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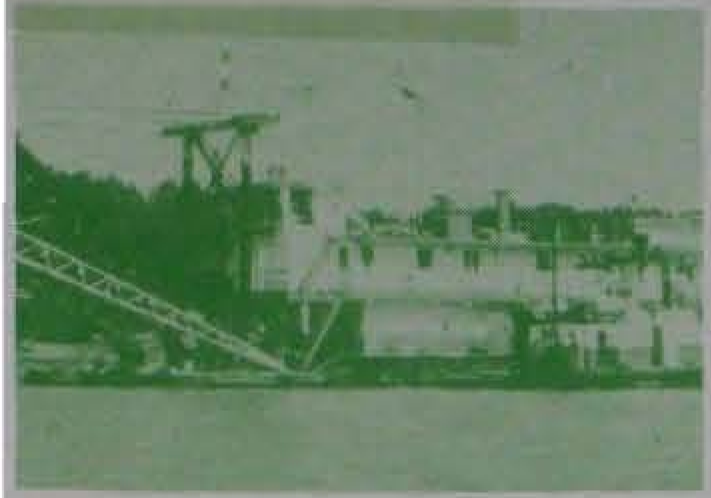

DREDGING OPERATIONS TECHNICAL SUPPORT PROGRAM

TECHNICAL REPORT D-90-4

MEASUREMENT OF HYDROLOGIC PARAMETERS OF CONFINED DREDGED MATERIAL AT WILMINGTON HARBOR, DELAWARE, CONTAINMENT AREA

by

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A computer model, Primary Consolidation and Desiccation of Dredged Fill (PCDDF), has been developed to predict the settlement of dredged material placed in confined disposal sites. PCDDF, a model that calculates both consolidation settlement and desiccation settlement, uses a well established theory to predict consolidation and employs an empirical formulation to predict desiccation. At present, no field or laboratory procedures exist for determining values for the empirical desiccation parameters. This study established procedures for quantifying these parameters through a field evaluation program in the US Army Engineer District, Philadelphia.

A water budget approach was used to calculate desiccation parameters for the dried crust of the desiccating dredged material at the Wilmington Harbor Containment Area near Wilmington, DE. The evaporation efficiency was found to be a constant value of 0.72, the

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drainage efficiency was 0.21, the saturation limit was 3.02, the desiccation limit was 2.69, the depth of second-stage drying was 0.20 m, and the percent saturation of the desiccated crust (including cracks) was 0.74.

The long-term water budget for the desiccated crust for the entire duration of the study clearly indicates that second-stage drying was largely completed when the study began. Because the study was initiated approximately 1 month after the dredged material was placed, these results suggest that both first- and second-stage drying are completed very rapidly at the Wilmington Harbor Containment Area.

The procedures utilized in the study at the Wilmington Harbor containment area can be employed at other dredged material disposal sites to determine quantitative values for the empirical desiccation parameters.

PREFACE

This report summarizes research performed by Dr. James E. Pizzuto, Department of Geology, University of Delaware, under contract to the US Army Engineer Waterways Experiment Station (WES) (Contract No. DACW39-87-M-2583). The original research was initiated at the request of Dr. Marian E. Poindexter-Rollings of the Water Resources Engineering Group (WREG), Environmental Engineer Division (EED), WES, Vicksburg, MS. The study was sponsored by the Dredging Operations Technical Support (DOTS) Program and funded by the Headquarters, US Army Corps of Engineers (HQUSACE). The DOTS Program is managed through the Environmental Effects of Dredging Programs (EEDP) of the EL. Dr. Robert M. Engler was Manager, EEDP; Mr. Thomas R. Patin was the DOTS Coordinator. The HQUSACE Technical Monitor was Mr. David B. Mathis.

