United States Department of the Interior

U.S. GEOLOGICAL SURVEY

Water Resources Division
9100 N.W. 36 Street
Suite 107
Miami, FL 33178

September 24, 2001

Mr. Steve Krupa
South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406

Dear Steve:

We are pleased to present to you the results of the seepage and water-level analysis to support the development of the integrated surface-water and ground-water (ISWGW) model for the Caloosahatchee River Basin. This analysis was performed at the request of the South Florida Water Management District. The information provided has not been approved for release by the Director of the U.S. Geological Survey. It should not be released to the public nor quoted.

We look forward to our continued association with the South Florida Water Management District. If you have any questions, please do not hesitate to call me at (305) 717-5802.

Sincerely,

Maria M. Irizarry
Subdistrict Chief

Analysis of Seepage and Water-Level Data for the Caloosahatchee Model Support Project

INTRODUCTION

The Caloosahatchee River in southwestern Florida receives water from runoff within the basin, from Lake Okeechobee, and from seepage from the surficial aquifer system. Man-made canals have been constructed throughout the basin to drain and irrigate agricultural and pasture land. In addition, natural channels have been dredged to drain and deliver water throughout the basin. The river system also provides the water supply for numerous urban needs. Because of the highly complex, interconnected hydrologic system, water management in the basin is challenging. The ability to quantify ground-water and surface-water interactions in the basin is needed to manage water issues and maintain a balance between supply and demand.

Enclosed are the results of a seepage and water-level analysis to support the development of an integrated surface-water and ground-water (ISWGW) model for the Caloosahatchee River Basin. The focus of this analysis is to compute seepage coefficients for basin channels using seepage data collected by Belanger (1999) and site survey data and ground-water-head data collected by the South Florida Water Management District (SFWMD) at six sites in the Caloosahatchee River Basin (fig. 1). The seepage coefficients calculated from the site data may be used to improve theoretical estimates used in the ISWGW model for the Caloosahatchee River Basin. Assuming the data can be correlated using Darcy's law, the computed hydraulic conductivity can be multiplied by the area of the channel to estimate ground-water flux into or out of the surface-water body.

METHODS AND DATA COLLECTION

Ground-water well transects perpendicular to two sites on the Caloosahatchee River and to four sites on nearby canals were constructed by the SFWMD with nested piezometers at varying depths. Data-collection sites are identified by the SFWMD by site identification name CRS01, CRS02, CRS03, CRS04, CRS05, and CRS06. However, for this report, the site names are simplified to site 1 for CRS01, site 2 for CRS02, and so on. Site locations are plotted in figure 1. A table containing well construction information prepared by the SFWMD for each site is attached to this report. Seepage meters and in-channel piezometers were installed at all six sites by Belanger (1999). Channel cross sections surveyed by the SFWMD and the approximate location of the seepage meters and ground-water wells at the six study sites are shown in figure 2. Each site contains two 2-well clusters, one cluster located within one channel width of the canal (near wells) and the other located 60 to 370 meters from the canal (far wells). Within each cluster there is the shallow well, with a 1.5-meter screen within about 3 meters of the channel-bottom elevation, and the middepth well, with a 1.5 screen located 6 to 16 meters below the channel-bottom elevation.

Seepage was measured one or more times at all sites during three site visits, October 23-24, 1998, December 4-5, 1998, and January 8-9, 1999. The total number of seepage measurements at each site per seepage meter ranges from 5 to 9 during the sampling period. During that time, only two heavy rainfalls occurred; one on October 22 and the other on November 5. Otherwise, the weather was very dry.

Survey data provided by the SFWMD and site descriptions provided by the Florida Institute of Technology (Belanger, 1999) were used to determine the approximate location of the seepage meters and to estimate ground-water-head data. Information from Belanger (1999) and survey notes from the SFWMD were used to infer in-channel piezometer elevations at each site as accurately as possible. Calculations used in this analysis assume no shifting of, or damage to, the in-channel piezometers between the time of their installation and the site surveys conducted several months later. For this report, water-level and survey data, provided by Belanger (1999) and the SFWMD, were converted from feet to meters for consistency.

During each seepage measurement, the average channel stages were determined using various data sources and methods. At sites 1 and 2, average stages were interpolated from the water-surface slope between the Ortona and Moore Haven Locks (river stage at the locks was obtained from the U.S. Army Corps of Engineers). The average stage on the Caloosahatchee River at its junction with the Jack Spratt Canal was used for site 3 (Steve Krupa, South Florida Water Management District, oral commun., 1999). At sites 4 and 6, average channel stages were estimated by subtracting the distance to the water surface (Belanger, 1999) from the SFWMD survey elevation of the top of the piezometers. The average channel stage and computed hydraulic gradient could not be determined at site 5 because the two in-channel piezometers were not surveyed.

Ground-water-head data for sites 1, 2, and 3 were from 15-minute data collected by SFWMD automatic recorders. Manual readings of ground-water head taken by the SFWMD on October 13, 1998, December 4, 1998, and January 8, 1999, were used for sites 4, 5, and 6.

Assuming that the canal at each site fully penetrates the surficial aquifer system or lies on a ground-water divide, and that flow through the aquifer system is defined for a porous media, the relation between measured seepage and the hydraulic gradient at the site can be defined by a form of Darcy's law:

$$Q' = -K_f \bar{h} \frac{dh}{dl}$$

where Q' is the average seepage measured times half the width of the channel (length/time); K_f is a functional hydraulic conductivity (length/time) based on observed data at the site and the assumptions above multiplied by a proportionality constant for equivalency of units; $\bar{h}$ is the average flow depth between the well and the channel (length); and dh/dl is the hydraulic gradient (length/length) between the channel and ground-water well (channel stage minus ground-water head). The average flow depth ($\bar{h}$) between the well and the channel was computed by averaging the vertical distance between the ground-water head for the well and the top of the well screen, and the vertical distance between the channel bottom at the point about one-quarter of the distance across the channel and the water surface in the channel.

Seepage, at seepage meters where in-channel piezometers provide a measure of the hydraulic gradient through the channel-bottom sediment, can be used to compute an estimate of the hydraulic conductivity or permeability of the sediment. For these seepage meters, seepage was plotted against the measured hydraulic gradient at each site based on Darcy's equation, which defines the movement of the water through porous media. The equation is expressed as:

$$V = -k\frac{dh}{dl}$$

where V is seepage velocity or seepage flow rate per unit area (length/time); k is the permeability or hydraulic conductivity of the media (length/time) multiplied by a proportionality constant for equivalency of units; and dh/dl is the hydraulic gradient along the flow path (length/length).

Hydraulic gradients can only be defined in the direction of the orientation of two points. In the case of the gradient computed between the river and the in-channel piezometers, this is a vertical direction. Gradients computed from the river to the shallow well clusters are virtually horizontal. Therefore, for the purposes of this report, these are considered horizontal hydraulic gradients. For the middepth wells, the hydraulic gradients from the river to the well clusters are oriented at some angle between horizontal and vertical (fig. 2). Defining the gradients between the river and the wells does not infer that flow is occurring in that direction.

Little is known about the surficial geology at most of the sites. Therefore, actual flow paths are unknown, and Darcy's equation cannot be used to compute the permeability or hydraulic conductivity of the material between the channel and the wells. However, plots of the seepage as a function of the hydraulic gradient can define proportional relations that provide estimates of seepage rates under various hydrologic conditions. An accurate conceptualization of the relation between positioning of seepage meters and hydraulic characteristics of the subsurface rocks is possible by combining ground-penetrating radar methods and test coreholes.

Seepage rates, as determined by Belanger (1999), are plotted and analyzed herein. The data include those identified as outliers or possible errors. Any rate reported as a range above a specific value is plotted and analyzed for that value.

ANALYSIS

Ground-water head, channel stage, measured seepage, and rainfall at Ortona Lock were plotted as a function of time for each site in figures 3 and 4. At some sites, the measured seepage rates differed considerably between meters. One possible explanation for variable seepage rates is heterogeneity in the pore-space network (caused by irregular dissolution) of the limestone that underlies the sites. Cunningham and others (2001) suggested that variations in the stratigraphy and solution-enlarged porosity of limestone have caused differences in seepage rates between seepage meters at site 6. Samples of limestone from the Caloosahatchee Formation, which were dredged from the canal near site 6 during construction, show inch-scale diameter, semivertical, solution-enlarged porosity that could act as conduits for vertical ground-water flow (Cunningham and others, 2001).

Vugs and narrow solution channels are known to occur in limestones common to the area. Belanger (1999) observed occasional "spring like" conditions in the Caloosahatchee River Basin where discontinuities and cracks in the limestone bedrock occur, contributing to high average seepage. Stan Locker (University of South Florida, oral commun., 1999) used reflection-seismic methods to examine subsurface features along the Caloosahatchee River, with results that suggest a local presence of fractures in the subsurface below the river bottom. However, these results have not been confirmed by geologic sampling. If these fractures exist, they could potentially extend upward to the river bottom and create areas of ground- and surface-water exchange in the Caloosahatchee River Basin.

Ground-water heads and channel stage can respond to several forcing functions. Rainfall affects ground water regionally, and a relatively rapid response of the ground water to rainfall (figs. 3 and 4) can be detected. Evapotranspiration removes water from the system and follows a daily cycle, peaking at midday. Shallow ground-water heads follow the changes in the river stage and more closely track the stage with proximity to the river. However, based on limited seepage data, there is little evidence that seepage rates respond to rainfall, ground-water heads, or channel stage. Generally, the highest seepage rates were measured in early December after a period of nearly 3 weeks with less than 1 inch of rain and with declining ground-water heads and channel stages. Factors that influence seepage require a better understanding of the flow fields and, perhaps, hydrogeology in the vicinity of these sites.

The average seepage rates for all seepage meters, during each sampling event, times half the width of the channel, Q', were plotted as a function of the average flow depth times the hydraulic gradient, dh/dl, for each site (fig. 5). The computation of dh/dl was based on the water levels observed or estimated at each site, except for site 5 where no canal stage could be determined (table 1). Ground-water heads for the shallow wells were assumed to represent the surficial aquifer system in connection with the channel water stages and, therefore, were used in computation of dh/dl for these plots. If seepage and hydraulic gradient are correlated according to Darcy's equation, the plot of channel inflow seepage and hydraulic gradient shows an inverse relation. When dh/dl becomes more positive, outflow from the channel increases. Conversely, when dh/dl becomes more negative, inflow to the channel increases.

Table 1. Water-level data used for computation of the hydraulic gradient at selected sites in the Caloosahatchee River Basin

[For sites 1, 2, and 3, the ground-water heads are computed from an average of the 15-minute well recorder data collected during the seepage measurement time range. SFWMD, South Florida Water Management District; USACE, U.S. Army Corps of Engineers. NA, not applicable]

Period of seepage measurement			Ground-water heads (meters above sea level)				
Date	Time range (hours)	Channel stage (meters)	Near shallow well	Near middepth well	Far shallow well	Far middepth well	Date manual measurement made by the SFWMD (no time reported)
			Site 1[1]				
10/23/98	1300–1700	3.35	3.36	3.37	3.75	3.57	NA
12/4/98	1400–1500	3.36	3.27	3.29	3.31	3.36	
	1500–1700	3.35	3.26	3.28	3.30	3.36	
1/8/99	1500–1700	3.38	3.27	3.32	3.35	3.43	
1/9-10/99	1700–0830	3.37	3.29	3.34	3.39	3.44	
			Site 2[2]				
10/23/98	1400–1700	3.33	3.62	4.01	4.11	4.35	NA
10/24/98	0900–1400	3.40	3.64	4.04	4.08	4.35	
12/5/98	1200–1400	3.30	3.23	3.87	3.97	4.16	
	1400–1700	3.30	3.23	3.87	3.97	4.16	
1/8/99	1030–1315	3.36	3.54	3.85	3.49	4.09	
	1330–1530	3.36	3.54	3.85	3.49	4.09	
			Site 3[2]				
10/23/98	1500–1800	3.34	3.33	3.57	3.36	3.48	NA
10/24/98	1500–1700	3.42	3.40	3.58	3.39	3.50	
12/5/98	1000–1100	3.32	3.30	3.45	3.29	3.38	
	1100–1300	3.31	3.30	3.45	3.29	3.38	
1/8/99	1100–1200	3.36	3.35	3.49	3.34	3.42	
1/9/99	1100–1330	3.43	3.43	3.53	3.40	3.47	

Table 1. Water-level data used for computation of the hydraulic gradient at selected sites in the Caloosahatchee River Basin (Continued)

[For sites 1, 2, and 3, the ground-water heads are computed from an average of the 15-minute well recorder data collected during the seepage measurement time range. SFWMD, South Florida Water Management District; USACE, U.S. Army Corps of Engineers. NA, not applicable]

Period of seepage measurement		Channel stage (meters)	Ground-water heads (meters above sea level)				
Date	Time range (hours)		Near shallow well	Near middepth well	Far shallow well	Far middepth well	Date manual measurement made by the SFWMD (no time reported)
			Site 4[3]				
10/23/98	1600–1800	4.82	5.58	5.55	5.76	5.55	10/13/98
10/24/98	1600–1700	4.74	5.58	5.55	5.76	5.55	
12/4/98	0800–1300	3.93	5.12	5.03	6.40	5.64	12/4/98
1/8/99	1100–1200	4.73	5.46	5.39	5.94	5.46	1/8/99
1/9/99	1200–1300	4.73	5.46	5.39	5.94	5.46	
			Site 5[4]				
10/24/98	1200–1400	--	8.05	8.08	8.17	7.92	10/13/98
12/4/98	1200-1600	--	7.41	7.47	8.23	8.23	
12/5/98	1400-1600	--	7.41	7.47	8.23	8.23	12/4/98
1/8/99	1600-1700	--	7.83	7.83	8.08	8.08	1/8/99
1/8-9/99	1700-1000	--	7.83	7.83	8.08	8.08	
			Site 6[5]				
10/24/98	0900–1330	4.87	5.09	5.00	5.21	5.21	10/13/98
12/4/98	1600–1700	4.66	4.85	4.75	4.94	4.94	12/4/98
12/5/98	1500–1600	4.66	4.85	4.75	4.94	4.94	
1/9/99	0900–1100	4.84	4.85	4.69	4.85	4.85	1/8/99

[1]Channel stages computed from USACE data collected at Ortona Lock.

[2]Channel stages computed from USACE data collected at Ortona and Moore Haven Locks and adjusted for water surface slope.

[3]Channel stages computed by subtracting outside water level (table 2) from top of nearshore deep piezometer elevation of 5.43 meters above sea level (surveyed by SFWMD).

[4]Data not available to compute channel stage at this site.

[5]Channel stages computed by subtracting outside water level (table 2) from top of nearshore deep piezometer elevation of 5.33 meters above sea level (surveyed by SFWMD).

Some of the plots show a generally inverse relation between Q' and h-bar times *dh/dl*. However, the sparsity of data through the range of seepage values creates some uncertainty and the need for a full range of data to support these relations. In other instances, the relation between Q' and h-bar times *dh/dl* is not clearly defined by the data. This suggests that the relation defined by Darcy's equation is not sufficient to fully assess flow at these sites, and no attempt was made to compute a best-fit linear regression for these plots. Flow may be multidirectional, and variations in the hydraulic characteristics of the stratigraphic layering could interrupt direct flow paths between the wells and the channel. Additional data collected over a broader range of hydraulic conditions may be needed to adequately define the relation between seepage and the hydraulic gradient for these sites.

Measured seepage rates are proportional to relevant hydraulic gradients; however, the location and orientation of the gradients are difficult to determine from sparse measurements. Seepage rates may not relate to gradients measured between two particular locations, because the seepage flow is not forced by this particular gradient. It is quite reasonable to expect gradients near the river, such as the difference between the river stage and the in-channel piezometers, to correlate better with measured seepage rates than the gradients between the river stage and ground-water heads in the wells farther from the river. More head measurements would be needed to better define the seepage field.

Based on the elevation of the middepth well screens compared with the channel-bottom elevation, these wells were not used to compute *dh/dl* for the surficial aquifer system. The middepth well data are best used to compare with shallow well data to infer information about the site geology. If the shallow ground-water heads are similar and consistent over time and varying hydraulic conditions with the middepth ground-water heads, a confining unit between the two well screens may not be present, which could provide limited information about the depth of the surficial aquifer system in the vicinity of the site. Conversely, when the shallow ground-water heads are consistently different from the mid-depth ground-water heads, a confining unit may be present. This comparison may support the assumptions that the channel fully penetrates the aquifer and that flow from lower aquifers may be contributing to the surficial aquifer system and, thus, the channel.

Because little correlation was observed between Q' and h-bar times *dh/dl* in figure 4, and measured seepage rates varied greatly among seepage meters at a single site, seepage at individual seepage meters was plotted as a function of the hydraulic gradient (figs. 6-15). As stated previously, the hydraulic gradient computed between the shallow wells and channel is nearly horizontal. Therefore, it is considered a horizontal hydraulic gradient. Between the middepth wells and channel, the hydraulic gradient has both a horizontal and vertical component. As with the plots in figure 4, the expected inverse relation between seepage and *dh/dl* is evident in some of the plots. However, the sparsity of data and the low range of the hydraulic gradient create uncertainty about the relations.

Belanger (1999) measured and reported the difference in water level in the channel and in the shallow and deep piezometers in the channel at each site (table 2). The slope of the hydraulic gradient between the river and piezometer and the seepage plot is the vertical hydraulic conductivity. Dividing this by the vertical distance between the riverbed and piezometer location yields the leakage coefficient. It must be kept in mind that the leakage coefficient is scale dependent; the values determined are based on the aquifer head measured at the piezometer depth. Attempts at determining larger scale leakage coefficients by way of the head gradient from the river to the well clusters showed insufficient correlation to determine a leakage coefficient. This suggests that leakage is heavily controlled by near-river aquifer properties.

