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Estimation of Infiltration Rates of Saturated Soils at Selected Sites in the Caloosahatchee River Basin, Southwestern Florida

By Pamela A. Telis

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Estimation of Infiltration Rates of Saturated Soils at Selected Sites in the Caloosahatchee River Basin

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ABSTRACT

Soil infiltration measurements were made at 23 sites in the Caloosahatchee River Basin in Glades, Hendry, and Lee Counties in southwestern Florida. The sandy soils of the basin are characterized by high infiltration rates limited in some areas by a high water table during the wet season. Because soil characteristics are similar within the basin, soils are classified by landscape group based on landscape cover and associated drainage. In accordance with this designation by the South Florida Water Management District, 11 sites are classified in the rock landscape group, 7 in the flatwoods landscape group, 4 in the slough landscape group, and 1 in the depression landscape group.

Data for 16 sites were fit to Horton's equation by using a regression analysis to estimate the infiltration rates of saturated soils. For some sites, an outlier value was removed prior to the regression analysis. Seven of the sites did not yield data that fit Horton's equation. The flatness of the plotted data suggests that saturated conditions may have been reached early in the test. The infiltration rate of saturated soils for these sites was estimated by averaging the data collected after the first 20 minutes of the test.

For all sites, the estimated infiltration rates of saturated soils ranged from 9.8 to 115 centimeters per hour in flatwoods, 3.4 to 66 centimeters per hour in rock, and 2.5 to 55 centimeters per hour in slough. The estimated soil infiltration rate at the one site in the depression was 181 centimeters per hour. Five sites were located on irrigation control berms where infiltration rates of the highly compacted and rocky soil may not represent the rates of less disturbed soils at sites within the same landscape groups.

INTRODUCTION

The Caloosahatchee River has been dredged, lengthened, and deepened over the past century to drain water from Lake Okeechobee into the Gulf of Mexico. Additionally, the river has been channelized to: (1) meet agricultural demands in the basin for irrigation and drainage for crops, such as citrus and sugar cane; (2) transport goods within the basin and across the state of Florida; and (3) provide reliable, high-quality water supply to expanding urban centers of Fort Myers and smaller communities. Today (2000), the Caloosahatchee River Basin serves an urban area of more than 250,000 people and an agricultural area that encompasses more than 1,295 km^2 (square kilometers) in southwestern Florida. The growth in population is expected to continue and increase dramatically through 2020. Agricultural land acreage also is expected to expand as unimproved pasture and other lands become productive through irrigation and drainage.

Beginning in 1997, development of a water-management plan for the Caloosahatchee River Basin was implemented to assist officials in the decision-making process regarding potential water-supply needs in southwestern Florida through 2020. The objectives of the plan are to estimate the future water-supply needs of urban and agricultural areas, weigh those demands against historically used water sources, and identify areas where the demands cannot be met without causing harm to the water resources and environment (Caloosahatchee Advisory Committee, written commun., 1999).

In accordance with this water-management plan, an integrated surface-water and ground-water (ISWGW) model was constructed to examine current and future water usage and sources and to test water-management techniques in the Caloosahatchee River Basin. The ISWGW model, developed by the Danish Hydrologic Institute, uses the MikeSHE model (Jacobsen, 1999), which simulates surface-water and ground-water interaction within a watershed. Model components used for the simulation include irrigation schemes, seasonal crop evapotranspiration demands, and infiltration through various soil profiles.

In 1998, the U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District (SFWMD), began a study to support the ISWGW model development effort by collecting and analyzing data to estimate saturated soil infiltration rates at selected sites in the Caloosahatchee River Basin. The vertical hydraulic conductivity of saturated soil, an input parameter to the MikeSHE model, was estimated from these measured infiltration rates under specified field conditions.

Purpose and Scope

The purpose of this report is to present estimates of the infiltration rates of saturated soils at selected sites within the Caloosahatchee River Basin in Lee, Hendry, and Glades Counties in southwestern Florida. The model area covers part of the basin that drains to the freshwater portion of the river between Moore Haven Lock and Franklin Lock (fig. 1).

Saturated soil infiltration rates were estimated at 23 sites in the study area using a double-ring infiltrometer. Time-series plots were generated for all of the sites. Horton's equation was used with a regression analysis at 16 sites to estimate the infiltration rates of the saturated soils; outliers were removed from 5 of these sites before the regression analysis was made. Horton's equation could not be used to describe data for the remaining seven sites. The nearly constant infiltration rates measured during the tests at these sites were averaged to estimate the magnitude of the infiltration rate of the saturated soils. Test results, presented herein, are arranged by landscape group as classified by the SFWMD.

Soil Characteristics and Landscape Groups

Most of the soils in the Caloosahatchee River Basin are characterized as shallow and sandy and have high infiltration rates that are limited in some areas by a high water table during the wet season. The nearly 70 different soil types in the model area have similar physical characteristics and hydraulic characteristics. Because of these similarities, the landscape cover and associated drainage were the principal attributes for combining soil types into hydrologic response groups. The landscape groups (Eric Flaig, South Florida Water Management District, written commun., 1998) used for this study are described below.

- Depression – Occurs in flatwoods and marsh and pond landscapes as shallow dips or depressions in the land surface where drainage is limited. Depressions are characterized by high organic matter content in the surface horizon that reduces infiltration and increases runoff.

- Flatwoods – Nearly level areas where scattered to numerous pine trees are common and saw palmetto, gallberry, and other woody plants flourish throughout the region. Soils associated with this landscape group include Immokalee, Myakka, and Oldsmar. Typically, this poorly drained soil occurs on broad irregular areas with a slope of less than 2 percent. The water table may be within 254 mm (millimeters) of the soil surface for up to 5 months. During the dry season, the water table is at least 1,270 mm below land surface.

- Rock – Areas with a soil type dominated by the presence of a shallow rock or clay layer. The shallow rock in these areas reduces the water-holding capacity and increases runoff. The magnitude of the effect on runoff depends on the depth of the rock from land surface.