This report was written by Dr. James E. Pizzuto and Dr. Marian E. Poindexter-Rollings under the general supervision of Dr. John J. Ingram, Chief, WREG, EL; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL. Acknowledgment is made to Mr. Bruce Uibel, US Army Engineer District, Philadelphia, who provided useful background information about the field site as well as some field assistance. Technical reviewers of this report were Dr. Michael R. Palermo and Ms. Anne MacDonald, EED. The report was edited for publication at WES by Mrs. Gilda Miller, Information Technology Laboratory.

COL Larry B. Fulton, EN, was Commander and Director of WES. Technical Director was Dr. Robert W. Whalin.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4.046873	square metres
feet	0.3048	metres
miles (US statute)	1.609347	kilometres
cubic yards	0.7645549	cubic metres

MEASUREMENT OF HYDROLOGIC PARAMETERS OF CONFINED DREDGED MATERIAL AT WILMINGTON HARBOR, DELAWARE, CONTAINMENT AREA

PART I: INTRODUCTION

Background

1. The US Army Corps of Engineers (USACE) is the Government agency charged with maintaining the navigable waters of the United States. In this role, the USACE is responsible for annually dredging and disposing of several hundred million yd^3* of sediment which must be placed in environmentally acceptable disposal sites (Poindexter 1988). To minimize the future need for additional disposal sites, the USACE has developed extensive procedures for managing upland (as opposed to subaqueous) disposal sites, i.e. sites where the dredged material can be dried, thereby decreasing the volume to be stored as well as providing dried material which can often be used as earth fill.

2. A computer program has been developed by the USACE to predict the physical behavior of dredged material placed in designated disposal sites. The program entitled "Primary Consolidation and Desiccation of Dredged Fill" (PCDDF) is capable of predicting both the consolidation and the desiccation settlements of these dredged material deposits (Cargill 1985). While the consolidation model is based upon technically correct, sound, finite strain consolidation theory, the desiccation portion relies upon an empirical desiccation model. As such, the level of detail and accuracy varies significantly between the two models. Also, a number of empirical parameters are required as input for the desiccation model. At present there is no established procedure for determining these parameters.

Purpose

3. The purpose of this research was to evaluate the characteristics of the empirical desiccation parameters used in PCDDF and to develop procedures

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

for and guidance on the selection and use of parameter values for various dredged material containment areas.

Scope

4. This project involved analysis of the desiccation model used in PCDDF. It also involved determination of specific values for the desiccation parameters for the Wilmington Harbor Containment Area in Wilmington, DE.

PART II: HYDROLOGIC EVALUATION PROCEDURES

5. The computer program PCDDF predicts the rate of consolidation and desiccation of sediment placed in dredged material containment areas (Cargill 1985). The program numerically solves the differential finite strain consolidation equations and empirical desiccation equations for specified initial and boundary conditions. The predicted patterns of settlement are used to estimate the useful lifetime of dredged material containment areas. As such, the consolidation and desiccation program represents a useful aid in planning and management of dredged material containment areas.

6. To use PCDDF, boundary conditions must be specified. One of the most important boundary conditions for the settlement of hydraulically placed dredged material involves specifying the void ratio and moisture loss at the upper surface of the dredged material. Unfortunately, this boundary condition cannot be specified according to rigorous physical laws due to the complex processes which influence the desiccation of the upper surface of the dredged material. The existing computer program relies on a rudimentary empirical formulation to represent the evaporation and desiccation processes active at the dredged material surface (Cargill 1985). As in any empirical approach, numerous adjustable coefficients need to be quantified before predictions can be made. The goal of this study is to quantify these adjustable coefficients for the Wilmington Harbor Containment Area and to establish a procedure by which these parameters may more accurately be quantified for various dredged material containment areas.