Table 2. Observed seepage and in-channel piezometer data for the Caloosahatchee River Basin sites

[Data from Belanger (1999); see footnote 1. Time range reported by T.V. Belanger (Florida Institute of Technology, oral commun., 1999). Location: ND1, nearshore deep at seepage meter 1; NS1, nearshore shallow at seepage meter 1; NS2, nearshore shallow at seepage meter 2; ND2, nearshore deep at seepage meter 2; FS3, farshore shallow at seepage meter 3. Dashes indicate not measured or not applicable]

Date	Piezometer				Time range for seepage measurement (hours)	Seepage rate (milliliter per square meter-hour)					
	Location	Inside water level (meters)	Outside water level (meters)	Water-level change (meters)		Meter 1	Meter 2	Meter 2A	Meter 3	Meter 4	Meter 5
Site 1											
10/23/98	ND1	0.56	0.58	0.02	1300-1700	499	163	--	111	--	--
12/4/98		.62	.62	.00	1400-1500	0	-74	--	236	--	--
					1500-1700	57	-65	--	143	--	--
1/8/99		.62	.62	.00	1500-1700	-145	84	--	-103	--	--
1/9/99-1/10/99		--	--	--	1700-0830	21	32	--	38	--	--
Site 2											
10/23/98	ND1	.29	.30	.01	1400-1700	--	158	--	46	36	106
		.39	.39	.00							
10/24/98		.23	.24	.01	0900-1400	96	93	--	15	-15	103
12/5/98		.34	.36	.02	1200-1400	39	137	--	29	153	28
					1400-1700	108	153	--	35	-28	101
1/8/99		.30	.29	-.01	1030-1315	-51	-110	--	11	21	32
					1330-1530	-16	-8	--	12	15	102
Site 3											
10/23/98	NS1	.35	.37	.02	1500-1800	1,421	135	--	1,489	--	--
	ND1	.49	.48	-.01							
10/24/98	NS1	.27	.27	.00	1500-1700	283	34	--	212	--	--
	ND1	.37	.39	.02							
12/5/98[1]	NS1	.53	.54	.01	1000-1100	296	0	--	434	--	--
					1100-1300	336	43	--	42	--	--
	ND1	.42	.45	.03	1000-1100	296	0	--	434	--	--
					1100-1300	336	43	--	42	--	--
1/8/99[1]	--	--	--	--	1100-1200	227	10	--	--	--	--
1/9/99[1]	--	--	--	--	1100-1330	-176	0	--	--	--	--
Site 4											
10/23/98	NS2	.34	.42	.08	1600-1800	1,200	>3,500	>3500	>3,500	--	--
	ND2	.53	.62	.09							
	FS3	.08	.12	.04							
10/24/99	NS2	.42	.50	.08	1600-1700	312	6,600	>10,000	7,200	--	--
	ND2	.62	.70	.08							
	FS3	.16	.20	.04							
12/4/98[1]	ND2	1.34	1.51	0.17	0800-0840	206	12,100	16,900	14,640	--	--
					0840-0915	929	13,040	21,900	18,480	--	--
					1200-1300	1,170	13,500	21,429	--	--	--
1/8/99[1]	ND2	.65	.70	.05	1100-1200	0	3,375	6,360	5,207	--	--
1/9/99[1]	ND2	.62	.70	.08	1200-1300	42	3,040	5,960	4,446	--	--
Site 5											
10/24/98	NS1	.05	.04	-.01	1200-1400	-710	94	--	45	--	--
	ND2	.20	.18	-.02							
12/4/98	--	--	--	--	1200-1600	--	46	--	23	--	--
					1200-1600	--	-66	--	-81	--	--
12/5/98	NS1	.81	.84	.03	1400-1600	828	62	--	21	--	--
	ND2	.93	.97	.04							

Table 2. Observed seepage and in-channel piezometer data forthe Caloosahatchee River Basin sites (Continued)

[Data from Belanger (1999); see footnote 1. Time range reported by T.V. Belanger (Florida Institute of Technology, oral commun., 1999). Location: ND1, nearshore deep at seepage meter 1; NS1, nearshore shallow at seepage meter 1; NS2, nearshore shallow at seepage meter 2; ND2, nearshore deep at seepage meter 2; FS3, farshore shallow at seepage meter 3. Dashes indicate not measured or not applicable]

Date	Piezometer				Time range for seepage measurement (hours)	Seepage rate (milliliter per square meter-hour)					
	Location	Inside water level (meters)	Outside water level (meters)	Water-level change (meters)		Meter 1	Meter 2	Meter 2A	Meter 3	Meter 4	Meter 5
1/8/99	--	--	--	--	1600-1700	-300	32	--	43	--	--
1/8-9/99	--	--	--	--	1700-1000	-30	19	--	19	--	--
Site 6											
10/24/98	NS2	.44	.46	.02	0900-1200	169	>4,000	--	0	857	--
	FS3	.30	.33	.03	1200-1330	159	>7,500	--	192	844	--
12/4/98	NS2	.65	.67	.02	1100-1200	240	14,000	--	0	800	--
	FS3	.50	.54	.03	1600-1700	155	8,950	--	0	600	--
12/5/98	--	--	--	--	1500-1600	218	8,625	--	97	554	--
1/9/99	NS2	.46	.49	.03	0900-1000	82	5,972	--	39	388	--
					1000-1100	107	6,071	--	71	400	--
	FS3	.64	.68	.02	0900-1000	82	5,972	--	39	388	--
					1000-1100	107	6,071	--	71	400	--

[1]Seepage data collected at sites 3 and 4 were revised (T.V. Belanger, Florida Institute of Technology, oral commun., 1999).

Seepage as a function of the hydraulic gradient is plotted for selected in-channel piezometers from the nearby seepage meter (fig. 16). A best-fit regression line having a Y intercept of zero was drawn for the four in-channel piezometer/seepage meter pairs, with more than two data points and a correlation coefficient (R^2 value) greater than 0.50. The vertical hydraulic conductivity (estimated by the best-fit linear regression of the data in fig. 16), nearby seepage meter, depths, and sediment descriptions for sites 1 to 4 are listed below:

Site No.	Piezometer depth below channel-bottom (meters)	Nearby seepage meter	Sediment description (Belanger, 1999)	Depth to hardpan (centimeters)	Computed vertical hydraulic conductivity (meters per day)
1	3.0	1	Sand	15	1.71
2	1.5	1	Sand and limestone	15	.25
3	1.5	1	Shelly sand	50	.50
4	2.3	2	Organic mud and sand	60	3.93

Although these results are limited, the relative magnitude of computed conductivities are generally consistent with the sediment description given above. Additional data collected over a broader range of site conditions would provide a better relation of hydrologic conditions and sediment description to estimates of channel-bottom permeabilities.

RESULTS

Seepage data collected by Belanger suggest that ground-water seepage directly to the Caloosahatchee River is not a significant water source during the dry season. Extremely high seepage rates observed at two of the four sites (sites 4 and 6) on agricultural canals in the Caloosahatchee River Basin indicate a potential for significant ground-water seepage to these canals. The highly variable seepage rates observed among the sites suggest that site-specific or local conditions, such as localized pumping or nearby irrigation, control surface-water/ground-water interaction. Variable seepage rates among seepage meters at a single site suggest that even smaller scale conditions, such as the irregular permeability of the underlying limestone, affect surface-water/ground-water interactions. Large- and small-scale site conditions likely interact to produce the seepage rates observed at these sites.

The sampling was done during a generally dry period. If seepage data also were collected during the wet season, the significance of ground-water seepage to the Caloosahatchee River and the agricultural canals could be better defined.

Reported seepage rates into the Caloosahatchee River converted to seepage fluxes are generally less than 0.25 centimeters per day. This flux occurs over the relatively small area of river bottom. Therefore, based on the results of this analysis, seepage into the Caloosahatchee River can be considered negligible in hydrologic models of the basin. However, seepage fluxes into the canals are sometimes three orders of magnitude higher than into the Caloosahatchee River. Therefore, seepage fluxes into these canals are significant and cannot be ignored in hydrologic models of the basin.

Plotting the seepage as a function of the hydraulic gradient using ground-water heads at nearby wells did not reveal strong relations that could be used to estimate seepage rates along channel reaches or over a range of hydrologic conditions. Additionally, plots of seepage rates and ground-water heads over time do not explain the variable response in seepage rates for meters at a single site. Some seepage meters consistently measured little or no seepage, whereas other seepage meters showed highly variable rates over time with no corresponding variability in ground-water heads, channel stages, or rainfall input. These observations indicate that other factors, such as irregular limestone permeability, local pumping, and irrigation, could influence surface-water/ground-water interactions at these sites.

The hydraulic conductivity of the channel-bottom sediments was estimated at four of the sites using seepage data collected by Belanger (1999); results ranged from 0.25 to 1.71 meters per day. Plots of the limited data suggest that some relation is apparent between seepage and the hydraulic gradient of the sediment. Seepage data collected over a broader range of hydraulic gradients would improve or verify these relations.

Results of this analysis highlight the variability and complexity of surface-water/ground-water interactions in the Caloosahatchee River Basin. Although analysis of the data collected here may not adequately describe the surface-water/ground-water system, results could help guide future efforts in this basin and others in southern Florida.

REFERENCES CITED

Belanger, T.V., 1999, Caloosahatchee River groundwater/surface water interaction monitoring study: Final report submitted by the Florida Institute of Technology to the South Florida Water Management District, 12 p.

Cunningham, K.J., Locker, S.D., Hine, A.C., Bukry, David, Barron, J.A., and Guertin, L.A., 2001, Surface-geophysical characterization of ground-water systems of the Caloosahatchee River Basin, southern Florida: U.S. Geological Survey Water-Resources Investigations Report 01-4084, 76 p.

Figures

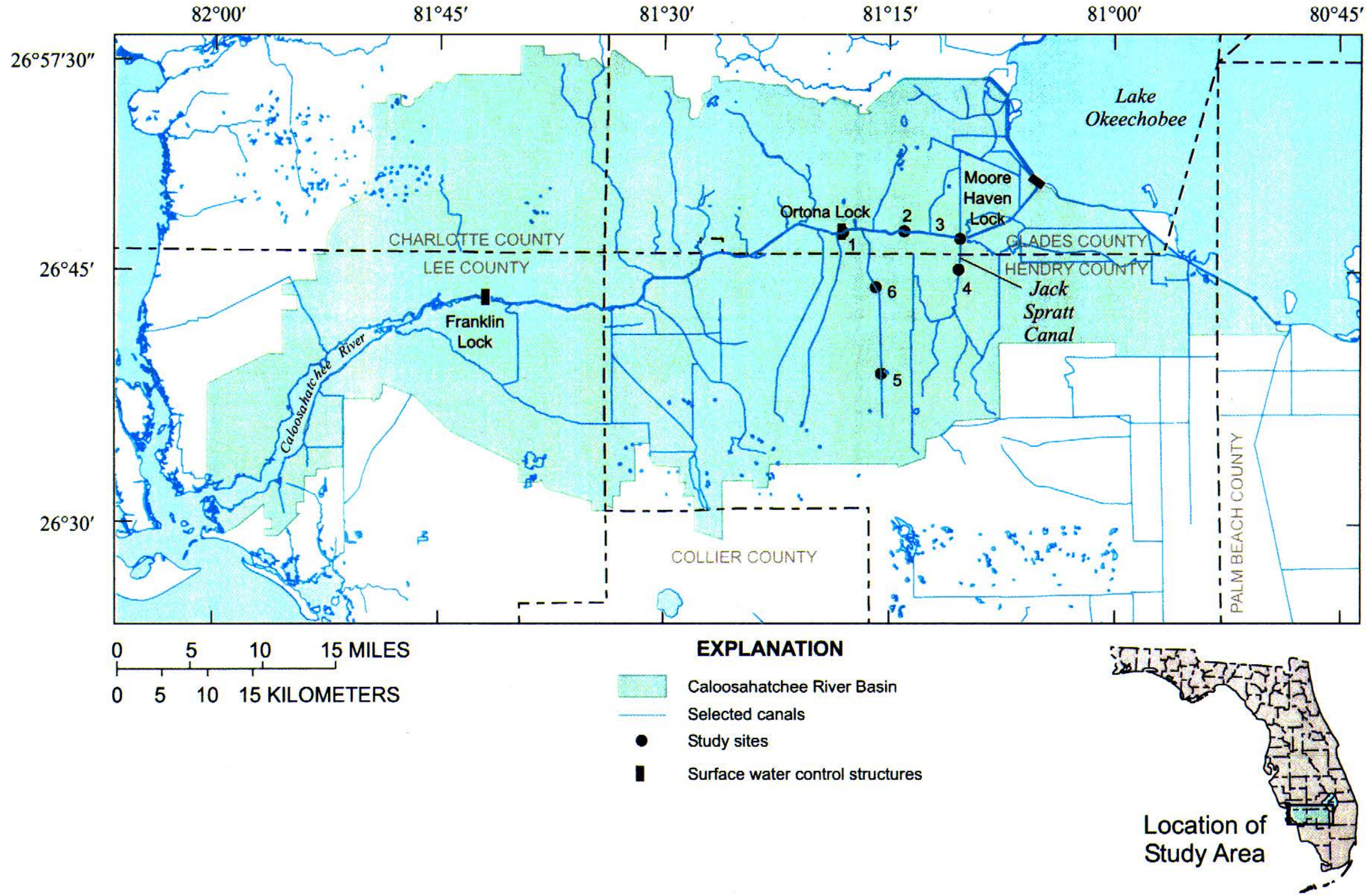


Figure 1. Location of study sites in the Caloosahatchee River Basin.

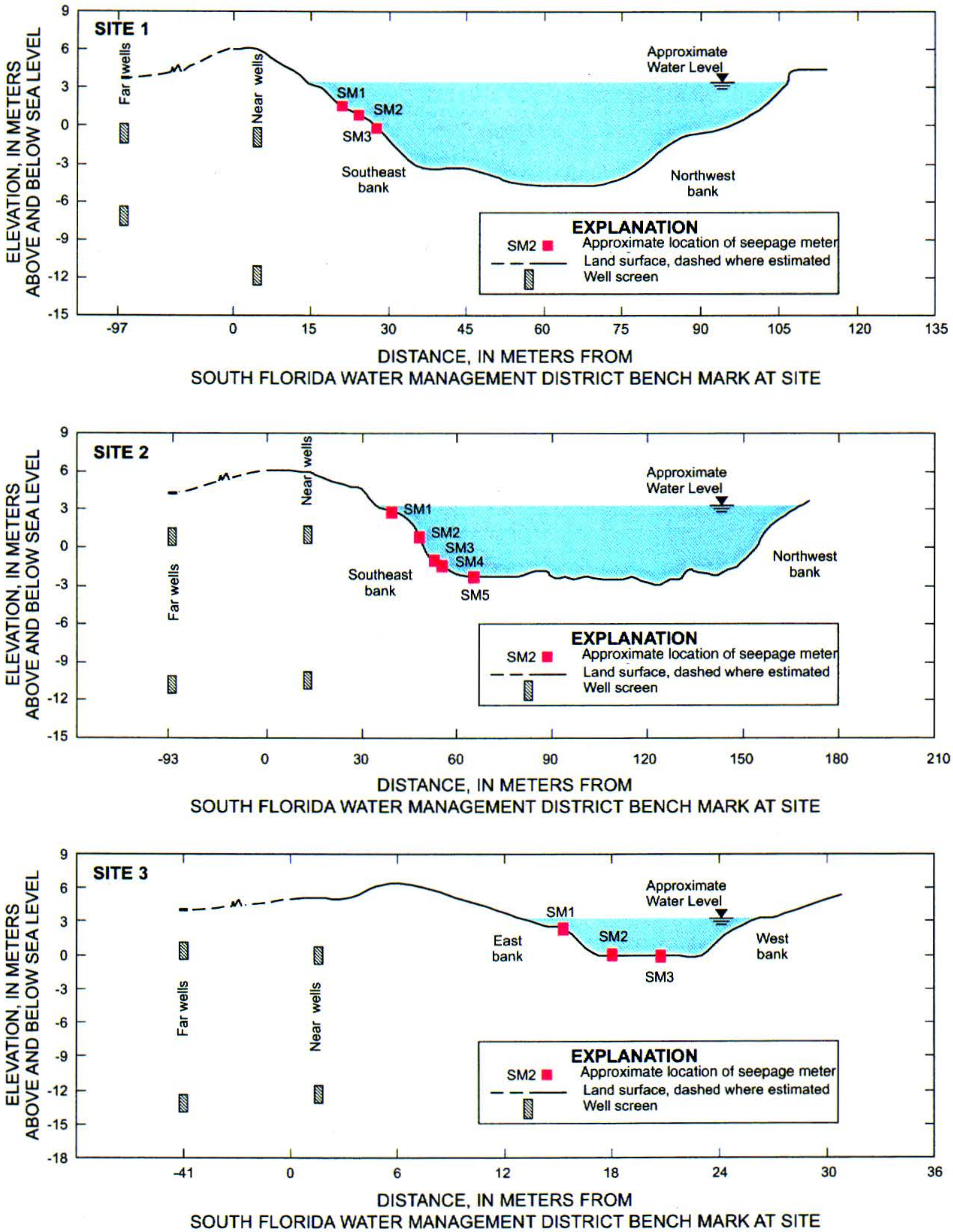


Figure 2. Channel cross sections showing location of seepage meters and ground-water wells at the study sites in the Caloosahatchee River Basin.