- Slough – Open grassland that is nearly level and has broad drainage courses. The plant community is dominated by blue maidencane, chalky bluestem, and bluejoint panicum. Sloughs generally are found between flatwoods and freshwater marsh plant communities. Typical slough soils are Pineda, Riviera, and Holopaw. The water table may be within 254 mm of the soil surface for up to 6 months during most years and between depths of 254 and 1,016 mm for much of the remaining time.
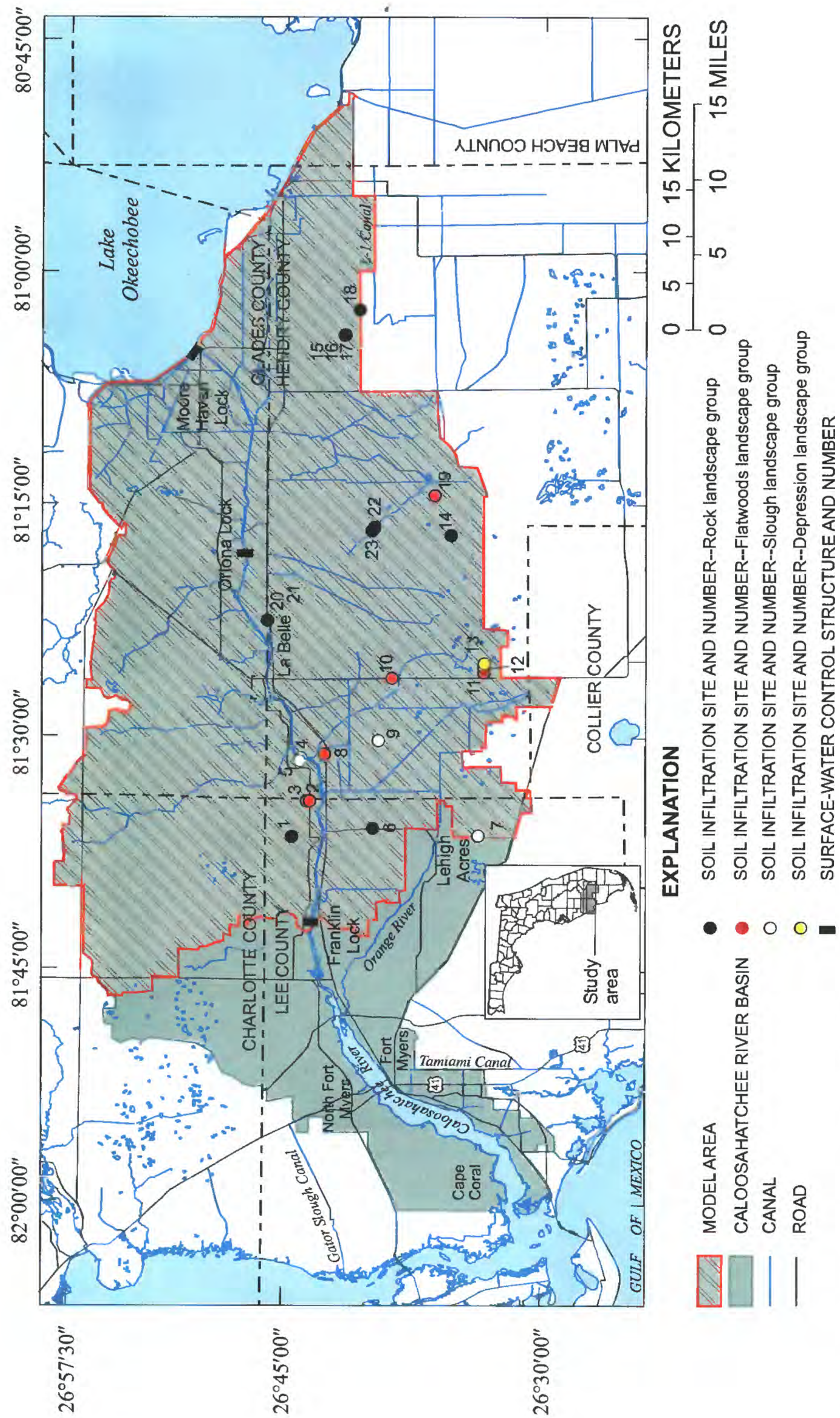
Figure 1. Caloosahatchee River Basin and location of soil infiltration sites in southwestern Florida.

Table 1. Typical soil profiles and associated hydraulic conductivities used in the integrated surface-water and ground-water model for various landscape groups

Landscape group	Soil Type	Soil Depth (meters)	Saturated vertical hydraulic conductivity (centimeters per hour)
Depression	Winder A1	0.00 - 0.08	13
	Winder E	.08 - .33	21
	Winder Btg	.33 - .58	2.7
	Winder C1	.58 - .89	1.5
	Winder C3	.89 - 21.7	.7
Flatwoods	Immokalee A1	.00 - .10	72
	Immokalee AE	.10 - .23	39
	Immokalee E1	.23 - .41	31
	Immokalee E2	.41 - .91	36
	Immokalee Bh2	.91 - 1.4	2.2
	Immokalee Bw/Bh	1.4 - 23	27
Rock	Boca A	.00 - .08	40
	Boca E1	.08 - .23	35
	Boca E2	.23 - .36	29
	Boca Bw	.36 - .64	19
	Boca Btg	.64 - 22.64	.3
Slough	Pineda E	.00 - .13	29
	Pineda Bw1	.13 - .33	29
	Pineda Bw2	.33 - .58	23
	Pineda E1	.58 - .91	19
	Pineda Btg/E	.91 - 1.37	.1
	Pineda Cg	1.37 - 22	.4

For each landscape group, a typical soil profile that generally represents the soil characteristics of the group was created for use in the ISWGW model. Model input for each soil type includes the vertical hydraulic conductivity of saturated soil (table 1).

Soil maps delineate areas dominated by one or more major types of soil. The boundary between two soil types in an area may be distinct, but more commonly is a merging of the soils where characteristics gradually change. Soils are related to geology, landform, relief, climate, and natural vegetation. The certainty of a soil type, however, can only be assured by site investigation and laboratory analysis of soil samples, which were not performed during this study.

Acknowledgments

ESTIMATING INFILTRATION RATES OF SATURATED SOILS

The process of water infiltrating through a surface soil is a complex interaction between rainfall intensity, soil type, and surface cover and condition. Soil surface conditions govern the ability or rate at which water passes into the soil, whereas the internal soil structure governs the rate at which water passes through the soil. Horton (1940) showed that when rainfall exceeds the infiltration rate, water infiltrates surface soils at a rate that decreases with time. According to Horton's equation:

$$f = f_c + (f_0 - f_c)e^{-kt},$$

where
f is the maximum infiltration rate at time t,
f_c is the saturated soil infiltration rate,
f_0 is the initial infiltration rate at time equals zero,
k is a constant that defines function f, and
t is time.
Ultimately, the infiltration rate reaches a constant value known as the saturated soil infiltration rate. Rubin and Steinhardt (1963) and Rubin and others (1964) showed that the final infiltration rate reached under these conditions is equal to the vertical hydraulic conductivity of a saturated soil. Several assumptions about boundary conditions must be met, however, including a constant hydraulic gradient with depth and flow through the soil column, which is vertical (no lateral component).

Soil Infiltration Measurements

Soil infiltration measurements were made at 23 sites in the Caloosahatchee River Basin (fig. 1 and table 2). Of these sites, 11 are classified by the rock landscape group, 7 by the flatwoods landscape group, 4 by the slough landscape group, and 1 by the depression landscape group. Sites were selected with assistance from the SFWMD based on soil type, land use, proximity to water source, site accessibility, and future study needs. Access to private property limited site location in several instances; therefore, less desirable nearby sites, such as those along roadways, were used as alternatives. In all instances, sites were selected to represent the typical land use and surface conditions of the surrounding area. At four sites, a second measurement was made in proximity to the first measurement to test the reproducibility of the data-collection method and to gain further insight about spatial variability in soil infiltration.

Soil infiltration was measured by using a standard double-ring infiltrometer (American Society for Testing and Materials, 1994), which consists of two concentric rings, a driving plate, and two calibrated Marriotte tube assemblies to deliver water to the rings during the measurement (fig. 2). The inner and outer rings are driven into the ground by raising and dropping a sliding weight on the driving plate placed on top of the rings. The saturated soil between the inner and outer rings vertically constrains flow through the inner ring. For this study, water used for the soil infiltration tests was taken from local groundwater wells and nearby canals when wells were not near the test site.

