from 3 to 15 m, and the lower Tamiami Aquifer is from 20 to 41 m (see Figure 7 for depths of lithologic units at site 7). Data from this study at site 7 indicated confinement between the depths of 19 and 20 m. Values for the transmissivity of the lower Tamiami Aquifer, determined from three tests near sites 6 and 7, ranged from only 500 to 3600 m^2/day (Knapp et al. 1986; Table 21).

The relative transmissivity profiles in Figure 6 indicate the distribution of permeability within the upper 60 m of surficial deposits in the study area. Because there were questions about possible intervals of open annulus during flowmeter logging in coreholes, the inflow and outflows inferred from these logs could be tied only to generalized lithologic units. It was assumed that local openings within the annulus would cause any local concentrations of inflow to be spread out over intervals as wide as several meters.

However, in the case of gravel-packed production wells for aquifer tests, the annulus is completely filled with gravel pack. In this situation, the flowmeter profile during pumping would more effectively indicate the distribution of flow within the screened interval. Flowmeter profiles were obtained during pumping in the production well at the site of corehole 9 (Figure 11). This profile indicates that much of the inflow is concentrated within a thin interval near 8 m in depth within the limestone aquifer. The very narrow zone of inflow confirms that upward or downward movement in the annulus could not have been significant during the flow logging in the production well. The precise thickness of the inflow zone is indicated by the difference in shape of fluid column conductivity logs obtained before and during pumping. If the 30,000 m^2/day transmissivity is evenly distributed across the 10 m thickness of the limestone aquifer at the corehole 9 location, then the aquifer has a vertically averaged hydraulic conductivity of about 3000 m/day. Such a relatively large hydraulic conductivity would characterize only the coarsest gravel aquifers (Davis and DeWiest 1966). If most of the hydraulic conductivity is confined to a zone only a few meters in thickness, then the hydraulic conductivity of this thin interval would be even greater. It is hard to credit such a thin zone of such high hydraulic conductivity to any characteristic other than solution openings within the limestone, and some vugular porosity was present in the core between the depths of 8 and 9 m. The presence of solution openings within the limestone aquifer at this site probably accounts for the much higher transmissivity of this aquifer unit in comparison with the sand directly beneath the limestone aquifer, and the sand aquifers units beneath the underlying confining units (Figures 7 and 8). These openings could be similar to the solution openings within the Fort Thompson Formation of the Biscayne Aquifer of southeastern Florida, which are associated with large well yields and transmissivities of greater than 100,000 m^2/day as described by Fish and Stewart (1991).

Conclusions

Characterization of the hydraulic properties of heterogeneous aquifers needs to be an integrated and an iterative process. Large-scale hydraulic properties are given by equipment and time intensive aquifer tests, but preliminary information on aquifer geometry is needed to ensure effective aquifer test design. Thus, the integration of lithologic descriptions of sediments, geophysical well logs, and conventional aquifer tests is critical to aquifer characterization. Borehole flowmeter profiles are a useful tool in bridging the gap between qualitative descriptions of aquifers given by logs and cores and quantitative estimates of hydraulic properties derived from hydraulic tests. Flow logs indicate the location of transmissive intervals in open or screened boreholes and identify where these units are separated by confining units. In the study described in this paper, aquifers are so transmissive that measurable drawdown cannot be generated without pumping at rates greater than 1000 L/min. Such large rates cannot be maintained in exploratory coreholes without elaborate well completion and gravel pack installation. Extensive test preparation can be applied only to a limited number of sites, each with production and observation wells screened over specific aquifer zones. Flowmeter logs were used in this study to identify the principle aquifer units and to identify a few locations where aquifer tests would be decisive in quantifying the hydrostratigraphic model given by the analysis. Thus, the effective integration of geologic descriptions, geophysical logs, flowmeter profiles, and aquifer tests was crucial in the successful characterization of the heterogeneous limestone and sand aquifers at the south Florida study site.

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