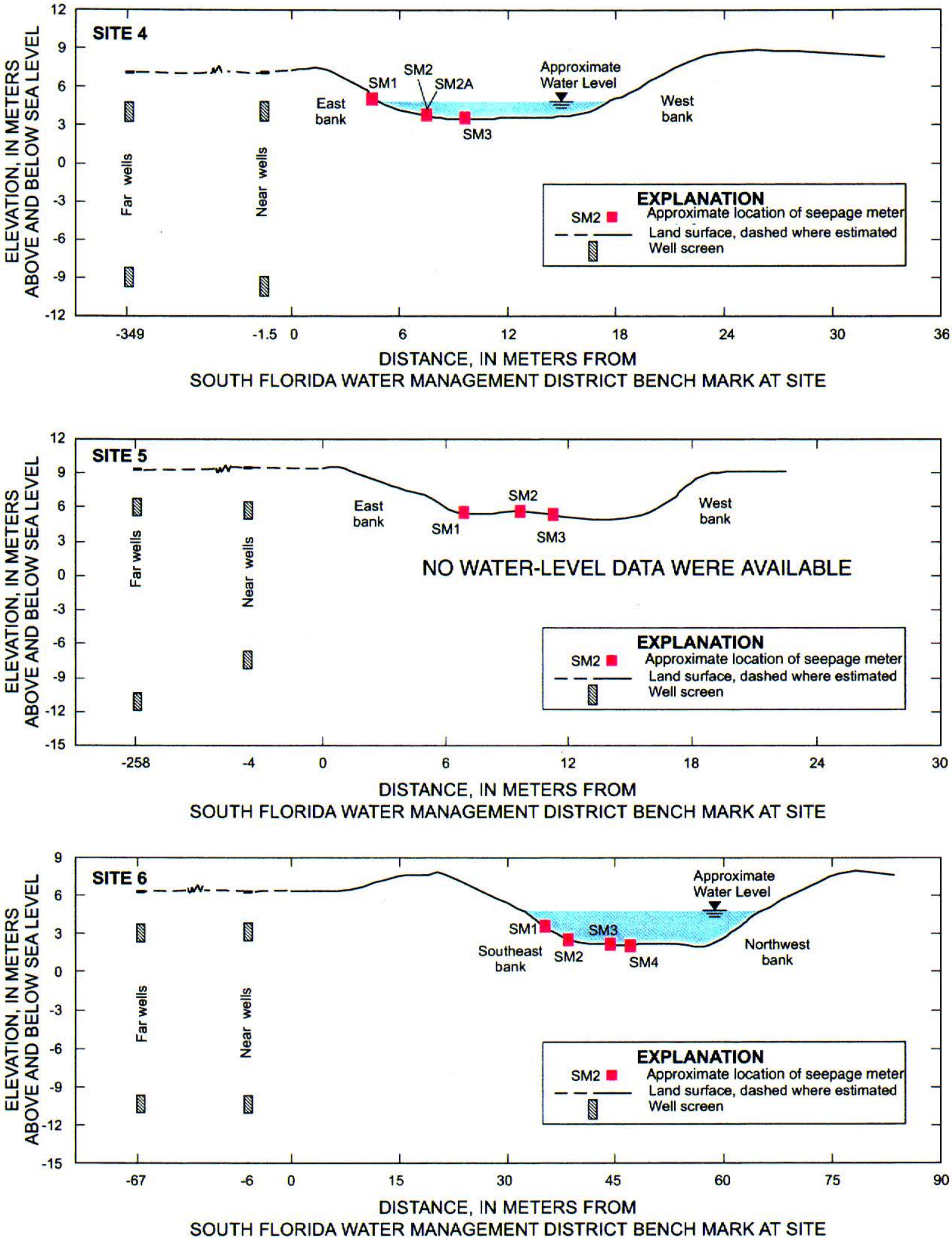


Figure 2. Channel cross sections showing location of seepage meters and ground-water wells at the study sites in the Caloosahatchee River Basin (continued).

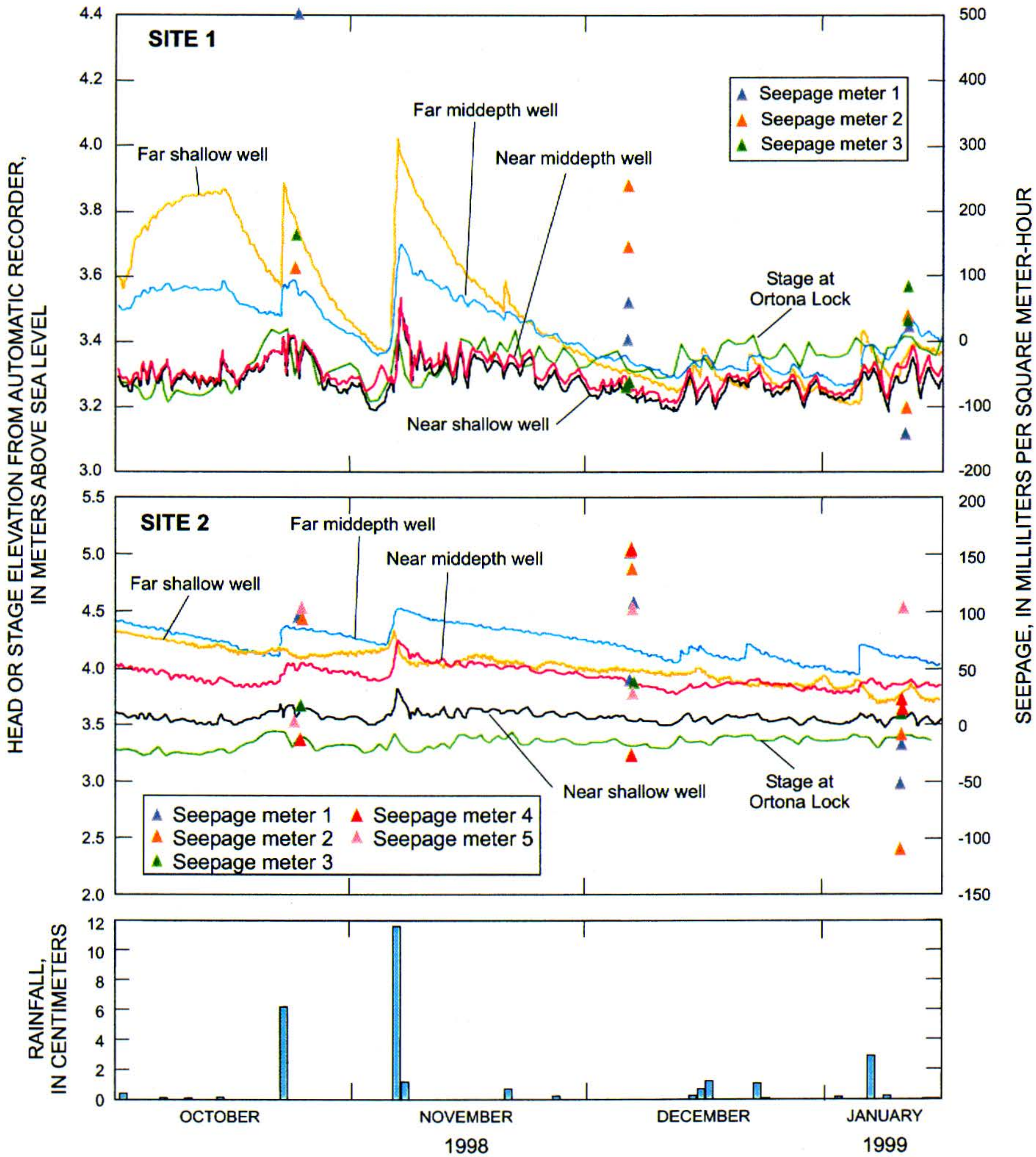


Figure 3. Seepage and ground-water head or channel stage elevation from an automatic recorder for the Caloosahatchee River Basin sites, October 1, 1998 to January 15, 1999.

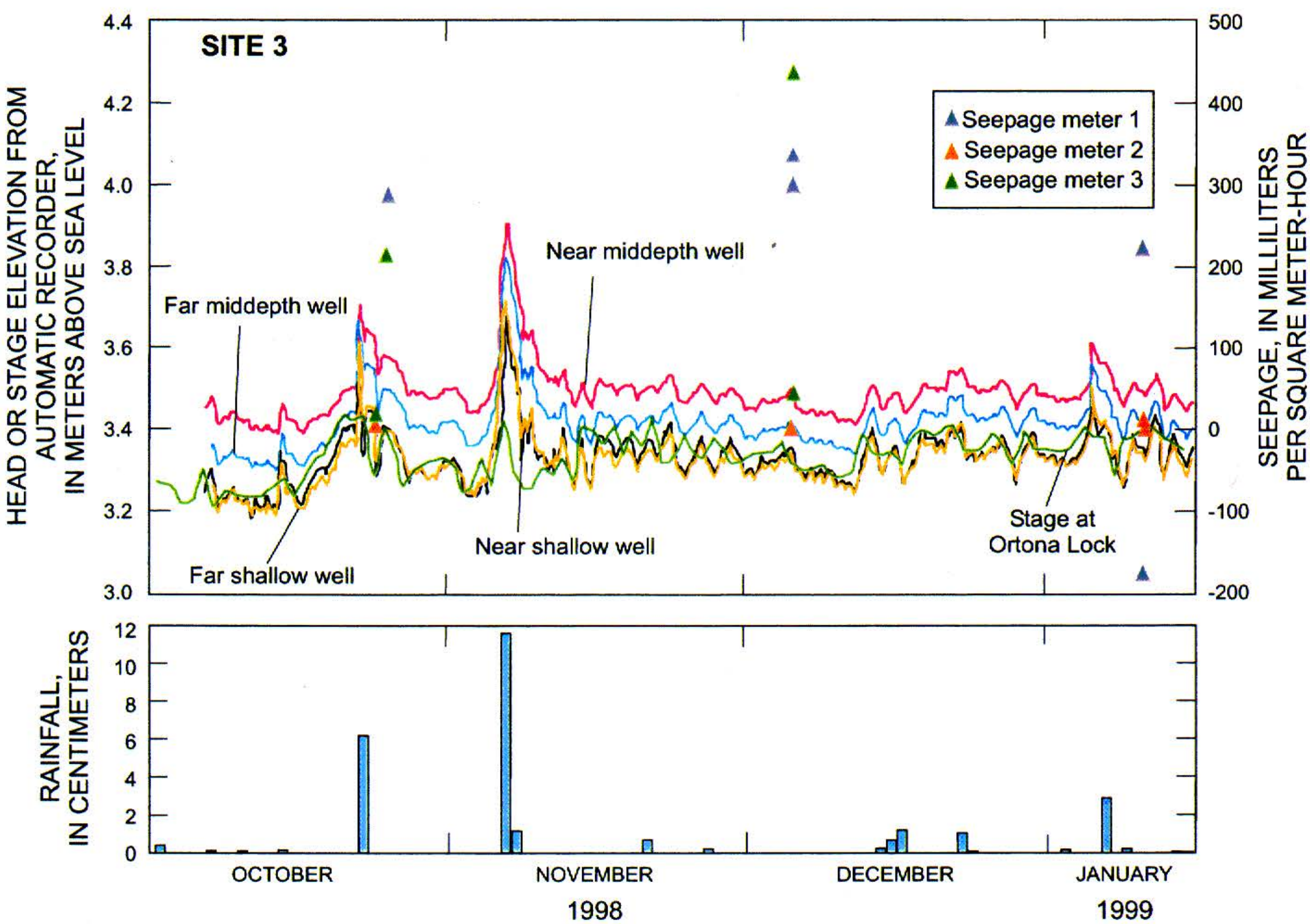


Figure 3. Seepage and ground-water head or channel stage elevation from an automatic recorder for the Caloosahatchee River Basin sites, October 1, 1998 to January 15, 1999 (continued).

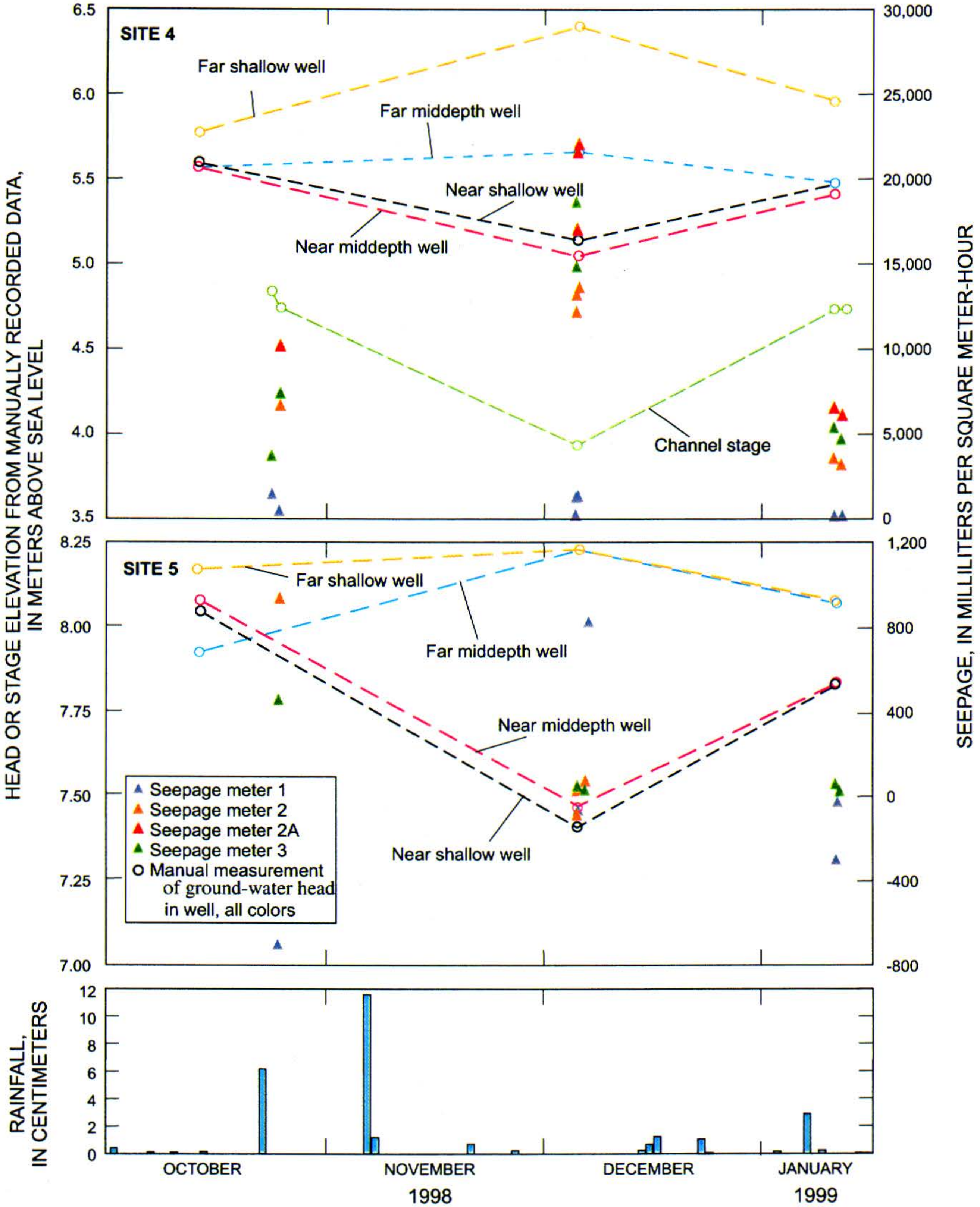


Figure 4. Seepage and ground-water head or channel stage elevation from manually recorded data for the Caloosahatchee River Basin sites, October 1, 1998 to January 15, 1999.

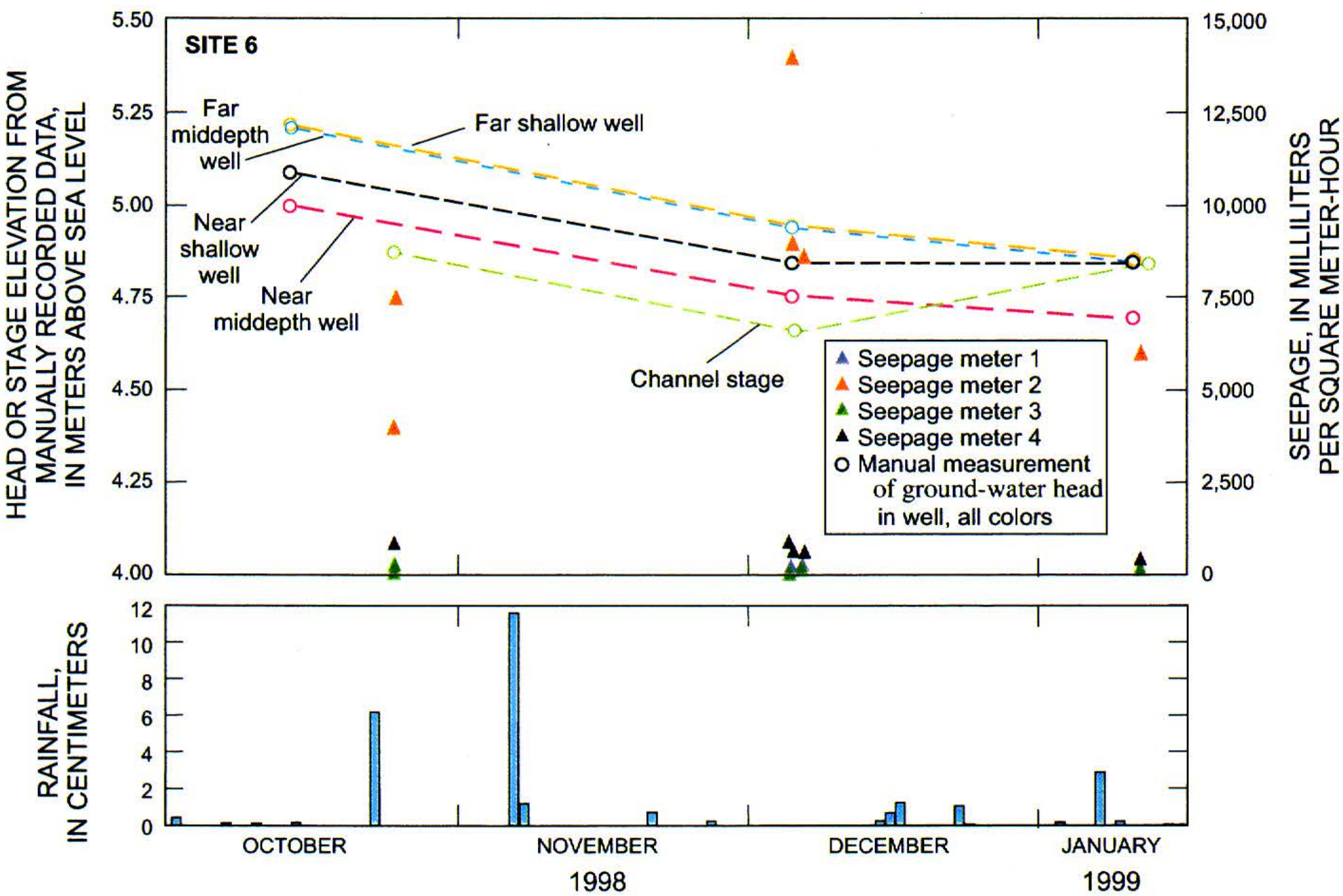


Figure 4. Seepage and ground-water head or channel stage elevation from manually recorded data for the Caloosahatchee River Basin sites, October 1, 1998 to January 15, 1999 (continued).