The rings were filled with water to a depth of about 51 to 76 mm. The Marriotte tubes have closed airtight tops designed to maintain a constant head in the rings by delivering water as it is lost by infiltration. The calibrated marking on the Mariotte tube generally is read at timed intervals to calculate the delivery rate of water to the inner ring. If a constant head is maintained in the inner ring, the delivery rate is the incremental infiltration rate.

At sites where the infiltration rate was higher than the maximum delivery rate of the tube to the inner ring, water was added directly to the inner ring. The additional water was recorded by measuring down to the water surface from the top of the inner ring at timed intervals. (To maintain a saturated barrier, water also had to be added directly to soil between the inner and outer rings.) During a single infiltration test, the water reservoir in the Marriotte tubes had to be replenished several times. Removal of the top of the Marriotte tube allowed water to move into the rings, and constant-head conditions had to be reestablished.

Soil infiltration tests were conducted on several irrigation control berms in the Caloosahatchee River Basin. Testing infiltration rates in the highly compacted and rocky berms was difficult, and thus, assumptions of vertical flow through the soil column were uncertain.

Table 2. Description of soil infiltration sites in the Caloosahatchee River Basin

[Soil type and landscape group classified by the South Florida Water Management District]

| Site no.	Site location		Observed land use and field observations	Soil type	Land-scape group
	Latitude	Longitude			
1	264433	813625	Site on side of road is in a heavily grassy area near a pasture with a citrus farm about 229 meters away	Pineda	Rock
2	264342	813408	Site on side of road is in a grassy area near a pasture	Immokalee	Flatwoods
3	264331	813406	Site is in a citrus grove	Immokalee	Flatwoods
4	264403	813121	Site is in a citrus grove that is adjacent to the Caloosahatchee River	Riviera	Slough
5	264408	813132	Site is in a citrus grove	Riviera	Slough
6	263951	813552	Site is at side of road in an area of thin grass	Boca	Rock
7	263344	813618	Site is at side of road in an area of thin grass	Oldsmar	Slough
8	264239	813107	Site is about 9 meters off road in a grassy area. Some rocks are deposited nearby	Immokalee	Flatwoods
9	263933	813013	Site is in a citrus grove	Malabar	Slough
10	263846	812611	Site is about 4.5 meters off road in a thinly grassy area adjacent to a pasture.	Oldsmar	Flatwoods
11	263326	812548	Site is on top of berm in citrus grove	Immokalee	Flatwoods
12	263326	812528	Site is on road at top of berm in citrus grove. Nearby are a pumping station and an irrigation canal	Immokalee	Flatwoods
13	263326	812513	Site is on top of berm in a citrus grove within an area of tall reedy weeds	Holopaw	Depression
14	263523	811659	Site is adjacent to a sugar cane field. Field was very moist as if irrigated recently	Holopaw, lime	Rock
15	264134	810406	Site is wooded with oaks, pines, and cypress trees	Hallandale	Rock
16	264135	810406	Site is wooded with cypress trees in campground	Hallandale	Rock
17	264133	810404	Site is wooded with pine trees	Hallandale	Rock
18	264044	810227	Site is pasture	Hallandale	Rock
19	263620	811424	Site is on side of road in a grassy area adjacent to pine forest	Oldsmar	Flatwoods
20	264602	812230	Site is in an open area with some trees	Boca	Rock
21	264602	812230	Site is in an open area with some trees	Boca	Rock
22	263949	811629	Site is on road at top of berm in a citrus grove. Soil was rocky and seemed highly compressed at surface	Pineda, lime	Rock
23	263957	811641	Site is on road at top of berm in citrus grove. Soil was rocky and appeared highly compressed at surface	Pineda, lime	Rock

A more extensive evaluation of soil infiltration rates in these compacted disturbed soils could validate or clarify rates reported herein. Additionally, soil characteristics and landscape groups for these sites may not be appropriate for comparison with less disturbed sites having the same soil characteristics and within the same landscape groups.