The Desiccation Model

7. The characteristics of the surface of hydraulically placed dredged material change considerably as the material dries and consolidates. Immediately after the dredged sediment is placed in the disposal site, the material has a very high water content and a correspondingly high void ratio. Initial values typically vary from 300 to 600 percent for the water content and from 8 to 14 for the void ratio (Poindexter 1987, 1988). Water is evaporated from the surface of the dredged sediment readily, much as water is evaporated from any standing body of water. After the material has dried and consolidated, however, the surface of the dredged sediment dries to form a cracked,

desiccated crust. This crust covers sediment which has a much higher moisture content and thus a much higher void ratio than does the crusted material. Evaporation from the surface of this dried crust is extremely slow.

8. The phenomena described above lead Brown and Thompson (1977), Gardner and Hillel (1962), and Cargill (1985) to define two stages of evaporative drying of the dredged material. The amount of evaporation, E, is first related to the evaporation measured using a Class A evaporation pan, EP, and the evaporation efficiency, C_e:

$$E = C_e EP \tag{1}$$

During the first stage of evaporative drying, the evaporation efficiency is constant with a value equal to or slightly less than 1.

9. At the end of first-stage drying, the formation of a desiccated crust limits the amount of water which can be transmitted by the soil. At this point, the upper part of the dredged material has reached a void ratio defined by Cargill (1985) as the <u>saturation limit</u>. The saturation limit extends at a constant value to a depth which will be referred to here as the <u>depth of first-stage drying</u>.

10. After first-stage drying has been completed, the rate of evaporation slowly decreases because the rapidly thickening desiccated crust inhibits the movement of water to the surface of the dredged material, and the evaporation efficiency slowly declines to near zero (Figure 1). At the end of second-stage drying, the void ratio of the dried crust has declined to a constant value referred to as the <u>desiccation limit</u> (Cargill 1985). The desiccation limit extends to a depth referred to as the <u>depth of second-stage drying</u>.

11. Clearly, the evaporation efficiency will be difficult to predict for a specific field setting. However, Cargill (1985) suggests that the evaporation efficiency should, as a first approximation, be related to the depth of the water table by the relationship:

$$C_e = C'_e \left(1 - \frac{h_{wt}}{h_2}\right) \tag{2}$$

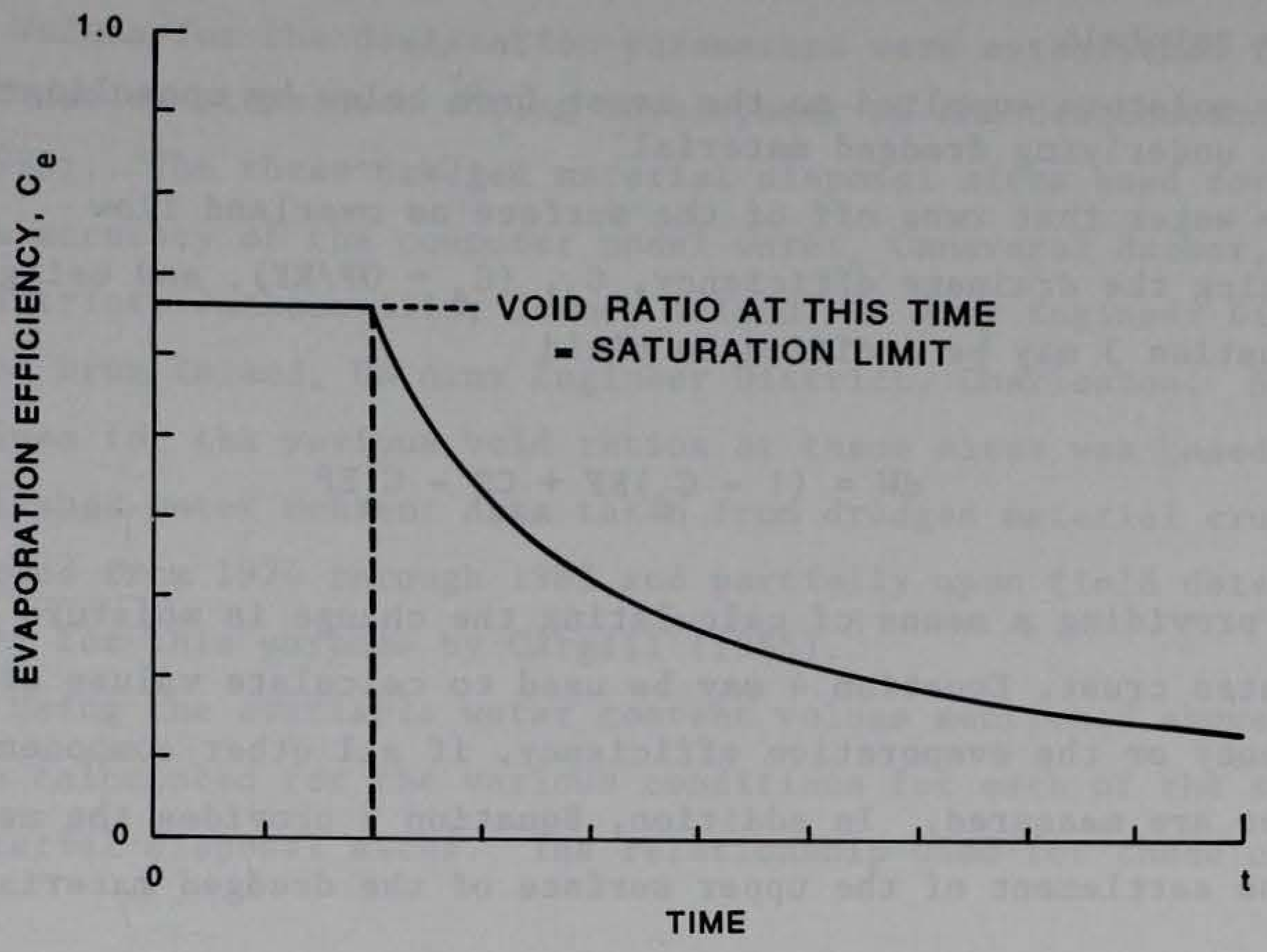

Figure 1. Time variation of the evaporation efficiency

where

h_{wt} = distance from the soil surface to the water table

h_2 = distance to the water table at the end of second-stage drying

C'_e = evaporation efficiency at the end of first-stage drying

(For convenience, symbols and abbreviations are listed in Appendix A.) Equation 2 provides a simple relationship that could be used to calculate the evaporation efficiency on the basis of a few simple field measurements.

Water Budget for the Desiccated Crust

12. Other processes besides evaporation are important in determining the moisture content of the upper layer of the dredged material. A complete water budget for the upper crust is defined by the equation

$$dW = RF + CS - OF - E \qquad (3)$$

where, for a specified period of time,

dW = change in the moisture content of the dredged material

RF = rainfall

CS = moisture supplied to the crust from below by consolidation of the underlying dredged material

OF = water that runs off of the surface as overland flow

By introducing the drainage efficiency, C_d, (C_d = OF/RF), and using Equation 1, Equation 3 may be modified to yield

$$dW = (1 - C_d)RF + CS - C_e EP \tag{4}$$

As well as providing a means of calculating the change in moisture content of the desiccated crust, Equation 4 may be used to calculate values of the drainage efficiency or the evaporation efficiency, if all other components of the water budget are measured. In addition, Equation 4 provides the means of calculating the settlement of the upper surface of the dredged material.

Desiccation Settlement

13. Cargill (1985) presents two equations for calculating the settlement of the crust, S, as a function of the change in moisture content of the crust. During first-stage drying, the settlement of the crust may be calculated from

$$S = -dW \tag{5}$$

During second-stage drying, the settlement of the crust may be calculated from

$$S = -dW - \left(1 - \frac{PS}{100}\right) h_{wt} \tag{6}$$

where

PS = gross percent saturation of the desiccated crust including the volume of cracks

Equations 5 and 6 demonstrate the importance of properly specifying dW, since the settlement at the top of the dredged material is directly dependent on dW.