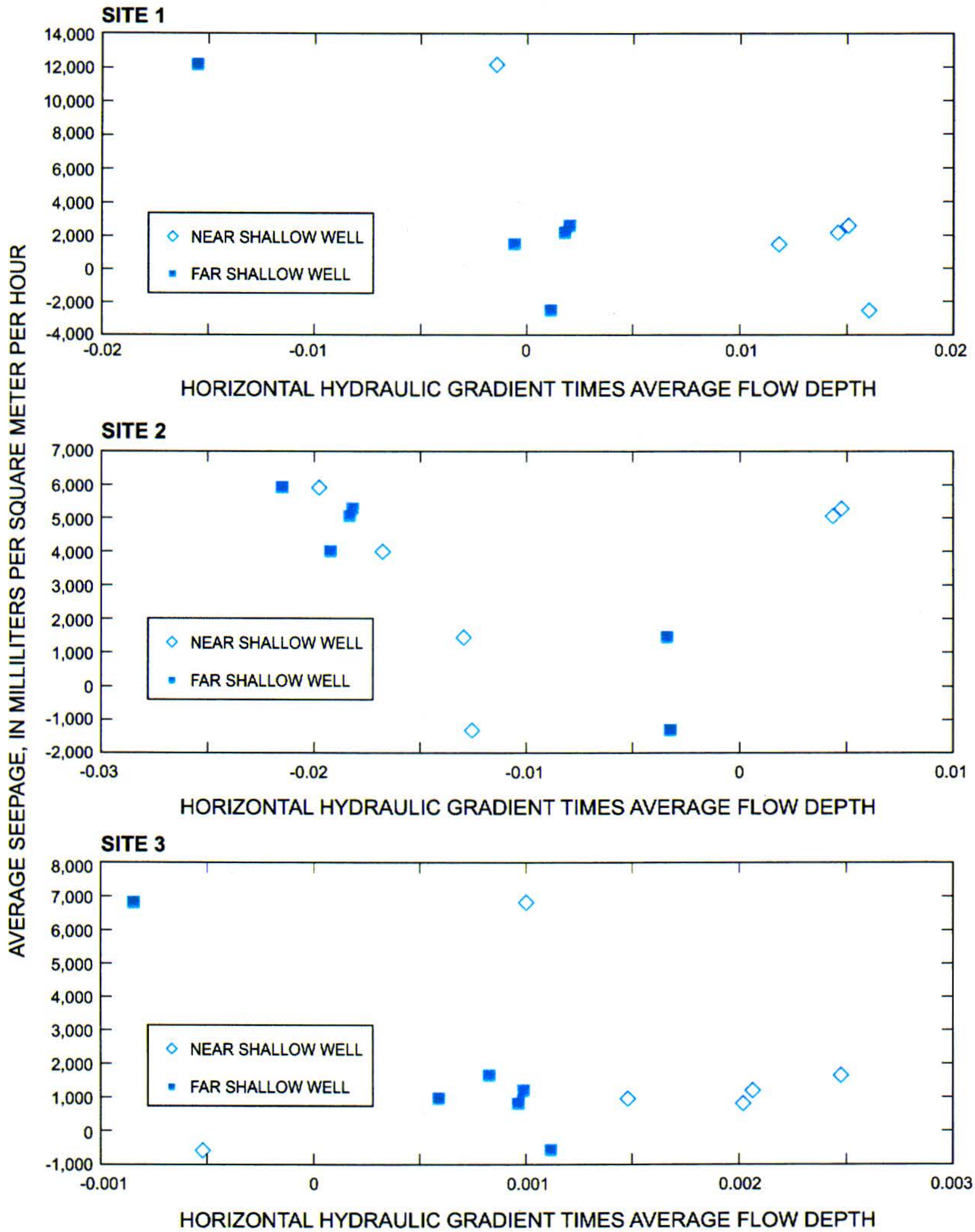


Figure 5. Average seepage as a function of the horizontal hydraulic gradient times average flow depth between channel and shallow wells at each site. Site 5 was not plotted because no channel stage data were available.

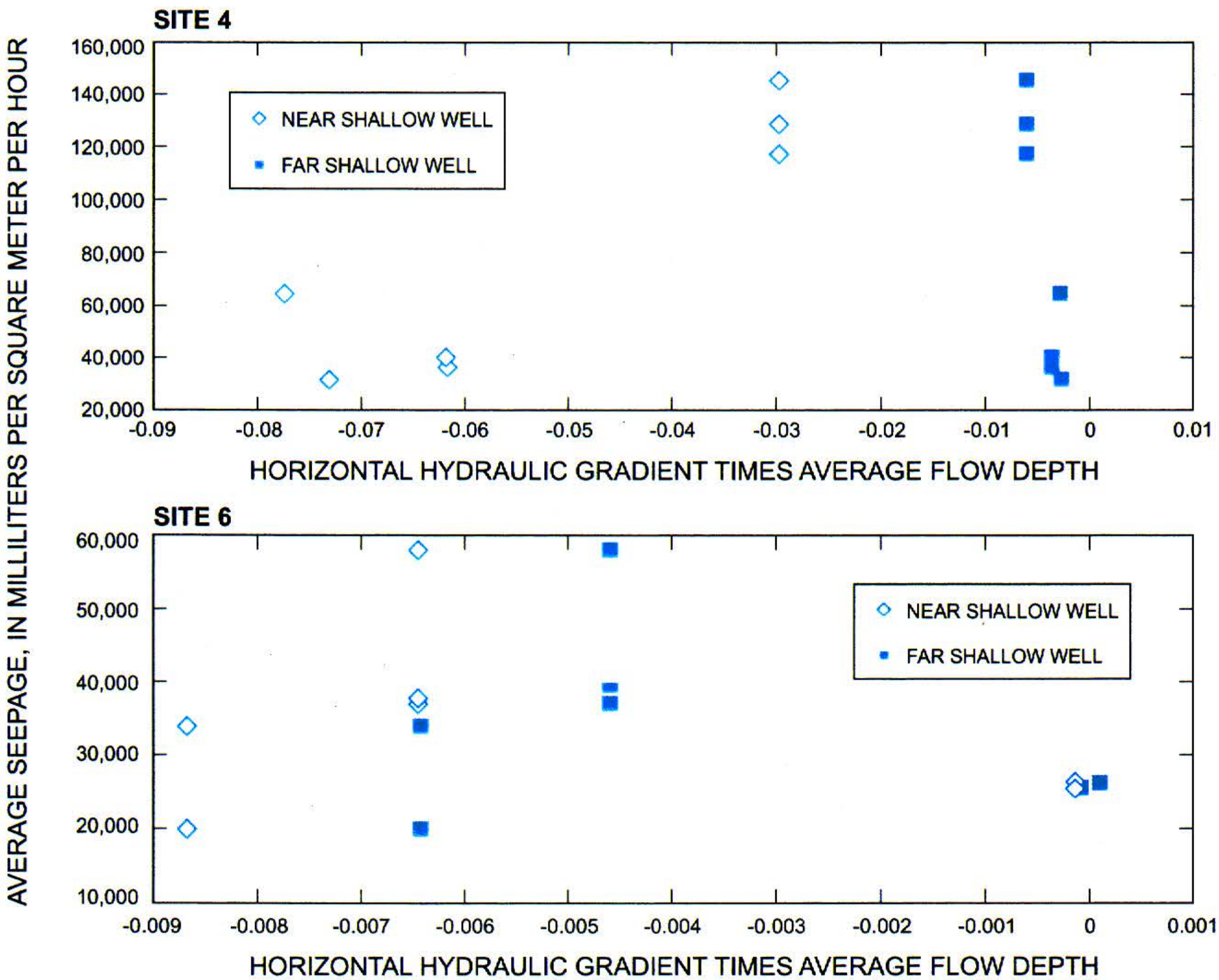


Figure 5. Average seepage as a function of the horizontal hydraulic gradient times average flow depth between channel and shallow wells at each site. Site 5 was not plotted because no channel stage data were available (continued).

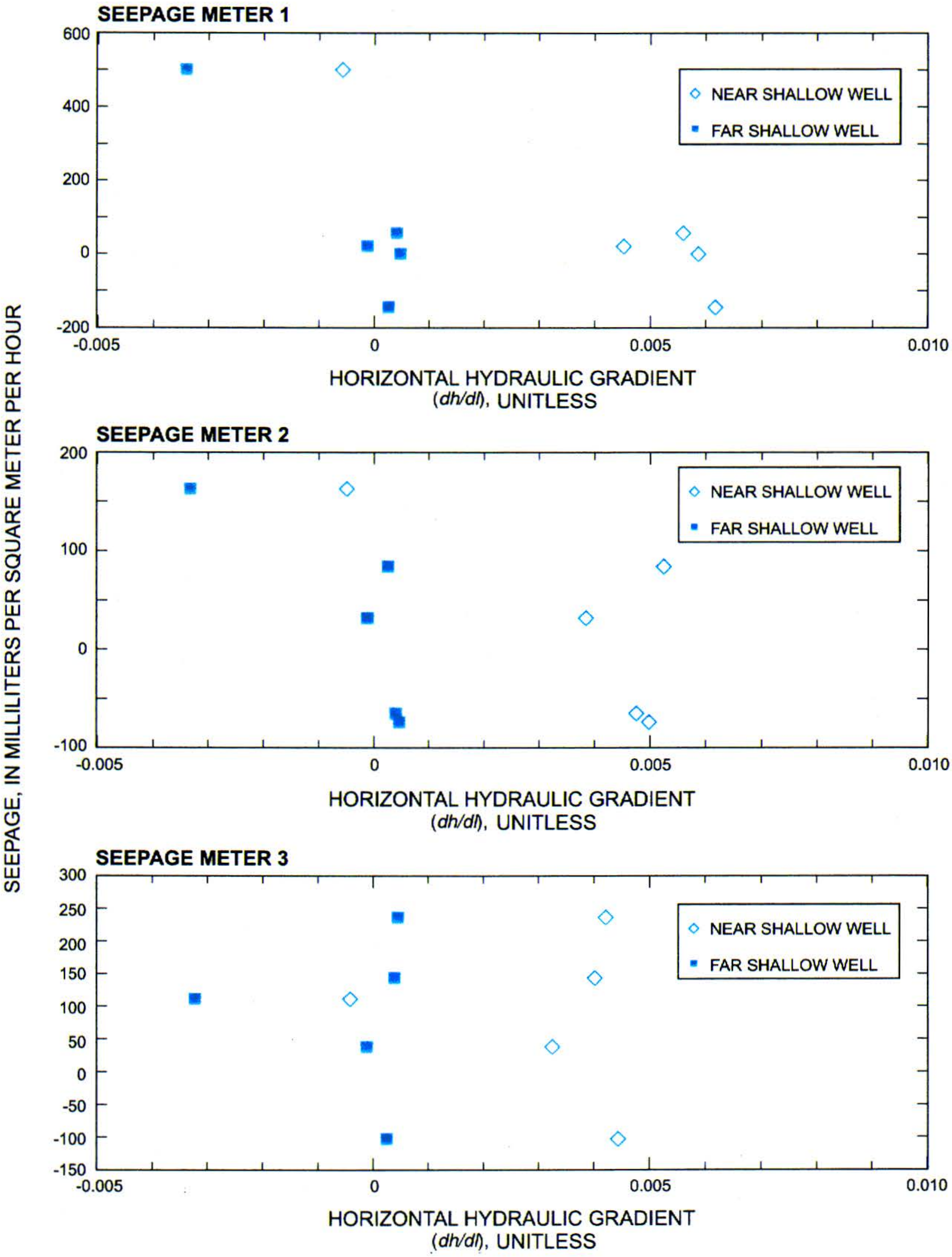


Figure 6. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 1.

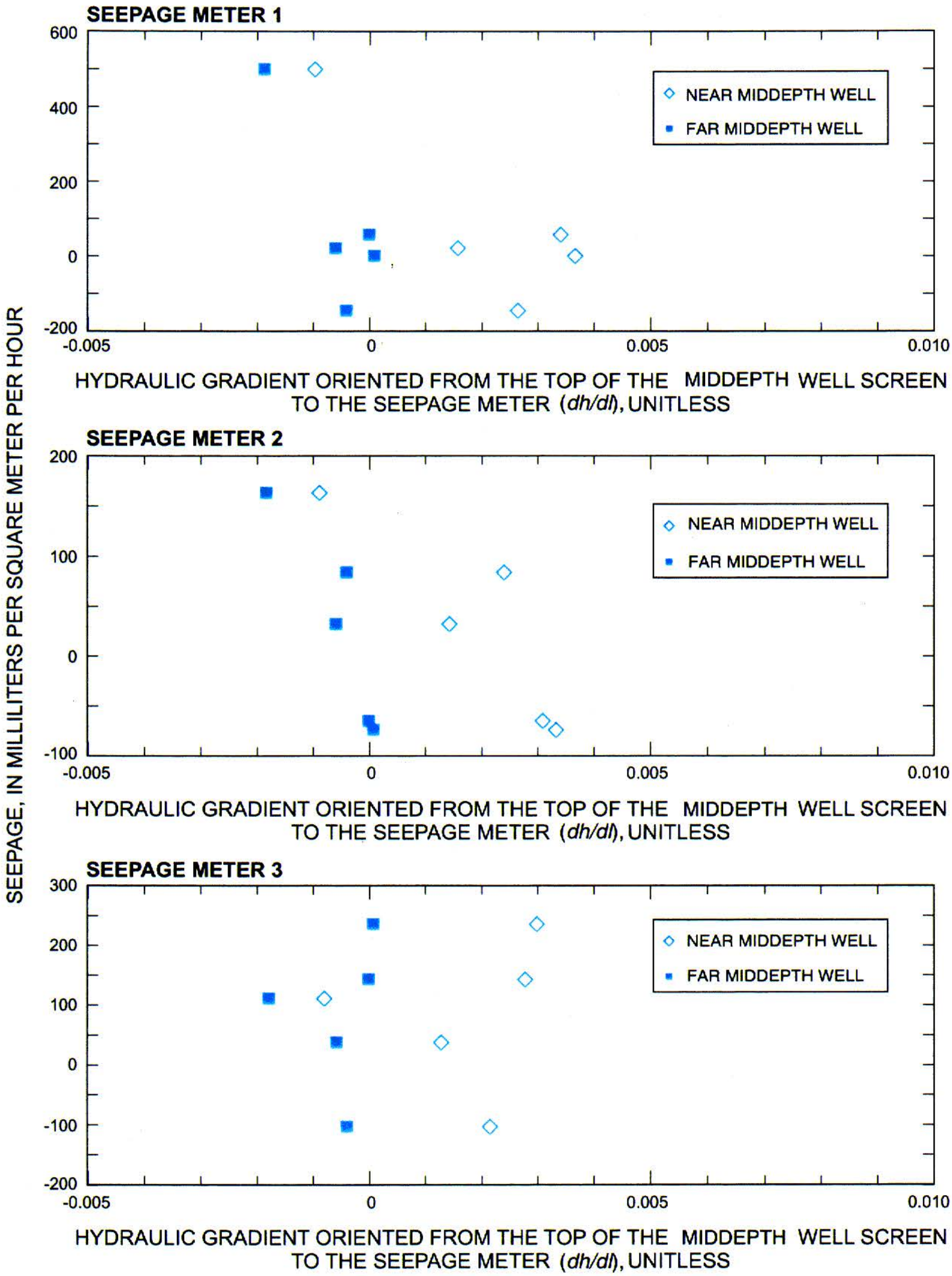


Figure 7. Seepage as a function of the hydraulic gradient between each meter and middepth wells at site 1.

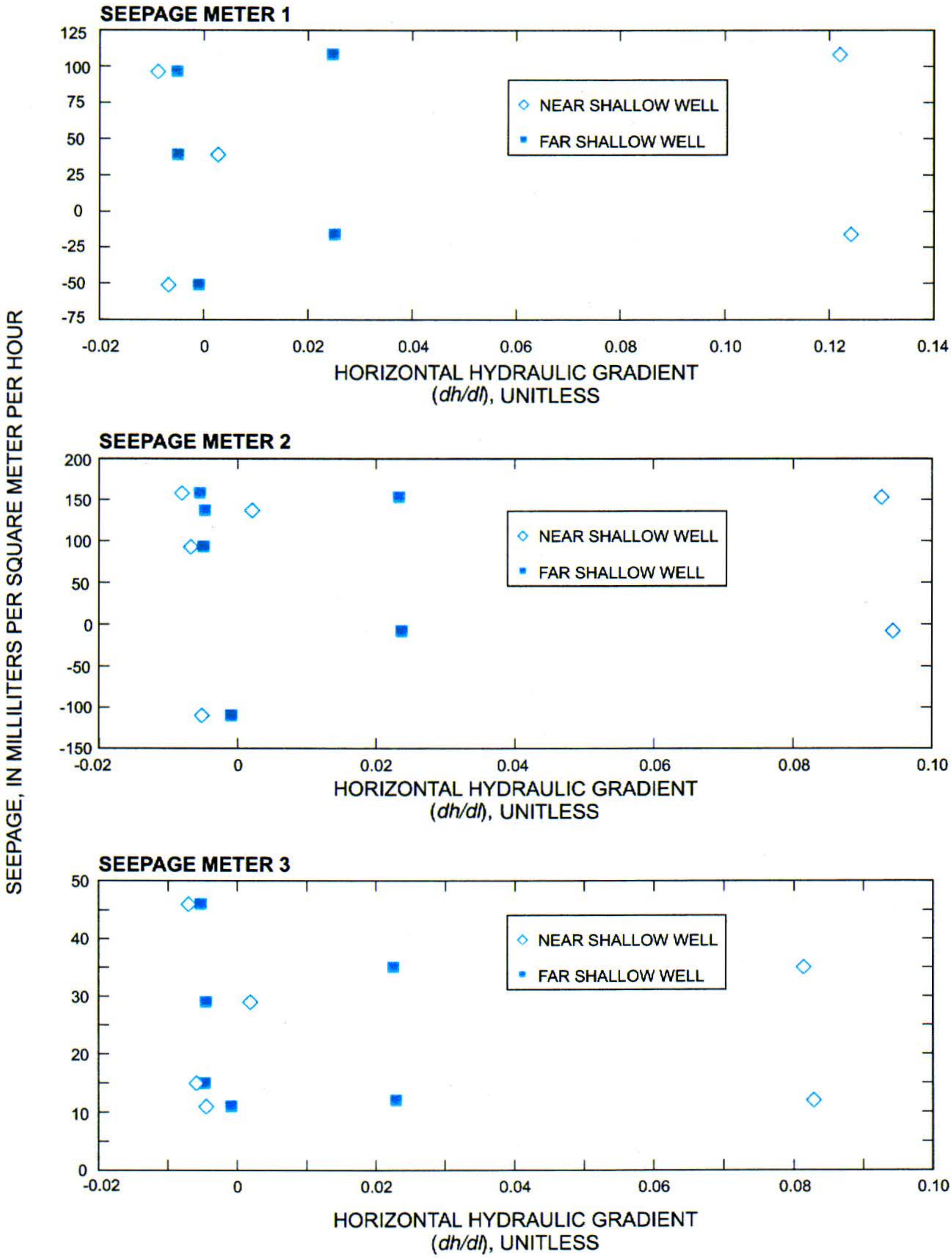


Figure 8. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 2.