Regression Analysis

Incremental soil infiltration rates, as a function of time, were plotted for each test; additionally, Horton's equation was fitted by multiple nonlinear regression to estimate f_c (the saturated soil infiltration rate). The time-series plots were examined for fit to Horton's equation and for providing reasonable estimates of f_c based on the observed data. In all instances, the estimated f_c is consistent with the data and with f_c values in the literature for soils in southern Florida. The final saturated soil infiltration rate with a 95-percent confidence interval was computed based on the standard error of the regression and the number of data points plotted.
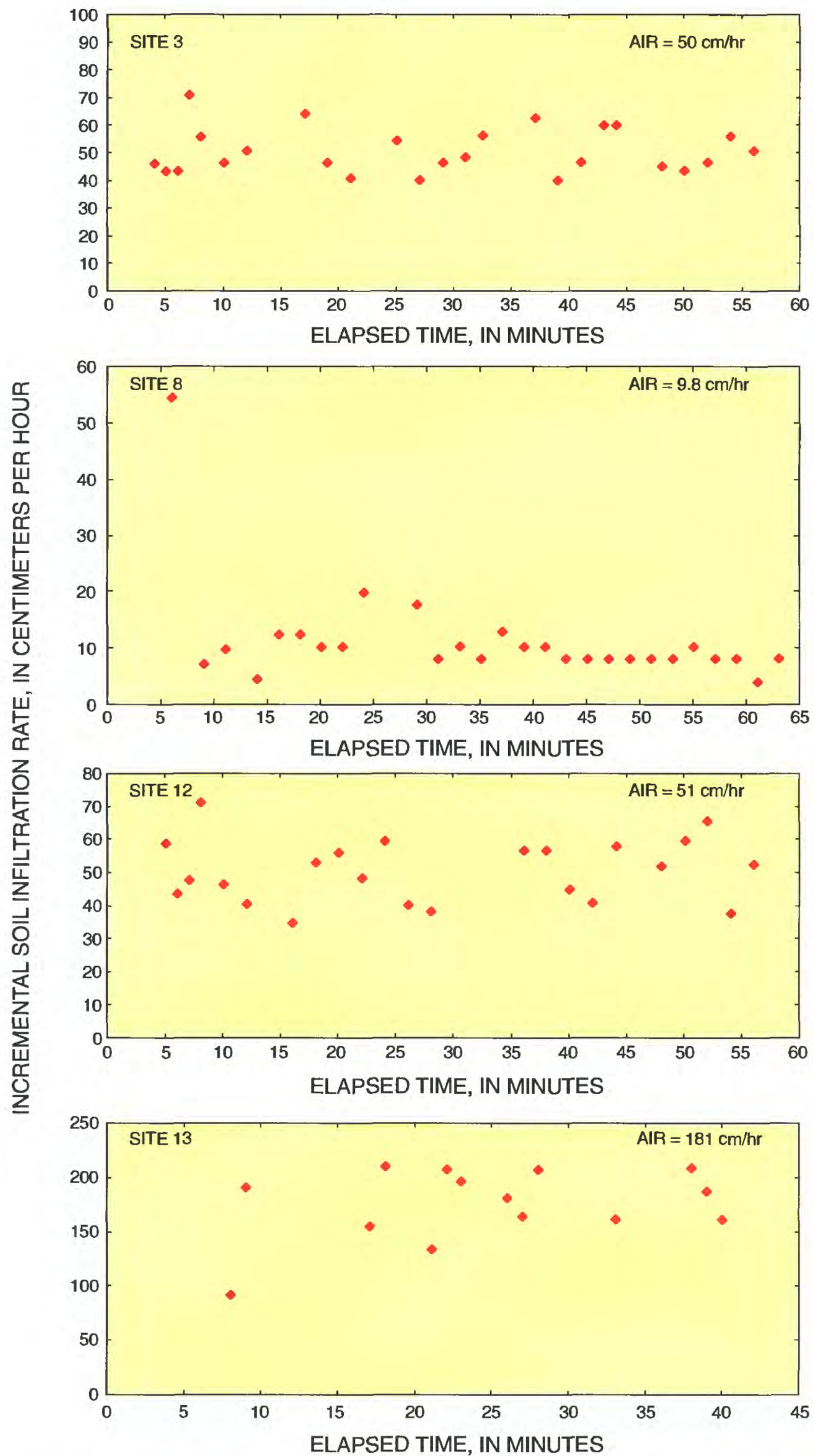
According to Horton's equation, infiltration rates become constant with time as the soil column reaches fully saturated conditions, which occurred about 20 to 30 minutes