Previously Collected Field Data

14. Values for the desiccation parameters were established for three field verification sites used during development of the desiccation model (Cargill 1985). The three dredged material disposal sites used for verification of the accuracy of the computer model were: Canaveral Harbor, US Army Engineer District, Jacksonville; Craney Island, US Army Engineer District, Norfolk; and Drum Island, US Army Engineer District, Charleston. Specification of values for the various void ratios at these sites was based partially upon unpublished water content data taken from dredged material crust over a 10-year period from 1974 through 1983 and partially upon field data collected specifically for this purpose by Cargill (1985).

15. Using the available water content values mentioned above, void ratios were calculated for the various conditions for each of the three dredged material disposal sites. The relationship used for these calculations is

$$e = \frac{\omega}{S} \cdot G_s \tag{7}$$

where

e = void ratio at condition of interest

ω = water content at void ratio at condition of interest

S = degree of saturation at condition of interest

G_s = specific gravity of dredged material

In making these calculations, the fact was used that the degree of saturation is 100 percent at the saturation limit (e_{SL}); a value of 80 percent saturation was used for the desiccation limit (e_{DL}) (Haliburton 1978, Cargill 1985). The selected values for the desiccation parameters at Cargill's verification sites are shown in Table 1. The percentages shown for the evaporation and drainage efficiencies were reported to be the best estimates at the time they were established.

Table 1

Previously Established Desiccation Parameters

(From Cargill 1985)

Parameter	Canaveral Harbor	Craney Island	Drum Island
Specific gravity of solids, G_s	2.70	2.75	2.60
Liquid limit, LL , %	143	125	140
Plastic limit, PL , %	40	42	49
Zero effective stress void ratio, e_{oo}	11.5	9.0	12.15
Saturation limit, e_{SL}	3.7	6.5	6.7
Desiccation limit, e_{DL}	2.5	3.2	3.1
Typical maximum crust depth, in.	11	6	10
Desiccation cracks as percentage of surface area	20	20	20
Maximum evaporation efficiency, %	75	75	75
Site drainage efficiency, %	100	100	100

Previous Guidance on Determining Values

16. At present, there are no recommended field or laboratory procedures for determining the various desiccation parameters. Various aspects of the desiccation process have been conceptualized, and the empirical parameters have been identified and defined. Specific values for the desiccation parameters were determined at the field sites investigated during formulation of the desiccation model (Cargill 1985), but procedures for physically determining these values were not reported.

17. The existing guidance for establishing desiccation values for confined dredged material subjected to drying (Cargill 1985) is given in the following paragraphs.

18. The void ratio at the saturation limit may be approximated as

$$e_{SL} = \frac{1.8LL \cdot G_s}{S} \qquad (8)$$

where

e_{SL} = void ratio at the saturation limit

LL = liquid limit of the dredged material

S = degree of saturation, which is taken to be 100 percent (used in decimal form)

19. The void ratio at the desiccation limit may be approximated as

$$e_{DL} = \frac{1.2PL \cdot G_s}{S} \qquad (9)$$

where

e_{DL} = void ratio at the desiccation limit of the dredged material

PL = plastic limit of the dredged material

S = degree of saturation, which is taken to be 80 percent (used in decimal form)

and other values are as previously defined.

20. The maximum depth of crust, degree of saturation of the entire crust (including open cracks), evaporation efficiency, and site drainage efficiency are determined based upon site-specific conditions, empirical evidence, and engineering judgment. There is no documented guidance for determining or even estimating these parameters.

Summary

21. Because the accuracy of the desiccation model and, thus, the entire prediction model depends directly upon values of the various desiccation parameters, it is essential to establish appropriate numeric values for the coefficients and adjustable parameters. These include the evaporation efficiency, the drainage efficiency, the gross percent saturation of the crust after second-stage drying, the depths of first- and second-stage drying, and the saturation and desiccation limits. The goal of this study is to quantify these parameters for the Wilmington Harbor containment area, thereby establishing procedures for more accurately determining the parameters for other disposal areas.