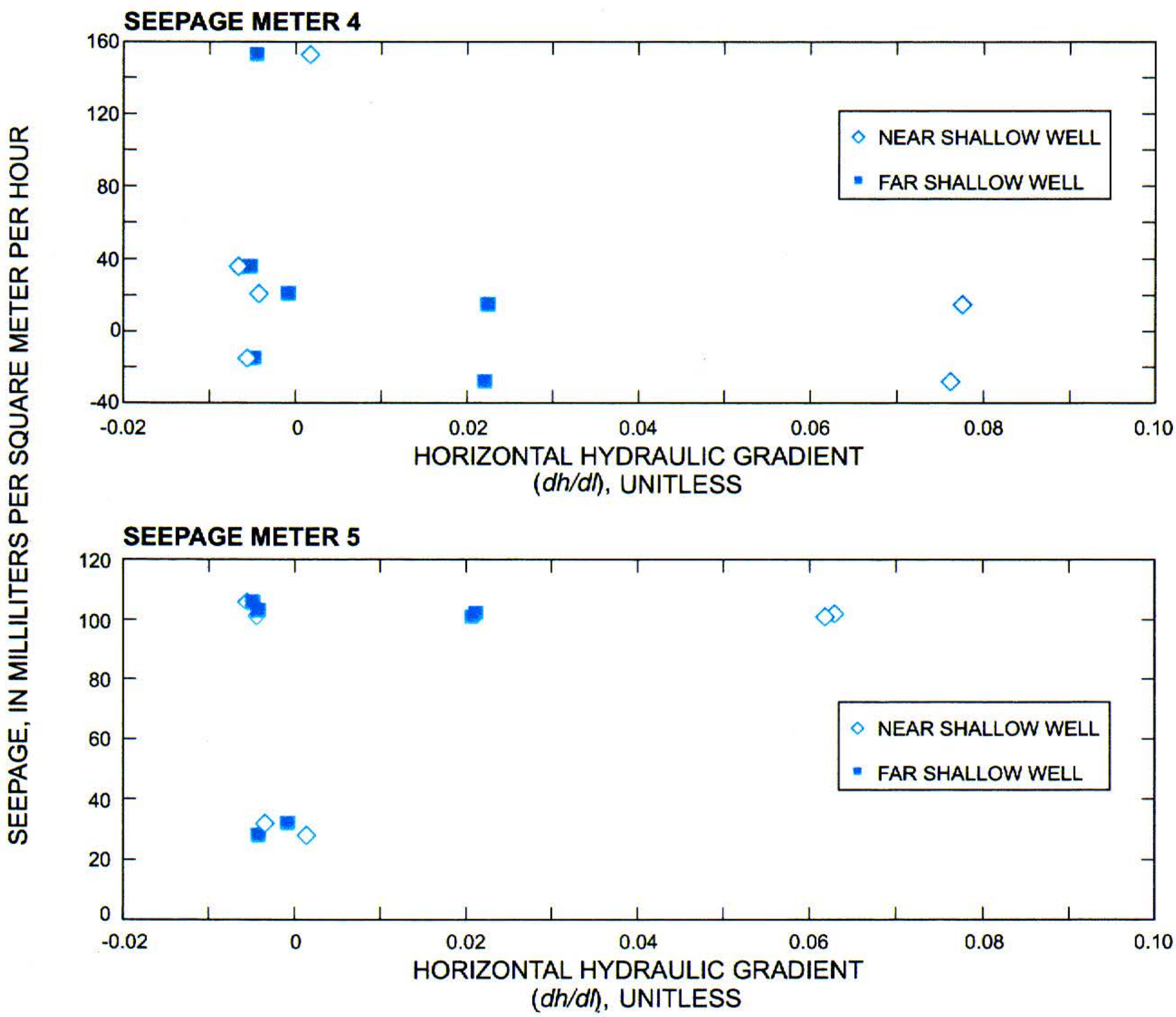


Figure 8. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 2 (continued).

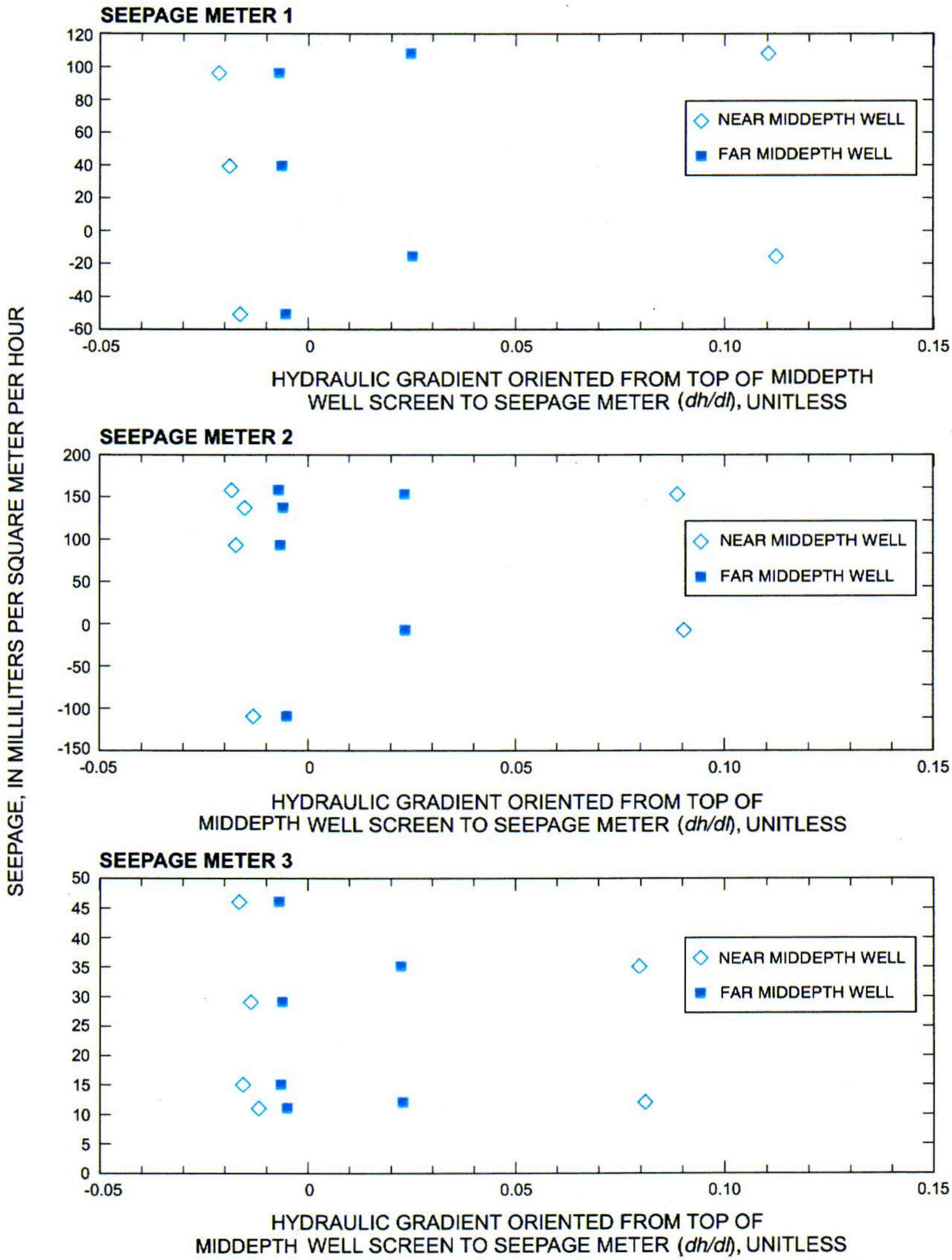


Figure 9. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 2.

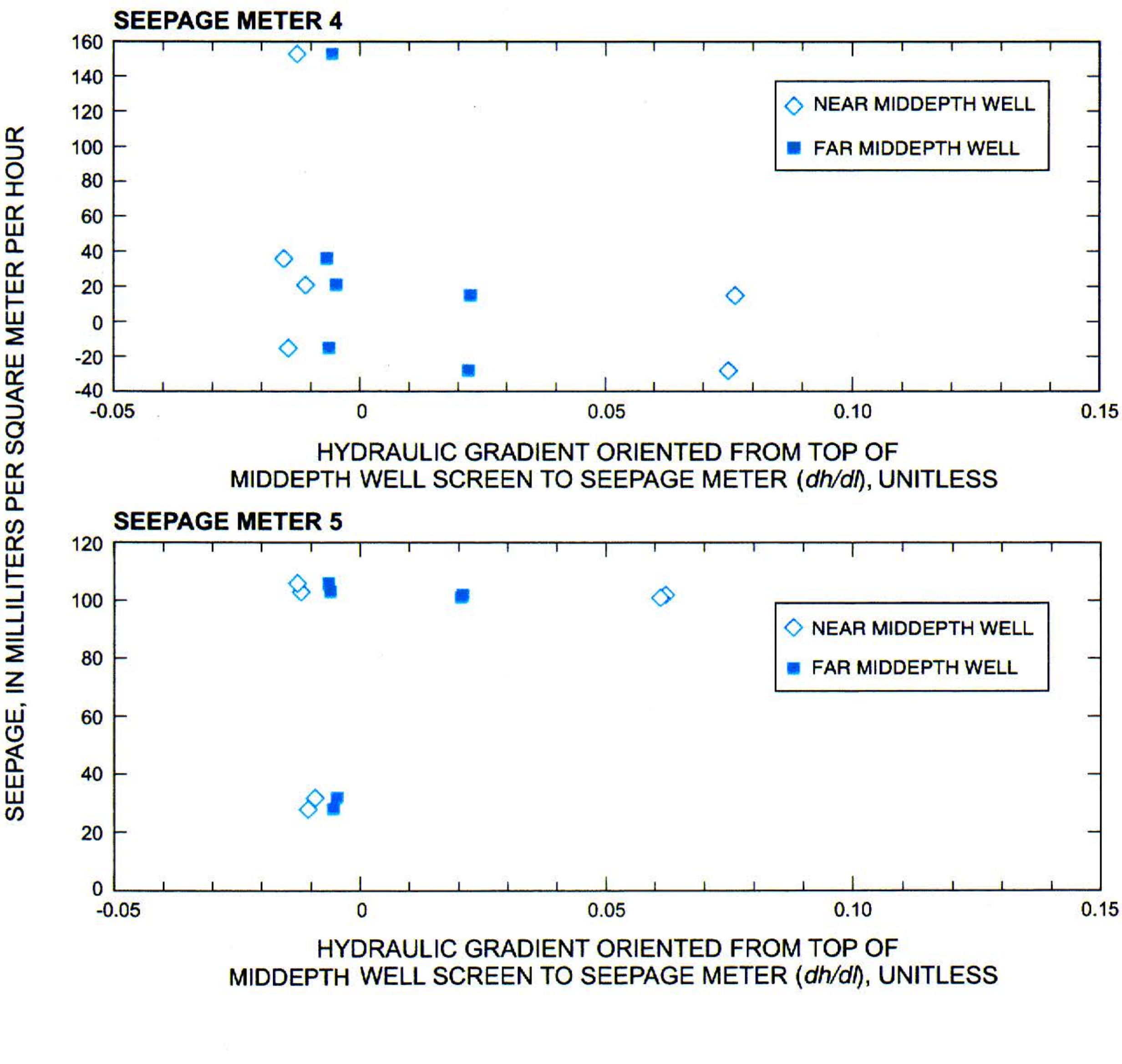


Figure 9. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 2 (continued).

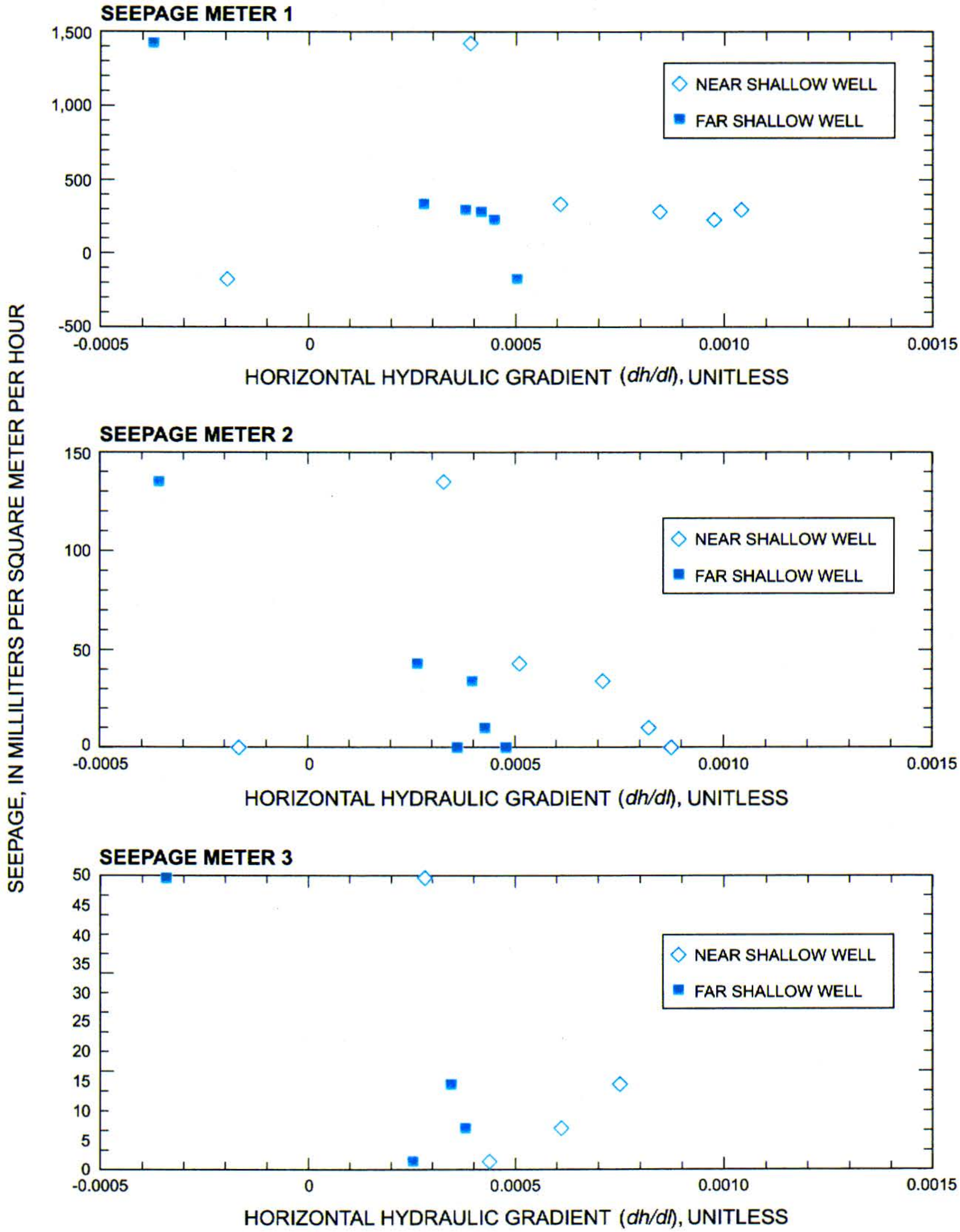


Figure 10. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 3.