into the test at most sites. For sites where data could not be fitted to Horton's equation, the flatness of the plotted data throughout the test suggests that saturated soil conditions may have occurred early in the test, and thus, maintained for the duration of the test. Because the characteristic curve based on Horton's equation (Horton, 1940) was not observed in the plotted data at seven sites, multiple nonlinear regression could not be used to estimate f_c (fig. 3). Based on the assumption that saturated soil conditions were reached within the first 20 minutes of the test, the incremental soil infiltration rates measured after the first 20 minutes were averaged to estimate f_c at these sites. The standard deviation of f_c provides an estimate of the variability of the data at the seven sites (table 3).
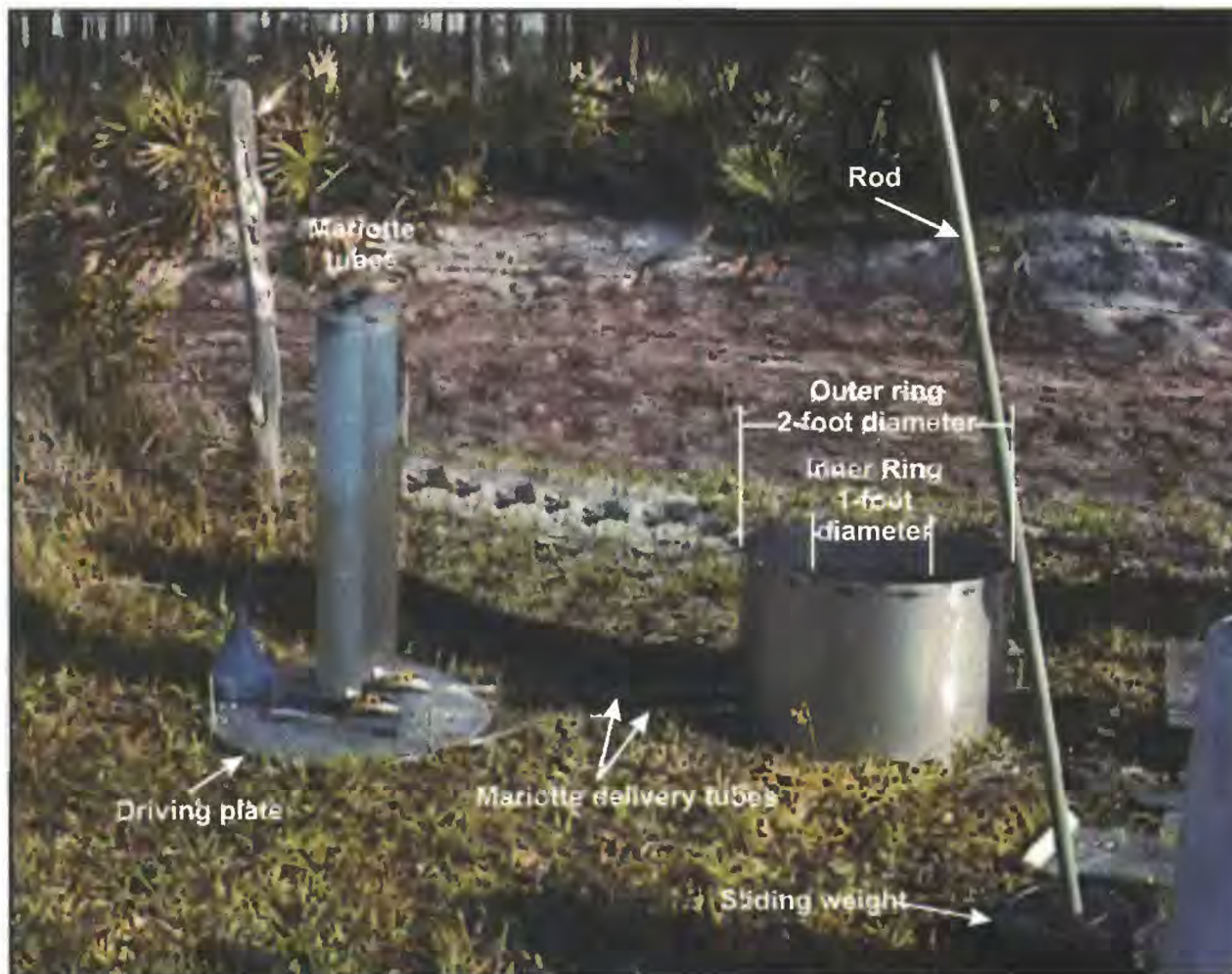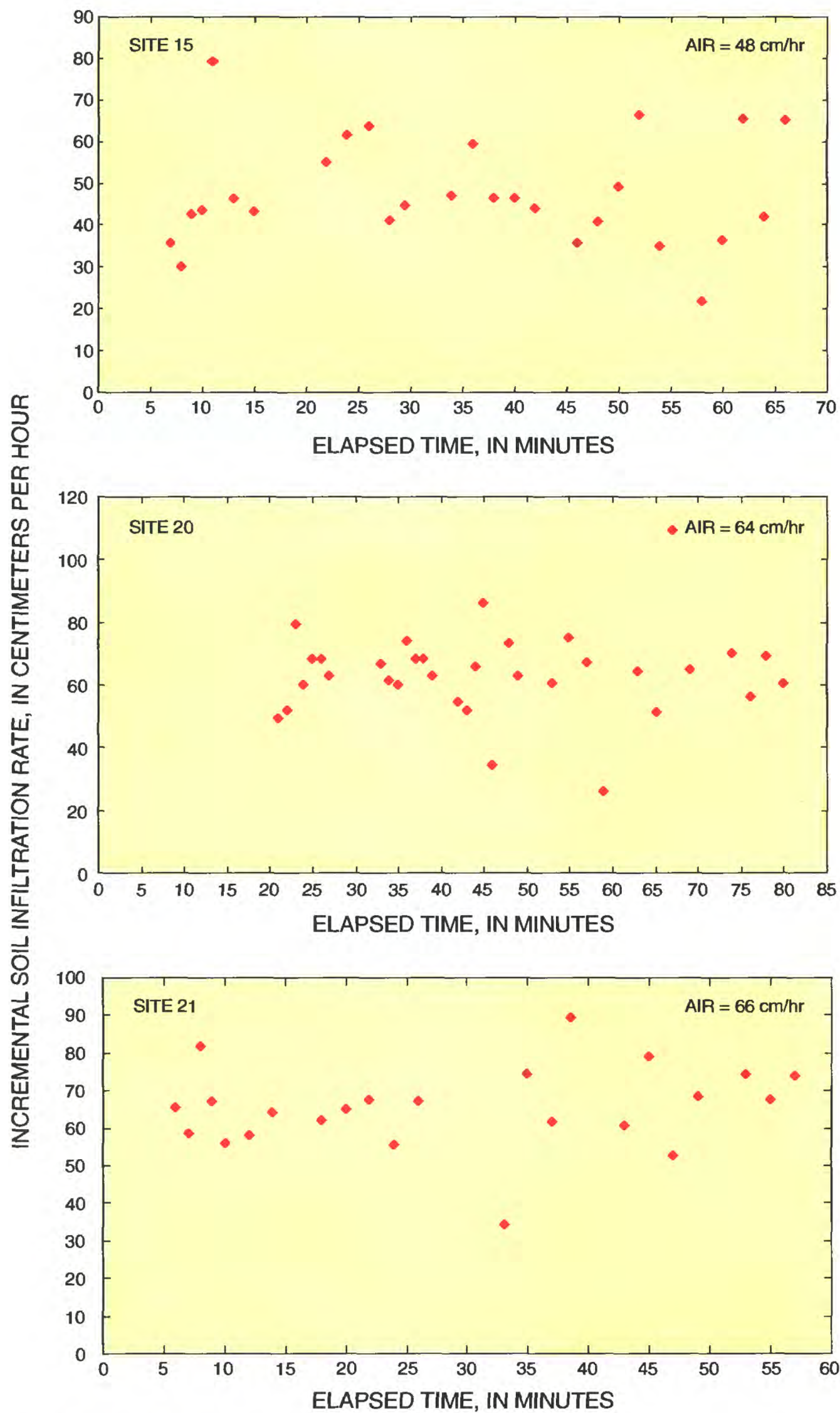