PART III: FIELD SITE CONDITIONS

Site Description

22. The Wilmington Harbor containment area is a 200-acre dredged material disposal area located adjacent to the Christina River near the Port of Wilmington, DE. As shown in Figure 2, it is located near the confluence of the Christina and Delaware Rivers. Configuration of the site is shown in Figure 3. This site has been used since the 1930's for dredged material disposal. The Port of Wilmington is presently establishing a joint program with the Delaware Solid Waste Commission to permit disposal of solid waste in the Wilmington Harbor containment area. The solid waste will be separated from the dredged material by interior dikes which must be constructed; management of the dredged material section will continue as normal.

23. Dredged material disposal is presently alternated between the Wilmington Harbor and the adjacent Edgemoor containment areas. Typical operations involve 2 years of active disposal into one site followed by 2 years of drying in the same site, while disposal operations occur at the other site. During active disposal operations, approximately 0.8 to 1.0 million yd^3 of dredged material is placed into the containment areas every 6 months. During the 2 years without active dredged material disposal, the sites are managed for dredged material dewatering; dike raising activities are also undertaken during this period using the dried material. During recent times the dikes have been raised approximately 10 ft during each 2-year drying cycle. A third containment area is currently under construction. Upon completion of this nearshore Wilmington Harbor South facility in 1991 to 1992, disposal operations will be rotated through the three facilities.

24. At present approximately 25 ft of dredged material is contained within the Wilmington Harbor containment area. The site has current surface elevation of about el + 25 ft mean sea level and is underlain by about 10 ft of compressible foundation soils.

25. The Wilmington Harbor containment area has one operational weir structure for removal of ponded surface water (Figure 3). The weir structure

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* All elevations (el) cited herein are in feet referred to National Geodetic Vertical Datum (NGVD) of 1929.