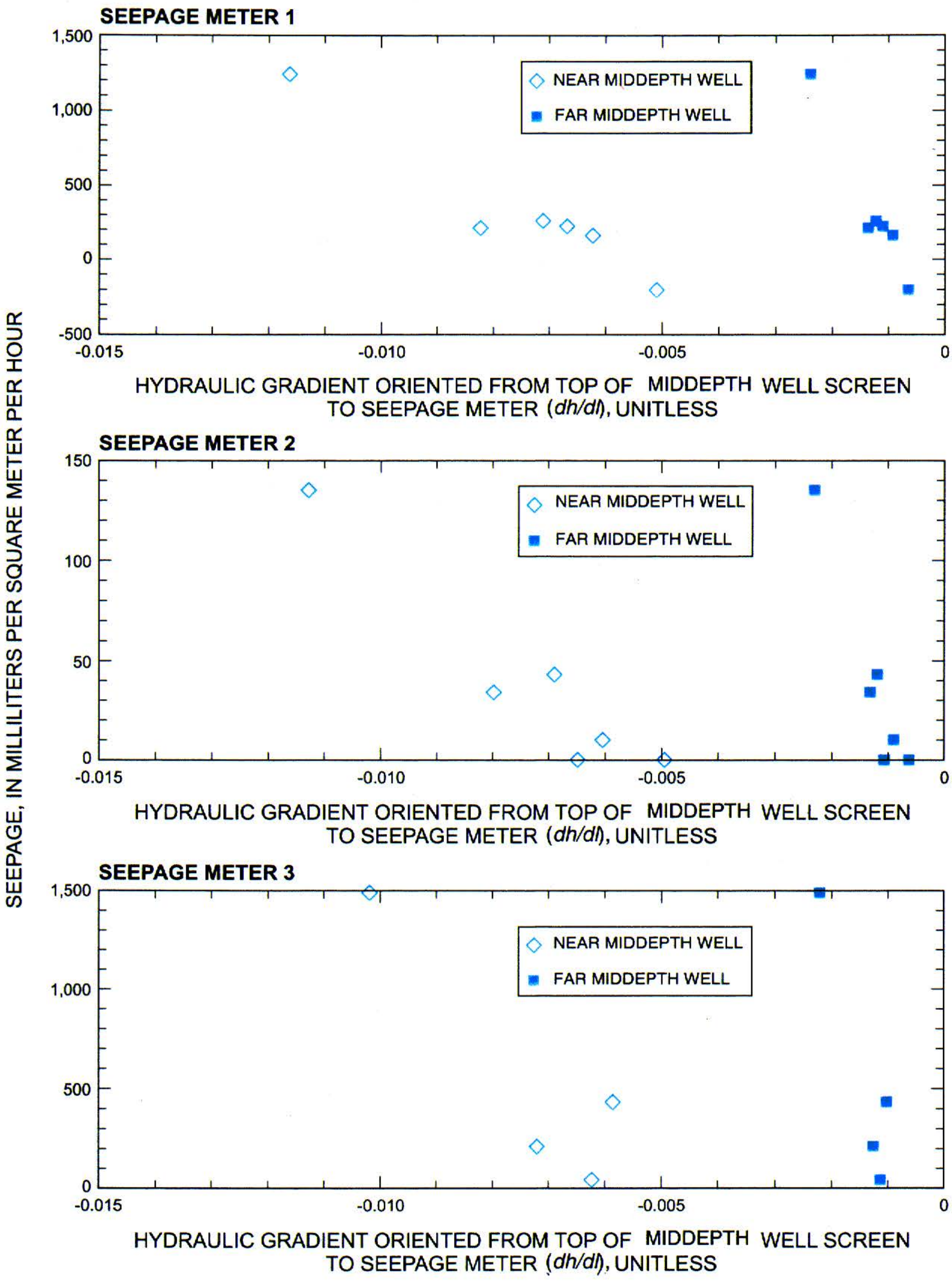


Figure 11. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 3.

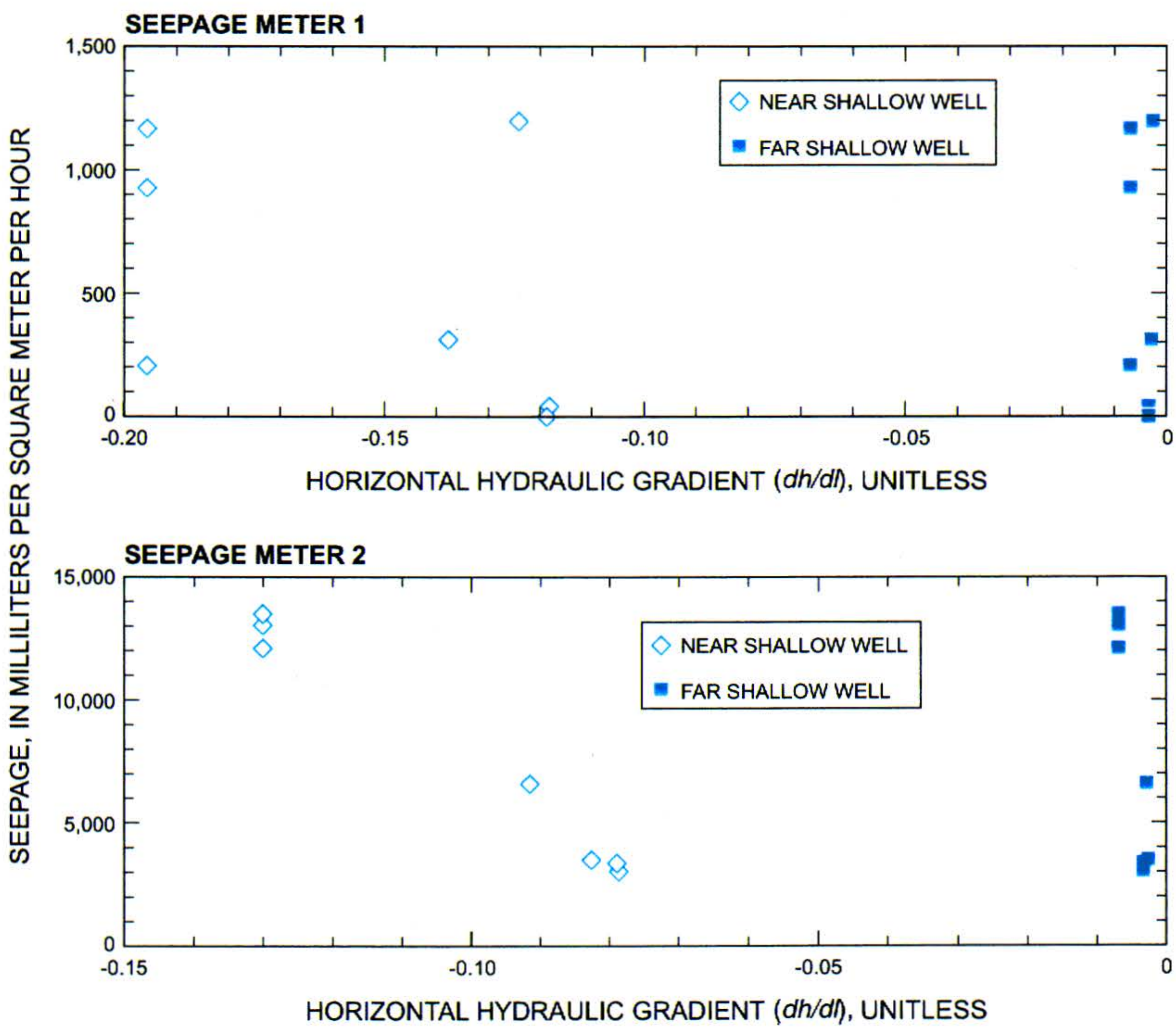


Figure 12. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 4.

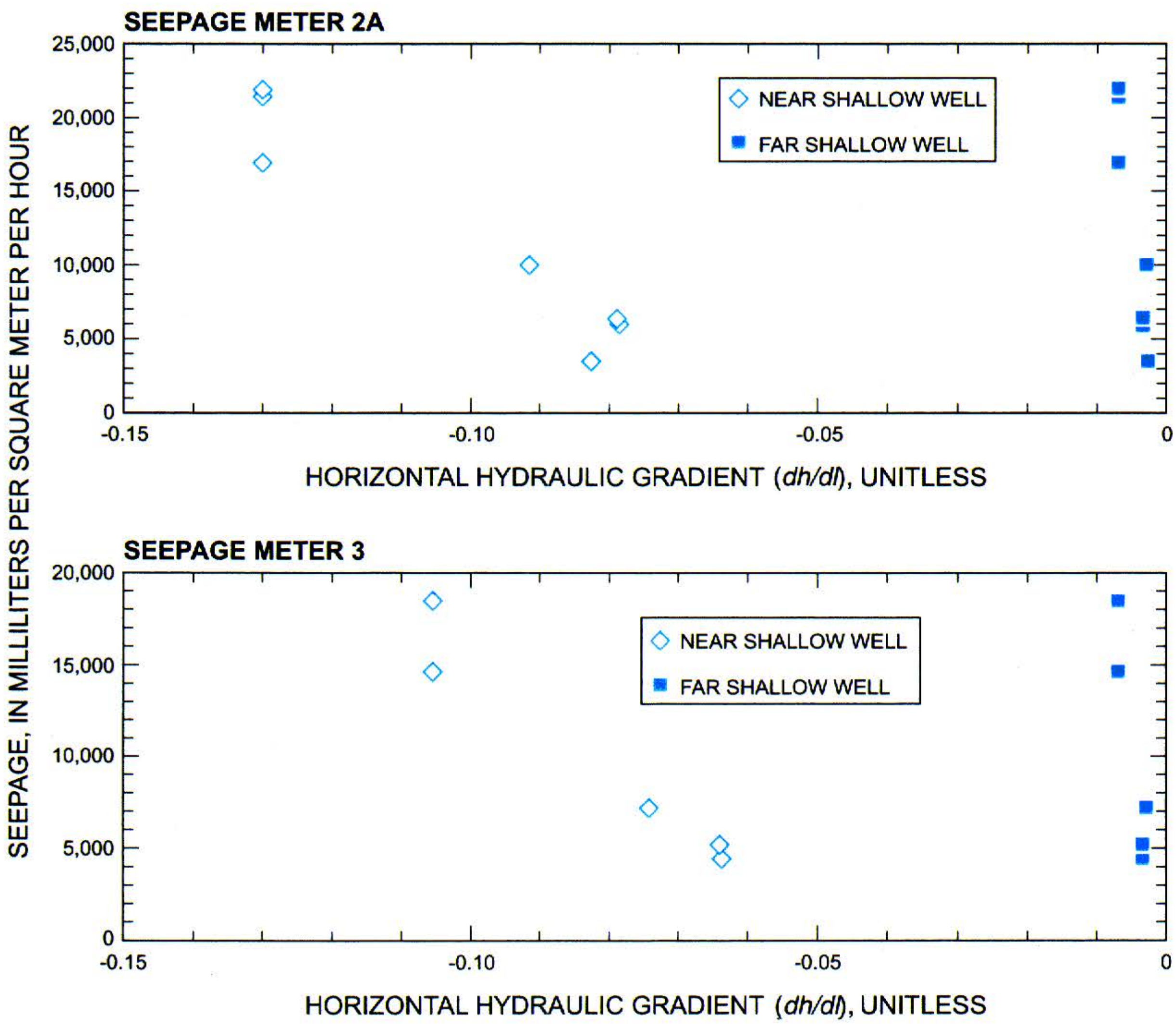


Figure 12. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 4 (continued).

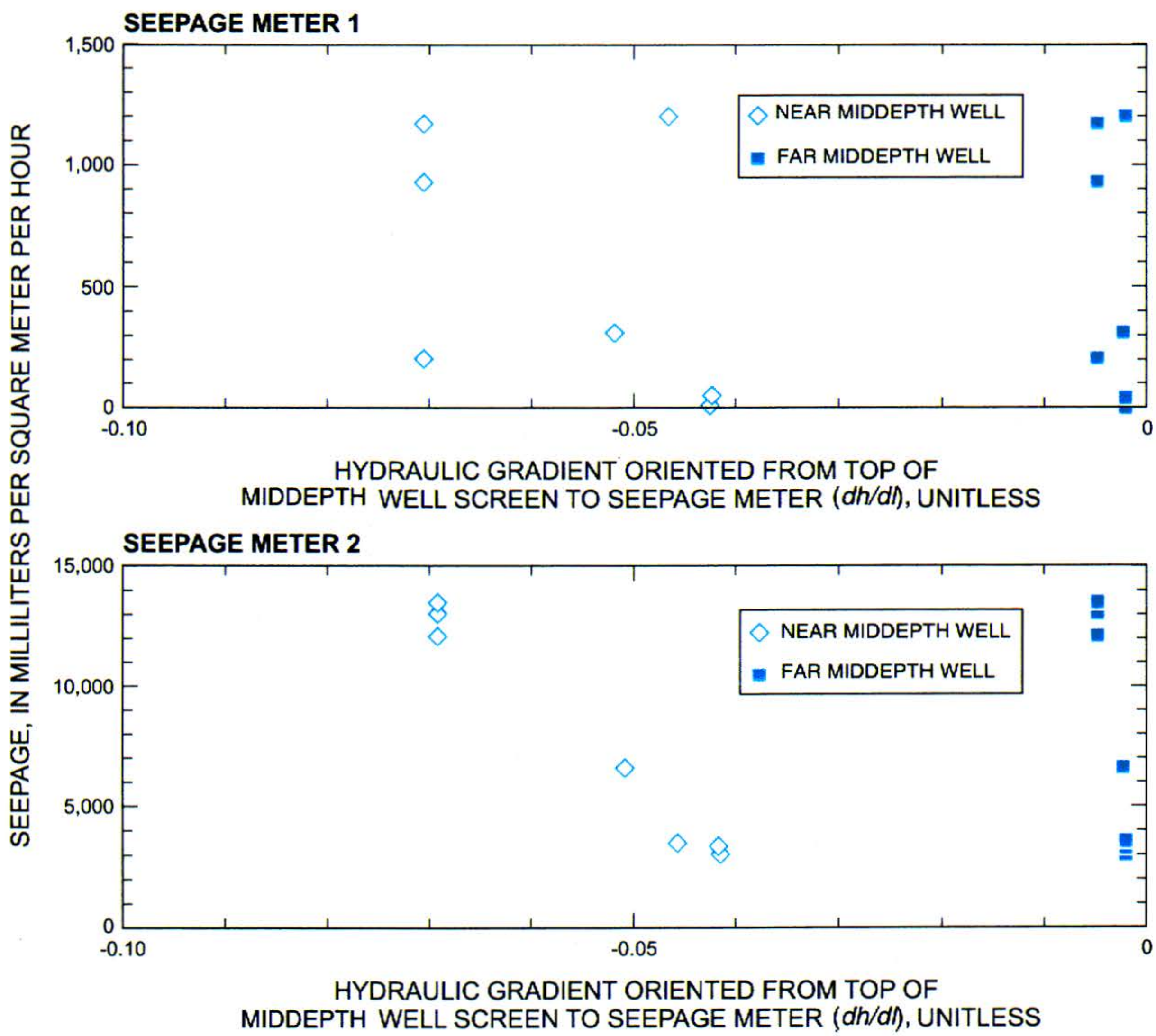


Figure 13. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 4.

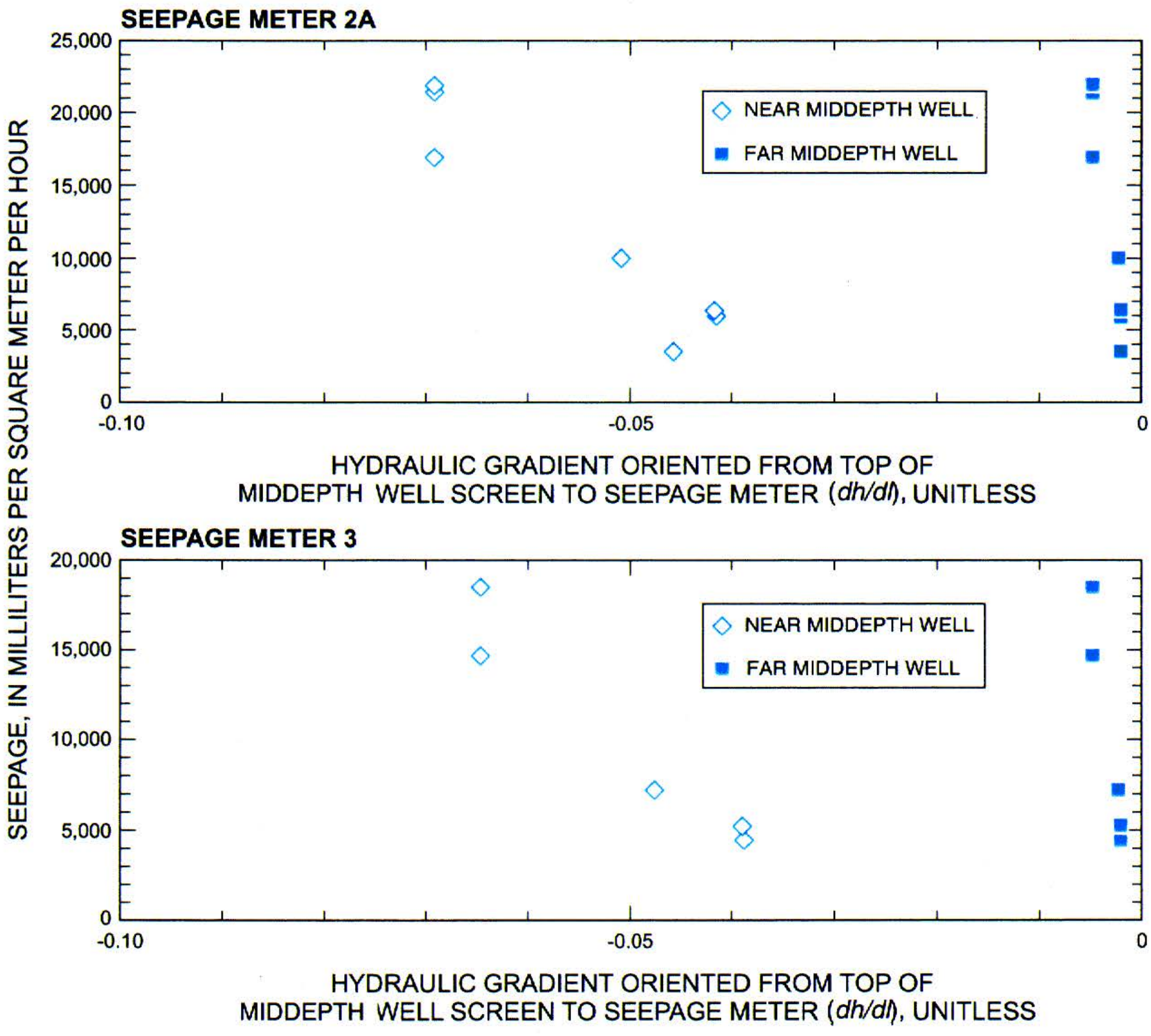


Figure 13. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 4 (continued).