Figure 2. Double-ring infiltrometer setup.

Figure 3. Soil infiltration rate as a function of time for sites where data could not be fitted to Horton's equation. The average infiltration rate (AIR) is for time periods greater than 20 minutes.

Figure 3. Soil infiltration rate as a function of time for sites where data could not be fitted to Horton's equation. The average infiltration rate (AIR) is for time periods greater than 20 minutes--Continued.

Table 3. Estimates of infiltration rates of saturated soils based on average incremental infiltration rates for time periods greater than 20 minutes

[f_c, saturated soil infiltration rate. Site 13 is located on berm where soil characteristics probably vary from undisturbed or less disturbed sites within the same landscape group]

Site no.	Landscape group	f_c (centimeters per hour)	Standard deviation (centimeters per hour)
3	Flatwoods	50	7.5
8	Flatwoods	9.8	3.4
12	Flatwoods	51	8.8
13	Depression	181	25
15	Rock	48	12
20	Rock	64	14
21	Rock	66	12

Data for 16 sites were fitted to Horton's equation by regression analysis (fig. 4). The difficulty in precisely measuring the water lost to infiltration at incremental times during the test probably resulted in the substantial amount of scatter in the plotted data. For sites 7, 16 (test 2), 19 (test 1), and 23 (test 2), the regression of Horton's equation converged only after removing an outlier value. The data were analyzed with and without outliers for site 18 (test 2); outliers were qualitatively determined. An analysis of the data suggests that removing these outliers probably is insignificant in estimating f_c. The infiltration capacities based on the regression analysis for the 16 sites and the 95-percent confidence intervals for these estimates are listed in table 4.
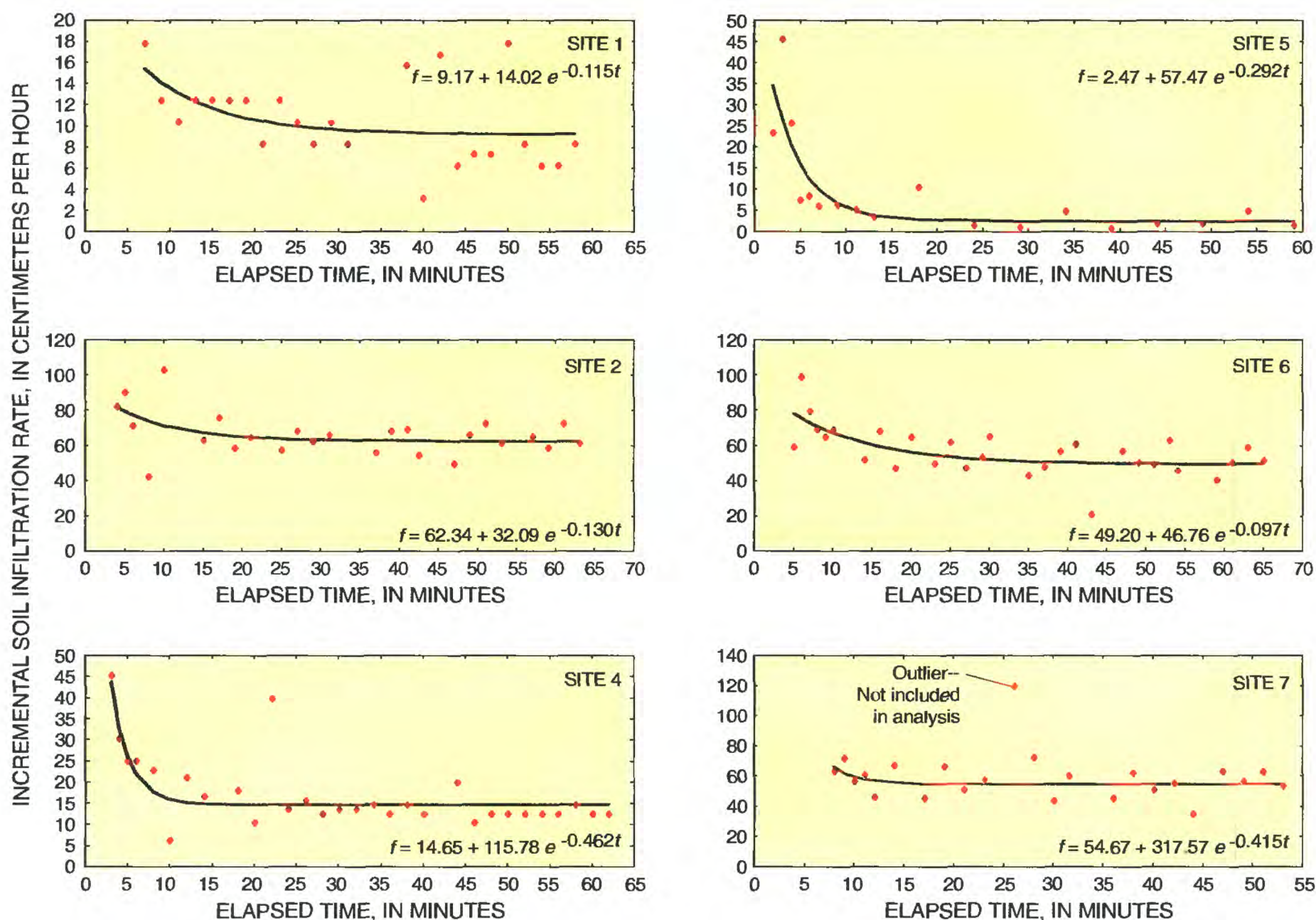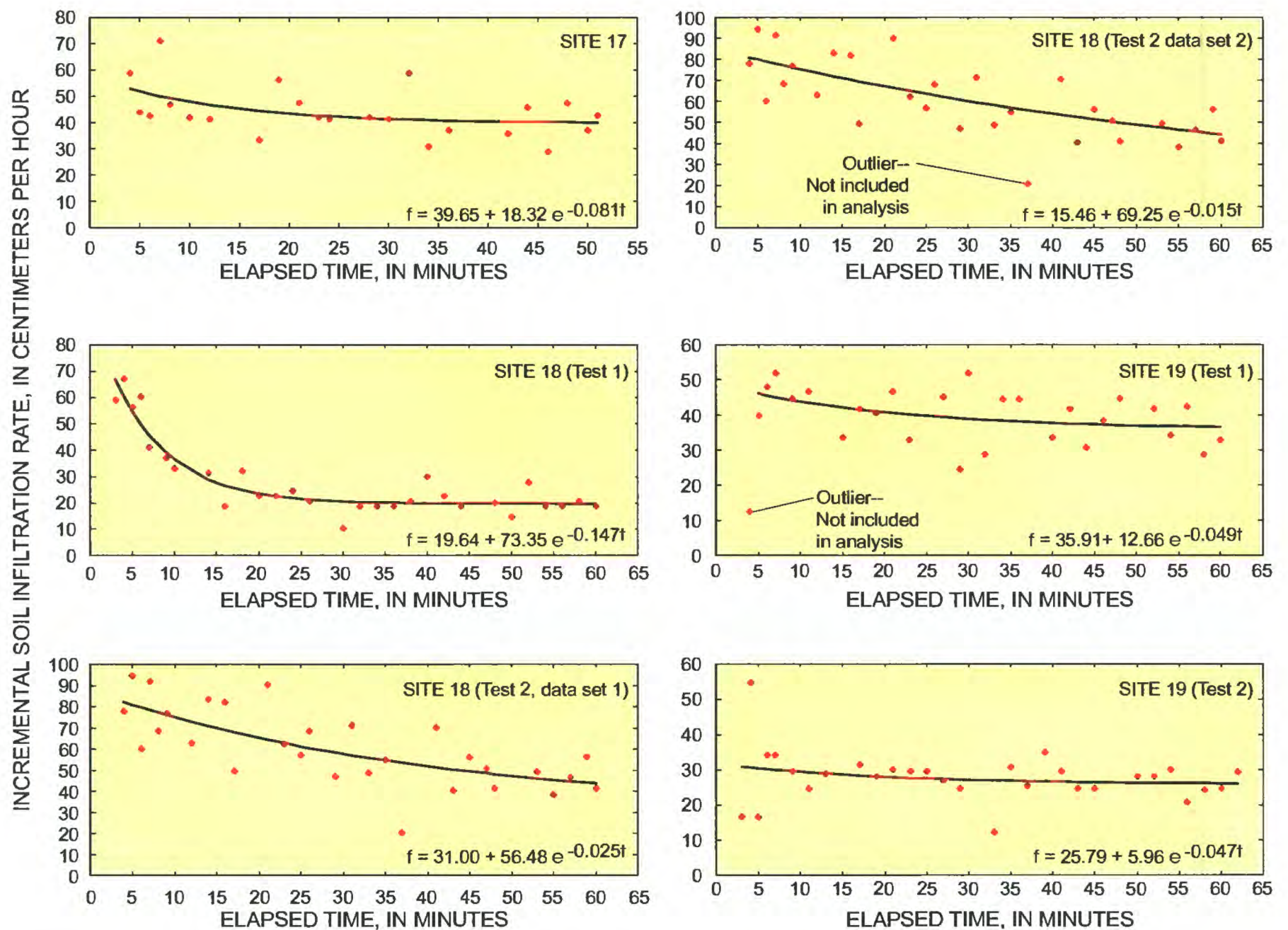