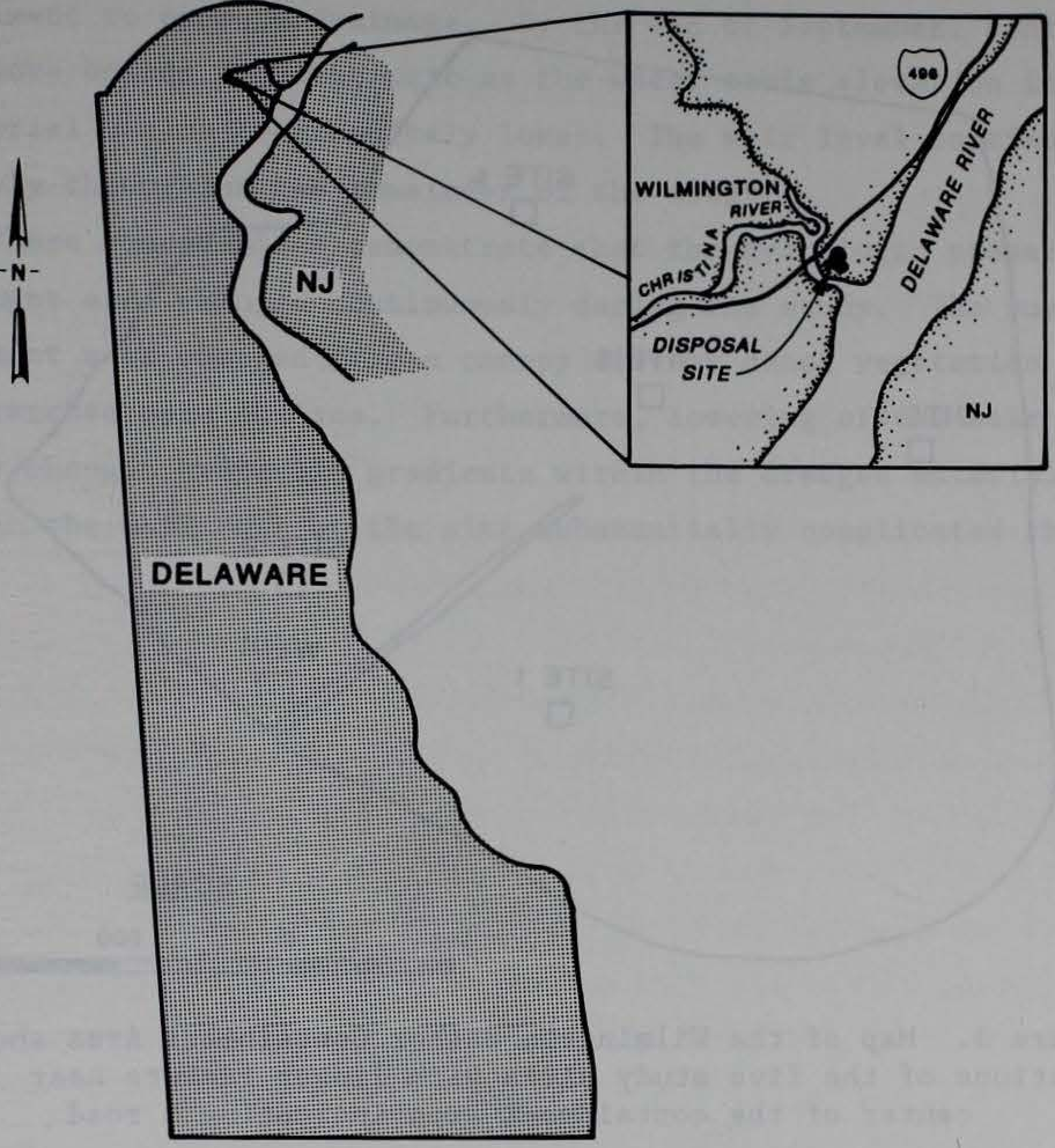


Figure 2. Location of the Wilmington Harbor Containment Area

is composed of four separate rectangular box weirs, or compartments, with adjustable crest elevations. Effluent water released from this site is returned to the Christina River via a drainage ditch. The dredged material inflow point is typically varied around the site with the specific location dependent upon the location of the dredging project and the relative surface elevations within the containment area.

Operation During the Study

26. Dredged sediment was placed in the Wilmington Harbor Containment Area early in June 1987. The contract for field instrumentation, data collection, and analysis for the current project was delayed and was not let