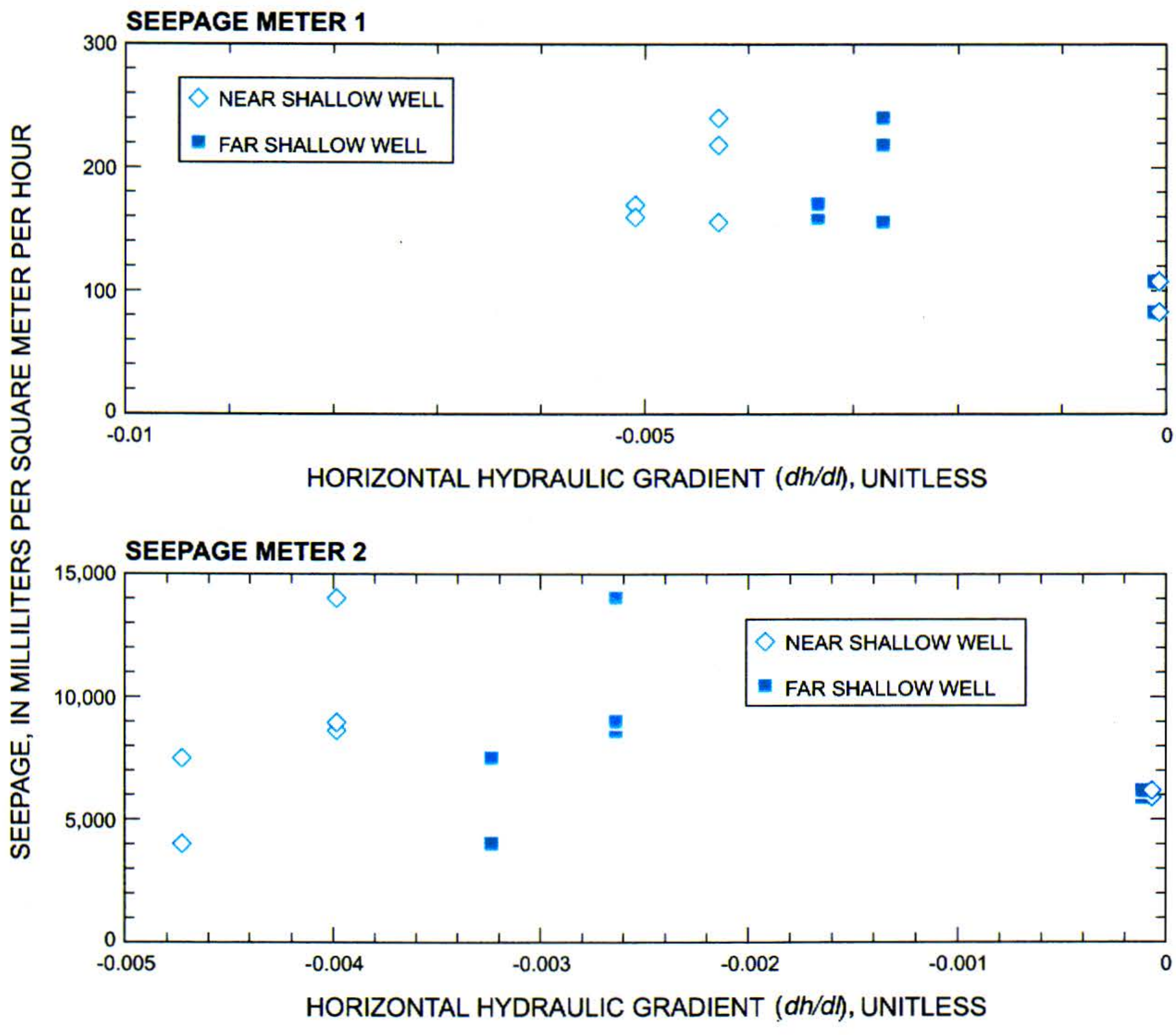


Figure 14. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 6.

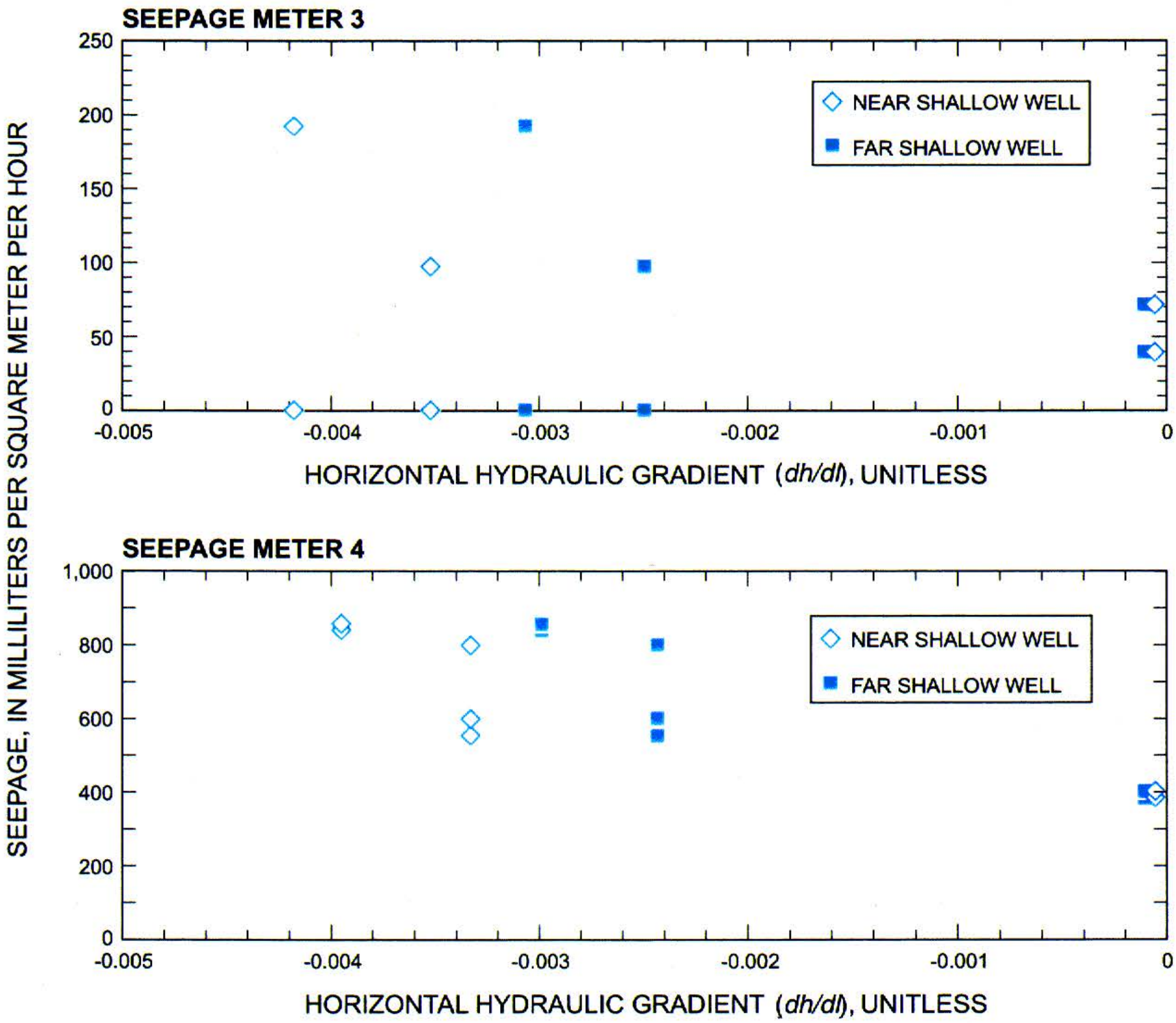


Figure 14. Seepage as a function of the horizontal hydraulic gradient between each meter and shallow ground-water wells at site 6 (continued).

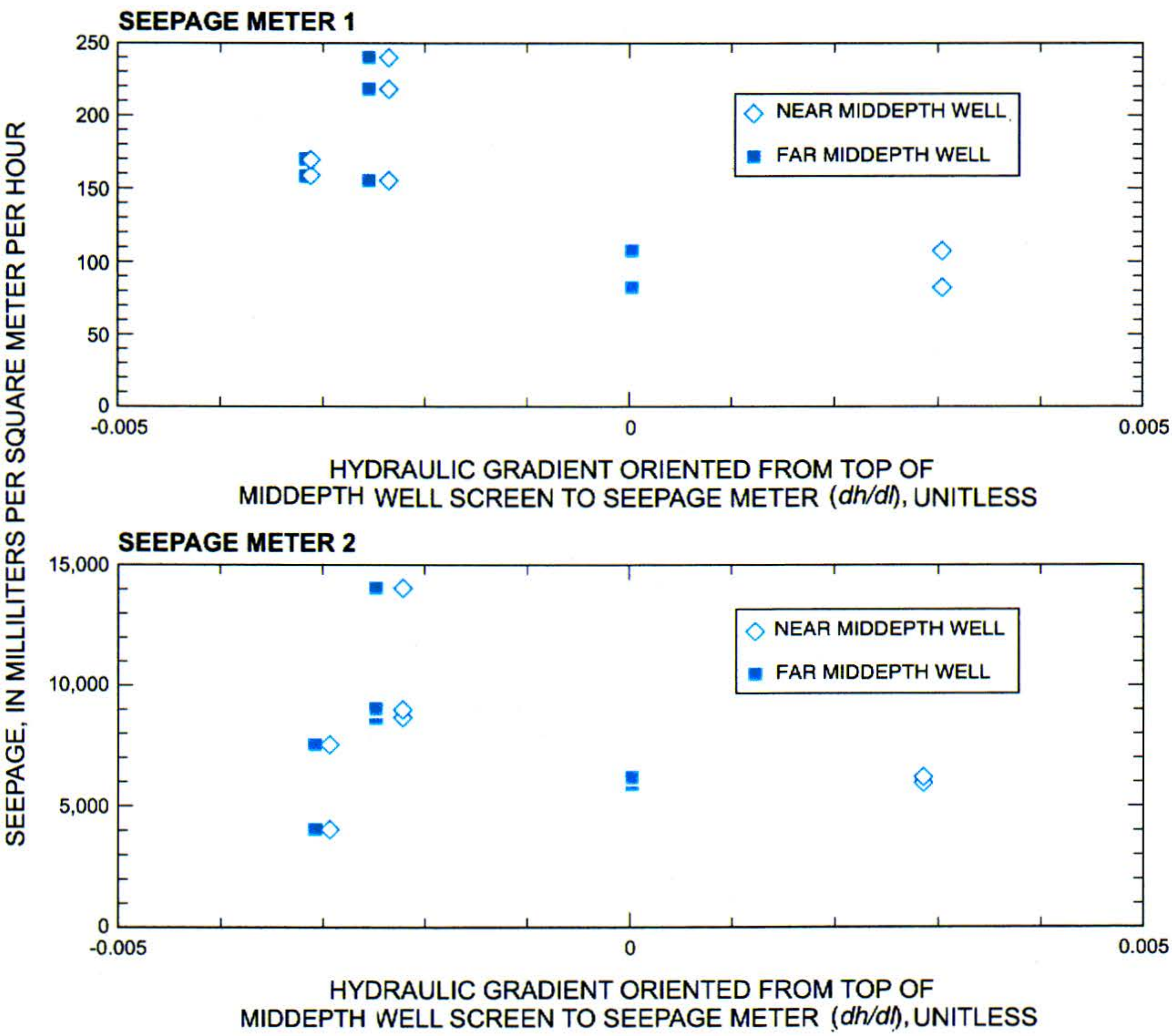


Figure 15. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 6.

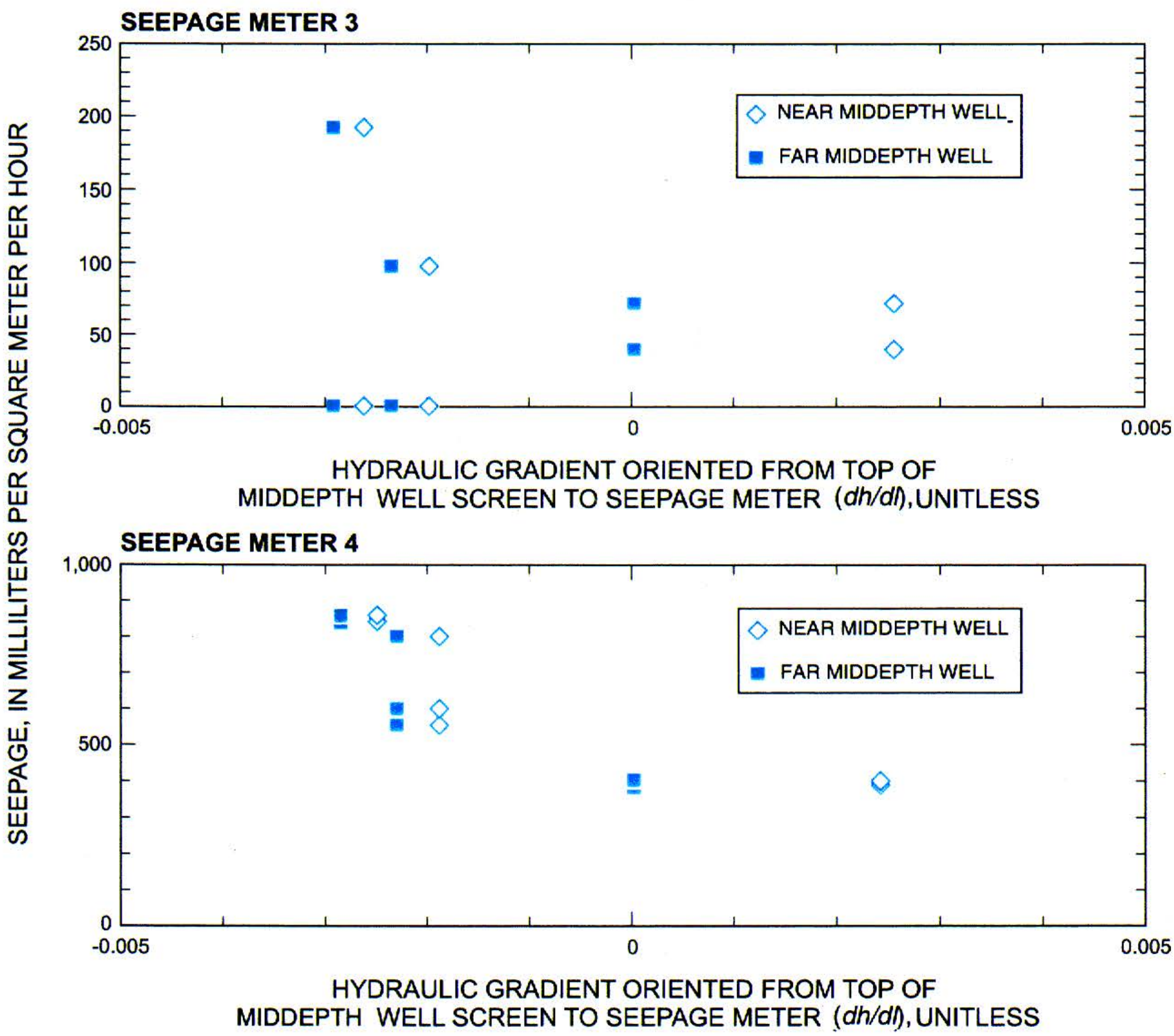


Figure 15. Seepage as a function of the hydraulic gradient between each meter and middepth ground-water wells at site 6 (continued).

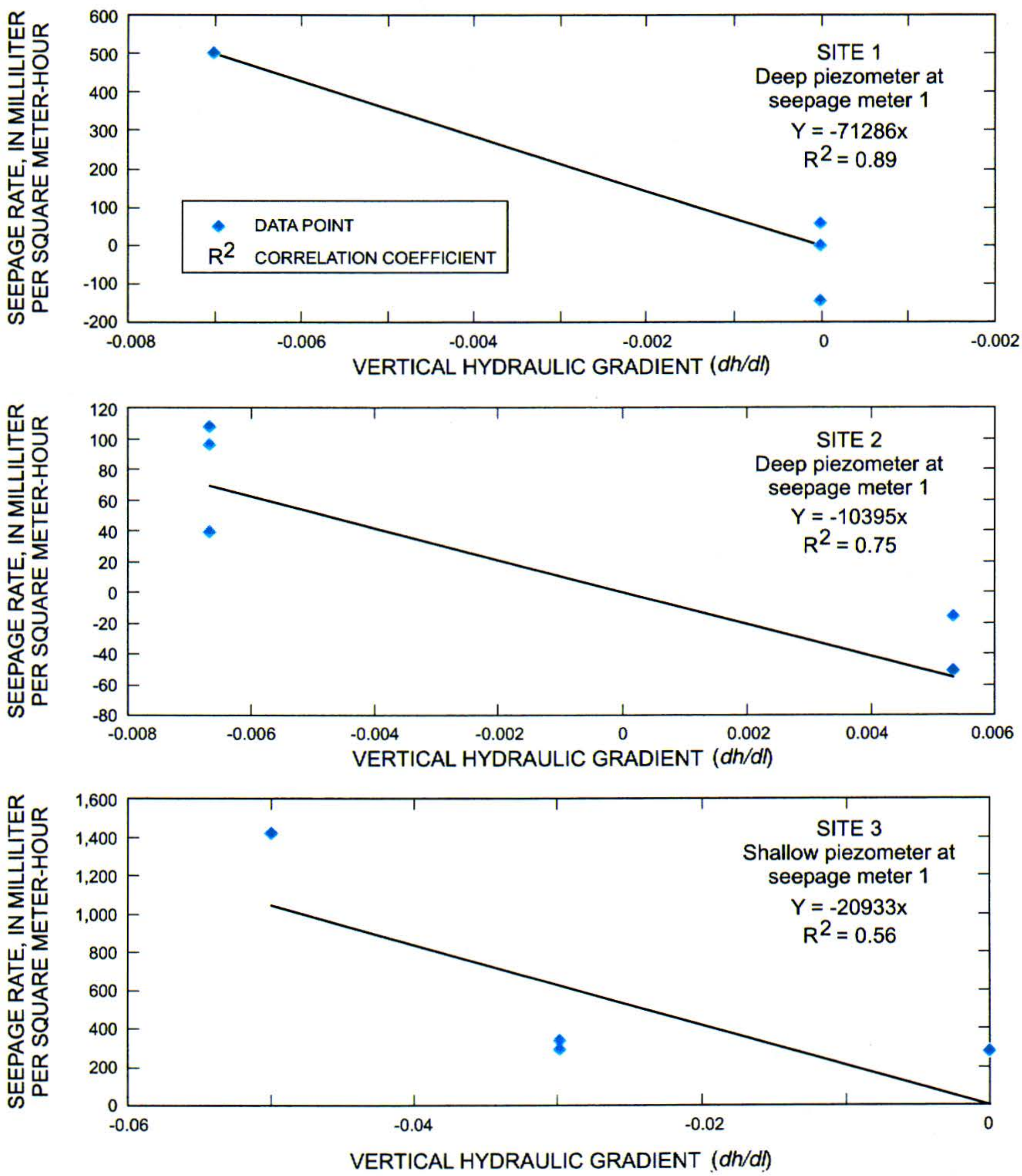


Figure 16. Seepage as a function of the vertical hydraulic gradient at selected in-channel piezometers.