Figure 4. Soil infiltration rate as a function of time for sites fitted to Horton's equation.
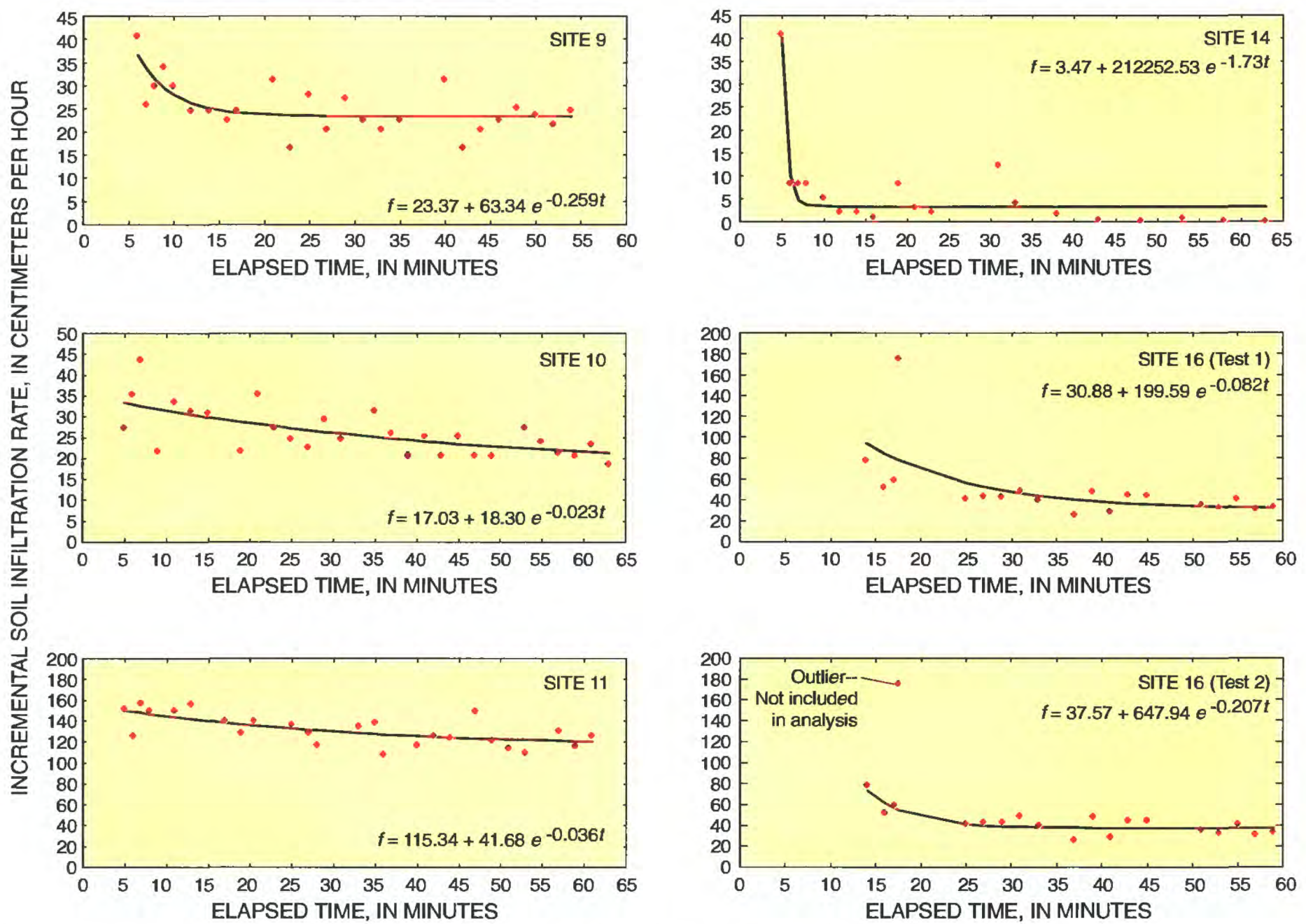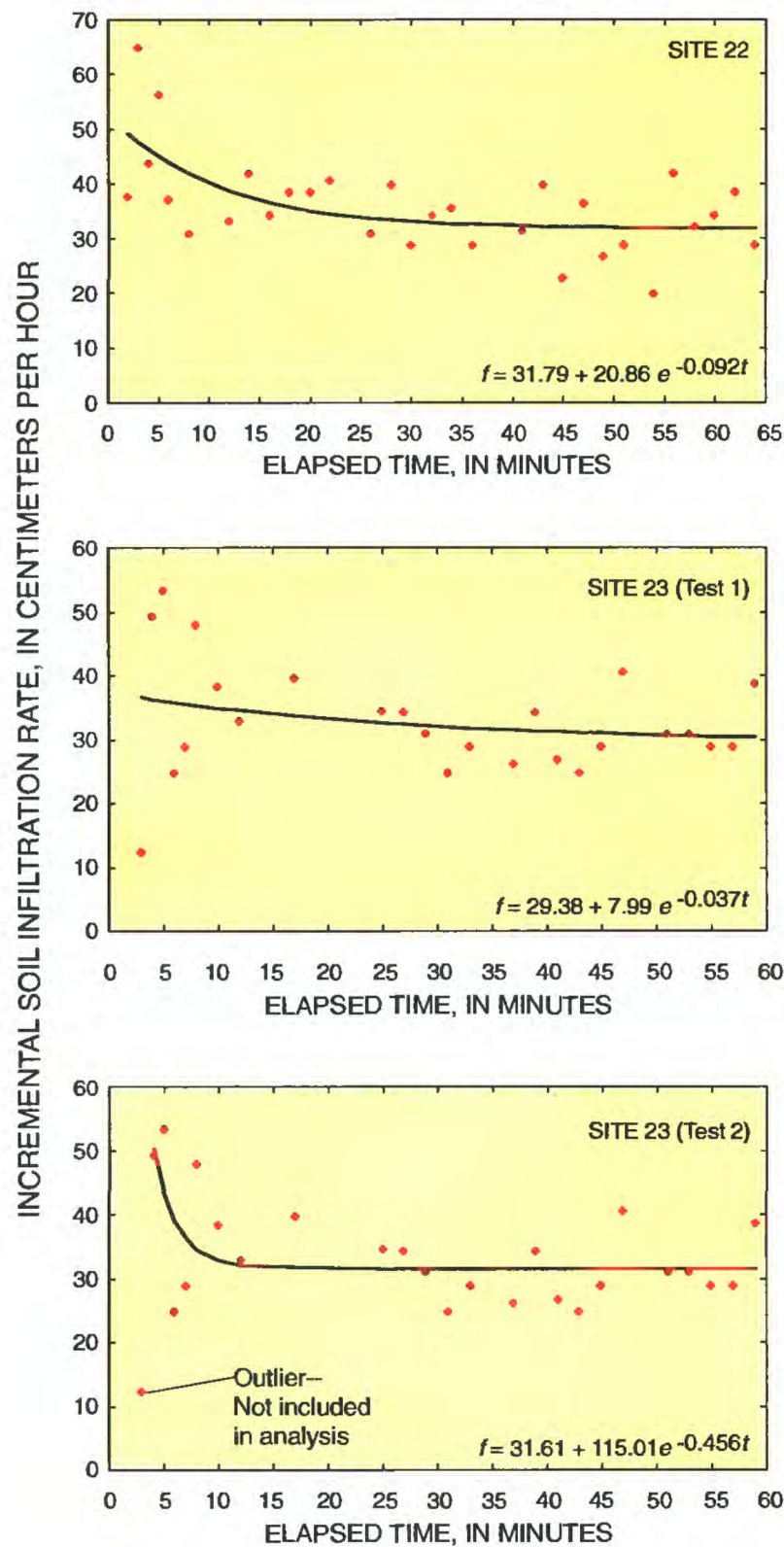
Figure 4. Soil infiltration rate as a function of time for sites fitted to Horton's equation--Continued.

Figure 4. Soil infiltration rate as a function of time for sites fitted to Horton's equation--Continued.

Figure 4. Soil infiltration rate as a function of time for sites fitted to Horton's equation--Continued.

Estimated f_c values are plotted for each landscape group and compared to the lowest saturated vertical hydraulic conductivity in the top 0.5 m (meter) of the "typical" model soil profiles used in the ISWGW model (fig. 5). This comparison is based on the assumption that the infiltration test wetted only the top 0.5 m of soil – an assumption that may not have been accurate for all tests. The mean and standard deviation of the estimated f_c are computed for the landscape groups having four or more tests.

The estimated infiltration rates of saturated soils ranged from 9.8 to 115 cm/hr (centimeters per hour) in the flatwoods landscape group, 3.4 to 66 cm/hr in the rock landscape group, and 2.5 to 55 cm/hr in the slough landscape group (fig. 5). For the depression landscape group, represented by site 13, the estimated saturated soil infiltration rate was 181 cm/hr and the lowest saturated vertical hydraulic was 2.7 cm/hr. Five sites (11, 12, 13, 22, and 23) were located on irrigation control berms. Infiltration rates of the highly compacted and rocky soil may not represent the rates of less disturbed soils at sites within the same landscape groups.

Table 4. Estimates of infiltration rates of saturated soils based on regression analysis

[f_c, saturated soil infiltration rate]

Site no.	Landscape group	f_c (centimeters per hour)	95-percent confidence interval for infiltration rate (centimeters per hour)[1]	Outlier deleted (yes or no)	Comments
1	Rock	9.2	2.6	No	
2	Flatwoods	62	7.0	No	
4	Slough	15	2.4	No	
5	Slough	2.5	4.7	No	
6	Rock	49	7.3	No	
7	Slough	55	5.1	Yes	
9	Slough	23	2.2	No	
10	Flatwoods	17	25	No	
11	Flatwoods	115	32	No	Located on berm where soil characteristics probably vary from undisturbed or less disturbed sites in same landscape group
14	Rock	3.4	1.9	No	
16	Rock	31 37	35 4.6	No Yes	Two tests conducted with and without outlier for complete data set
17	Rock	40	10	No	
18	Rock	20 31 15	2.8 66 162	No No Yes	Two tests conducted for complete data set. Test 1 conducted with outlier; test 2 conducted with and without outlier
19	Flatwoods	36 26	12 11	Yes No	Two tests conducted with and without outlier for complete data set
22	Rock	32	4.7	No	Located on berm where soil characteristics probably vary from undisturbed or less disturbed sites in same landscape group
23	Rock	29 32	25 147	No Yes	Two tests conducted with and without outlier for complete data set. Located on berm where soil characteristics probably vary from undisturbed or less disturbed sites in same landscape group

[1]Estimate of f_c for site 1, for example, is 9.2 ±2.6 centimeters per hour, with a 95-percent confidence interval based on the data.
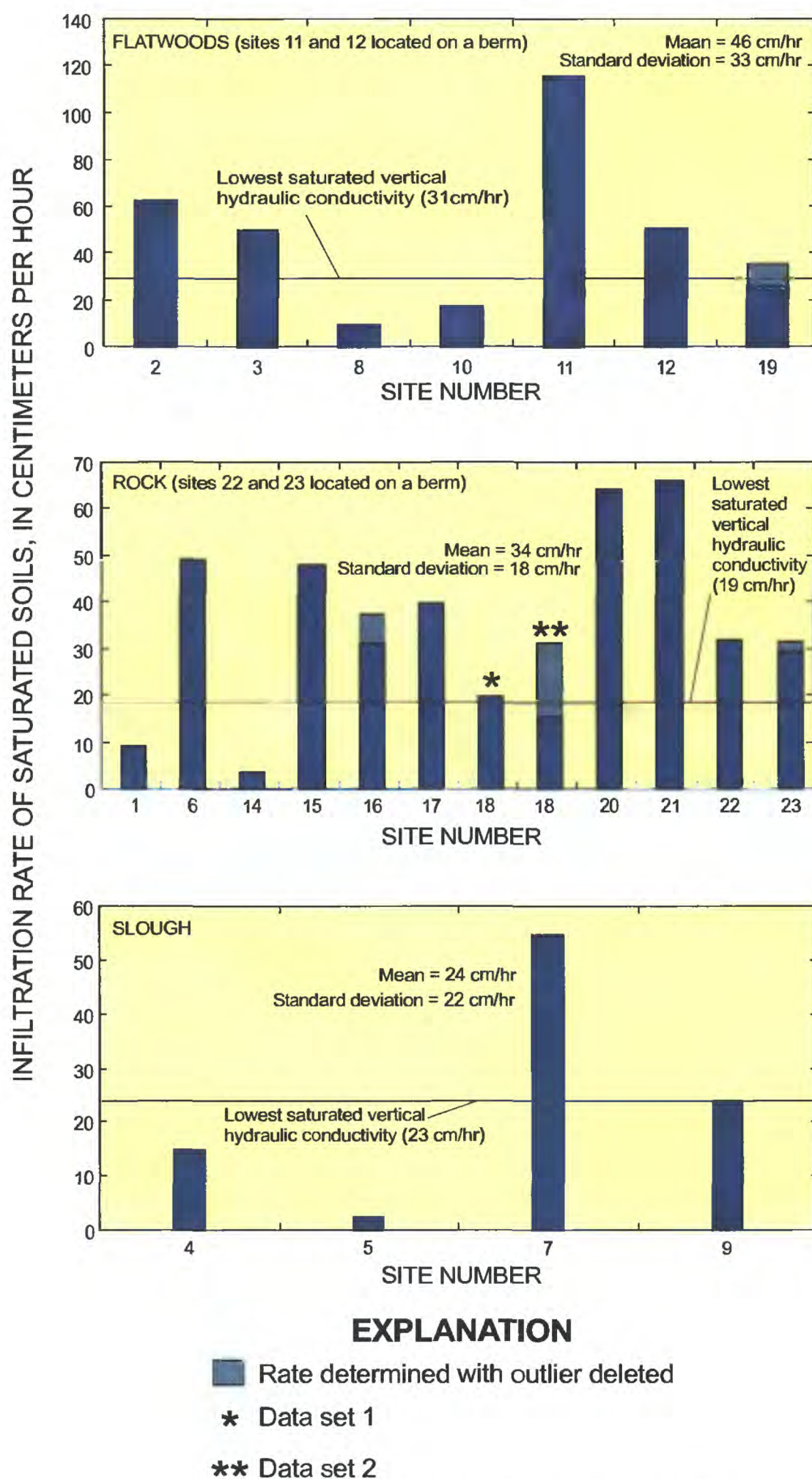
Figure 5. Estimated saturated soil infiltration rates for sites by landscape group compared with lowest saturated vertical hydraulic conductivity used in the integrated surface-water and ground-water model.

CONCLUSIONS

The high infiltration rates of saturated soils in the Caloosahatchee River Basin made collection of accurate double-ring infiltrometer data difficult. Several factors influenced the tests including the fact that standard infiltrometer water-supply reservoirs could not deliver enough water at the needed rates; measuring rapidly changing water levels was difficult, and therefore, subject to inaccuracy; and local site features such as atypical root density, large rocks below land surface, or areas of compaction not visible at the surface may have affected individual test results.

Verification of assumptions used in this study requires more extensive data-collection efforts, such as using augers or backhoes to penetrate below land surface following an infiltration test to verify vertical flow, homogeneous soil profiles, and actual depth of saturation. Potentiometers could be used to verify the assumption of unit hydraulic gradient with depth. In some places where the water table is shallow, water mounding under the infiltrometer produces a "back pressure" and an equilibrium hydraulic gradient that is less than one. For this study, tests were conducted during a drought period in April 1999, when the water table was expected to be well below the soil layers saturated for this analysis.

REFERENCES CITED

American Society for Testing and Materials, 1994, Standard test method for infiltration rate of soils in field using double-ring infiltrometer: ASTM Publication D-3385-94, 7 p.

Horton, R.E., 1940, An approach towards a physical interpretation of infiltration capacity: Soils Science Society of America Proceedings, v. 5, p. 399-417.

Jacobsen, T.V., 1999, Caloosahatchee Basin Integrated Surface Water-Ground Water Model: Danish Hydraulic Institute Report, 106 p.

Rubin, J., and Steinhardt, R., 1963, Soils water relations during rain infiltration; Part I--Theory: Soils Science Society of America Proceedings, v. 27, p. 246-251.

Rubin, J., Steinhardt, R., and Reiniger, P., 1964, Soil water relations during rain infiltration: Part II--Moisture content profiles during rains of low intensities: Soils Science Society of America Proceedings, v. 28, p. 1-5.