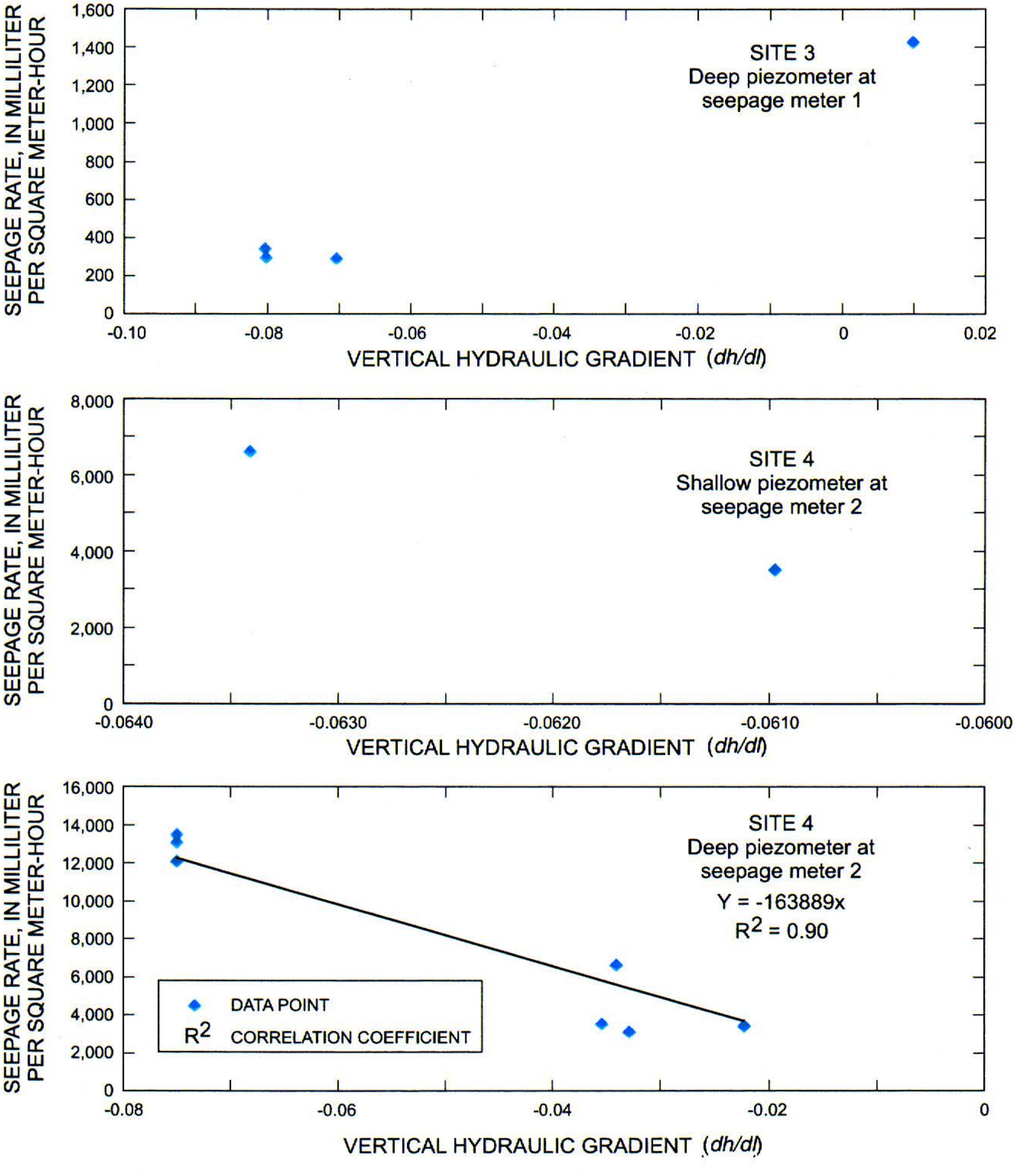


Figure 16. Seepage as a function of the vertical hydraulic gradient at selected in-channel piezometers (continued).

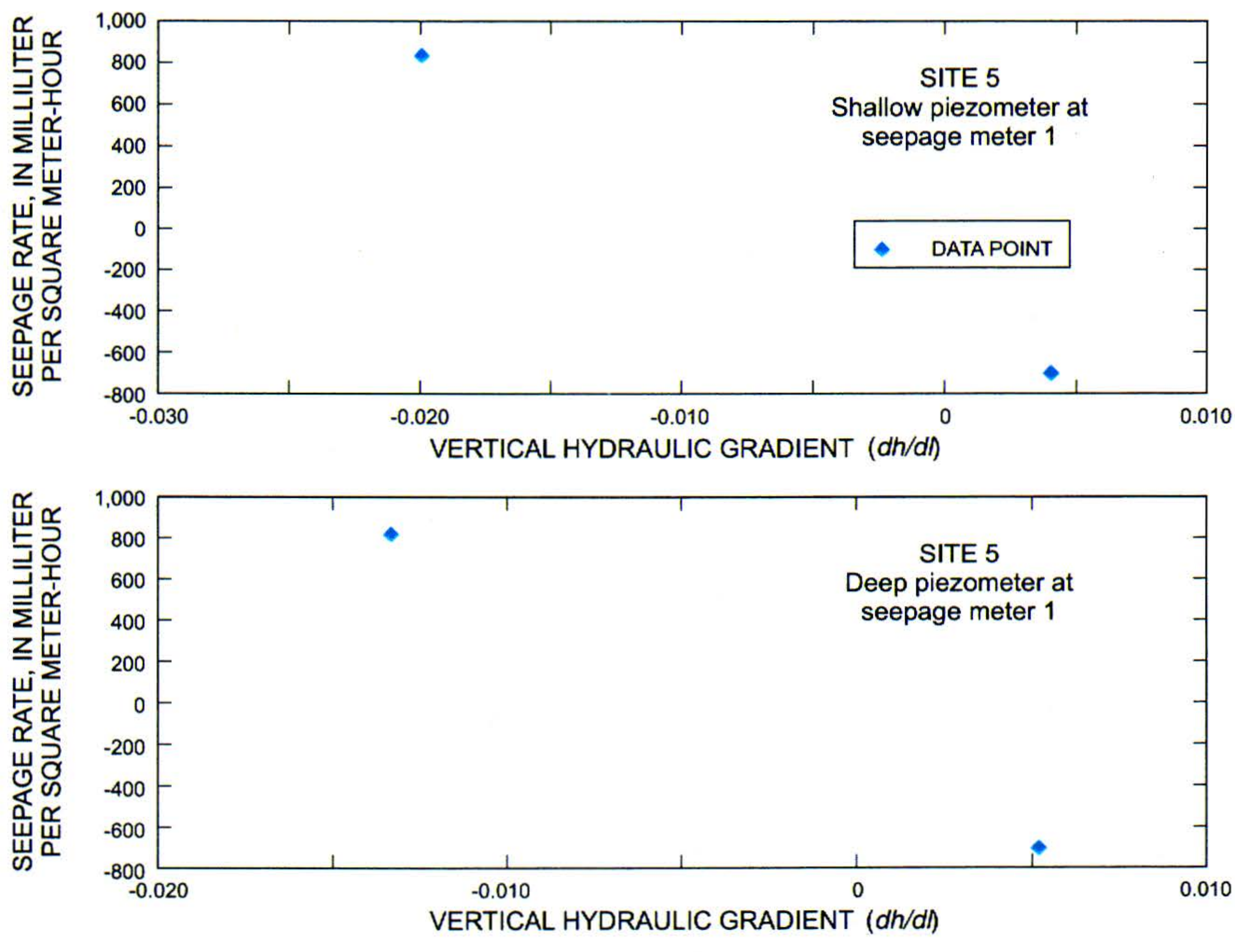
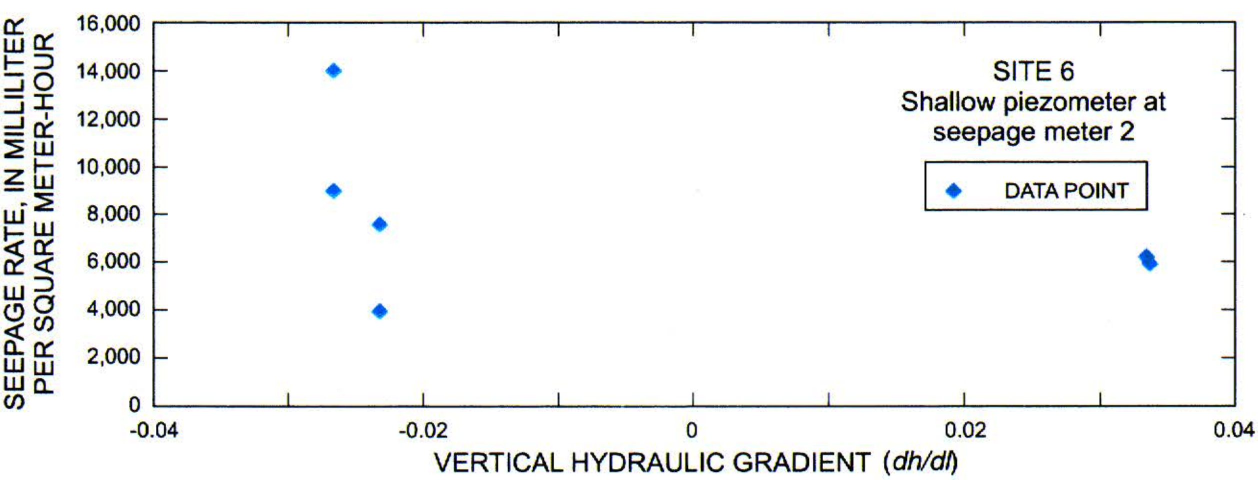


Figure 16. Seepage as a function of the vertical hydraulic gradient at selected in-channel piezometers (continued).



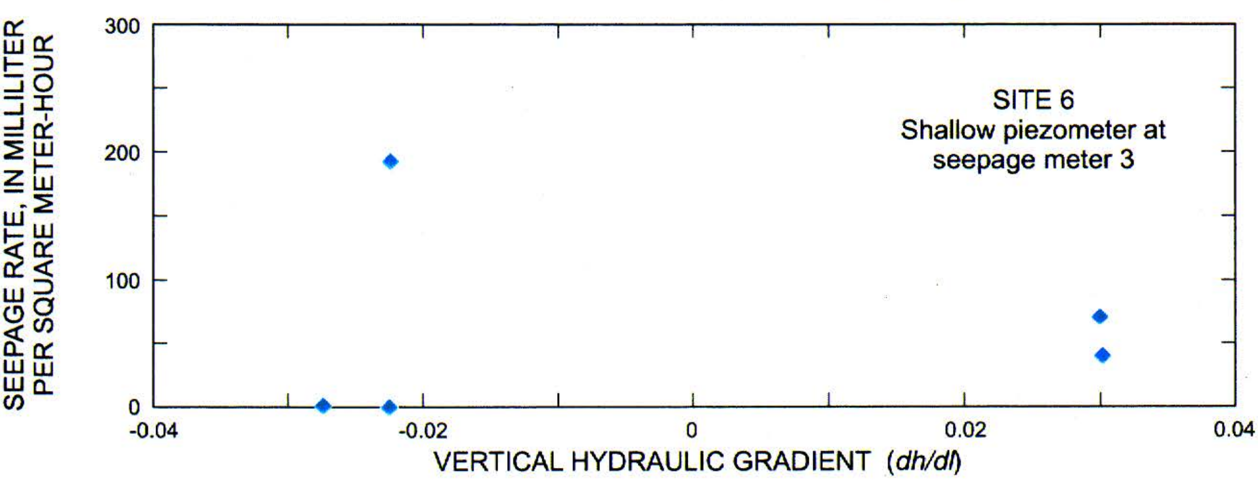


Figure 16. Seepage as a function of the vertical hydraulic gradient at selected in-channel piezometers (continued).

Attachment

The table was provided by the South Florida Water Management District and is presented without change

Well Construction Information For Caloosahatchee River Basin Seepage Study

Site ID	Station Type	State Planar Easting 1927 Datum (feet)	State Planar Northing 1927 Datum (feet)	Well Construction Material	Ground Surface Elevation - feet (1) (Currently, site benchmark)	Casing Length above ground	Estimated ground surface elevation	Elevation at Top of Casing (1)	Depth of Well (feet below LS)	Depth at Top of Screen Interval - feet	Screen Length - feet	Screen Slot Size (inch)	Elevation at Top of Well Screen - feet (1)	Elevation at Bottom of Well Screen - feet (1)
CRS01N+S	Well	557831.589	892534.391	2" PVC	21.7	5.19	18.05	23.24	27.6	22.6	5.0	0.020	-0.90	-5.90
CRS01N+M	Well	557831.589	892534.391	2" PVC	21.7	4.97	18.65	23.62	64.0	59.0	5.0	0.020	-37.28	-42.28
CRS01N+ST	SW (data logger)	557831.589	892534.391											
CRS01F+S	Well	557891.616	892205.684	2" PVC	21.7	4.12	12.54	16.66	26.6	21.6	5.0	0.020	0.15	-4.85
CRS01F+M	Well	557891.616	892205.684	2" PVC	21.7	4.88	11.99	16.87	48.3	43.3	5.0	0.020	-21.63	-26.63
CRS02N+S	Well	579982.837	892796.857	2" PVC	24.44	5.2	19.79	24.99	24.2	19.2	5.0	0.020	5.21	0.21
CRS02N+M	Well	579982.837	892796.857	2" PVC	24.44	4.44	19.61	24.05	62.1	57.1	5.0	0.020	-32.64	-37.64
CRS02N+ST	SW (data logger)	No Station	No Station											
CRS02F+S	Well	579823.685	892487.065	2" PVC	24.44	5.3	14.23	19.53	24.3	19.3	5.0	0.020	5.14	0.14
CRS02F+M	Well	579823.685	892487.065	2" PVC	24.44	4.58	14.14	18.72	63.3	58.3	5.0	0.020	-33.83	-38.83
CRS03N+S	Well	600171.996	890109.033	2" PVC	16.5	5.92	17.02	22.94	19.4	14.4	5.0	0.020	2.10	-2.90
CRS03N+M	Well	600171.996	890109.033	2" PVC	16.5	4.35	17.24	21.59	60.6	55.6	5.0	0.020	-39.09	-44.09
CRS03N+ST	SW (data logger)	600171.996	890109.033											
CRS03F+S	Well	437161.702	890568.271	2" PVC	16.5	5.5	13.62	19.12	18.3	13.3	5.0	0.020	3.22	-1.78
CRS03F+M	Well	437161.702	890568.271	2" PVC	16.5	4.94	13.33	18.27	63.1	58.1	5.0	0.020	-41.63	-46.63
CRS04N+S	Well	436413.030	879614.433	2" PVC	22.94	4.18	23.46	27.64	12.2	7.2	5.0	0.020	15.74	10.74
CRS04N+M	Well	436413.030	879614.433	2" PVC	22.94	5.35	23.31	28.66	58.0	53.0	5.0	0.020	-30.06	-35.06
CRS04N+ST	SW (data logger)	436413.03	879614.433											
CRS04F+S	Well	600720.528	879038.224	2" PVC	22.94	4.82	23.46	28.28	12.1	7.1	5.0	0.020	15.84	10.84
CRS04F+M	Well	600720.528	879038.224	2" PVC	22.94	4.55	23.50	28.05	55.7	50.7	5.0	0.020	-27.76	-32.76
CRS05N+S	Well	571719.77	841597.617	2" PVC	31.04	4.73	31.50	36.23	14.7	9.7	5.0	0.020	21.34	16.34
CRS05N+M	Well	571719.77	841597.617	2" PVC	31.04	4.60	31.56	36.16	58.3	53.3	5.0	0.020	-22.26	-27.26
CRS05N+ST	SW (data logger)	571719.77	841597.617											
CRS05F+S	Well	572553.696	841610.578	2" PVC	31.04	5.04	30.80	35.84	13.7	8.7	5.0	0.020	22.34	17.34
CRS05F+M	Well	572553.696	841610.578	2" PVC	31.04	4.80	31.09	35.89	70.8	65.8	5.0	0.020	-34.76	-39.76
CRS06N+S	Well	569796.585	872701.843	2" PVC	20.78	4.15	21.16	25.31	13.0	8.0	5.0	0.020	12.78	7.78
CRS06N+M	Well	569796.585	872701.843	2" PVC	20.78	4.23	20.90	25.13	58.1	53.1	5.0	0.020	-32.32	-37.32
CRS06N+ST	SW (data logger)	569796.585	872701.843											
CRS06F+S	Well	569996.181	872725.157	2" PVC	20.78	4.30	21.35	25.65	13.5	8.5	5.0	0.020	12.28	7.28
CRS06F+M	Well	569996.181	872725.157	2" PVC	20.78	4.95	20.33	25.28	58.3	53.3	5.0	0.020	-32.52	-37.52
CRS01pzSD	Piezometer	557801.577	892580.738	1" PVC				13.16	10.0		1.0			
CRS02pzSD	Piezometer	580038.164	892865.767	1" PVC				12.26	7.5		1.0			
CRS03pzSS	Piezometer			1" PVC					5.0		1.0			
CRS03pzSD	Piezometer			1" PVC					10.0		1.0			
CRS04pzSD	Piezometer	599557.624	879076.108	1" PVC				17.82	7.6		1.0			
CRS05pzSh	Piezometer	571698.546	841585.898	1" PVC				26.41			1.0			
CRS06pzOS	Piezometer	569673.629	872623.151	1" PVC				17.50	4.0		1.0			
CRS06pzSS	Piezometer	569691.645	872631.791	1" PVC				16.58	3.0		1.0			

(1) All elevations are 1929 NGVD