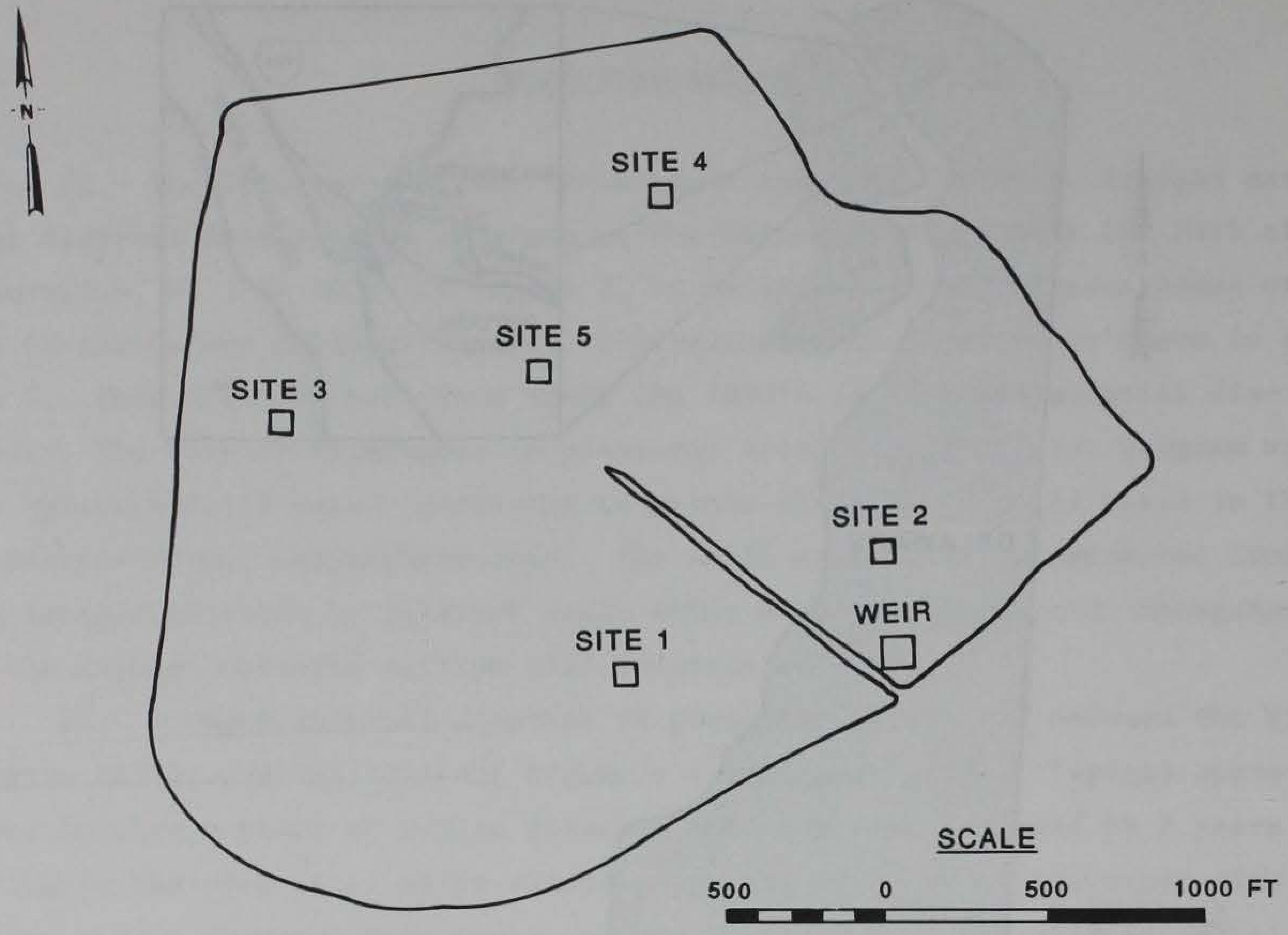


Figure 3. Map of the Wilmington Harbor Containment Area showing locations of the five study sites with linear feature near center of the containment area indicating a road

until the end of July. Thus, considerable moisture losses had occurred before any measurements could be made. By the end of July, the surface of the dredged sediment was covered with deep cracks and free standing water was present only in localized depressions. In addition, a thick canopy of vegetation had covered the surface of the containment area. Thus, first-stage drying was probably complete at the beginning of the present study.

27. During August, the canopy of vegetation became progressively denser, and by the end of August, the entire surface of the containment area was covered by a dense stand of plants approximately 1 to 1.5 m high. Near the end of August, an amphibious vehicle began to cut the vegetation. By the end of September, most of the large vegetation had been destroyed, but many smaller plants were still growing.

28. Early in September, contractors began to trench the surface of the dredged sediment to promote drainage. By the end of September, contractors began to remove boards from the weir as the water table elevation in the dredged material became progressively lower. The weir level continued to be lowered slowly throughout the remainder of the study.

29. These observations demonstrate that the hydrologic properties of the containment area changed continuously during the study. The surface of the containment area changed from a canopy of very dense vegetation to an intensely trenched bare surface. Furthermore, lowering of the weir outlet continuously changed hydraulic gradients within the dredged material. These variations in the character of the site substantially complicated the present study.

PART IV: METHODS

Evaporation Efficiency

30. A water budget for the desiccated crust provides a framework for collecting and analyzing data. Equations 3 and 4 define the water budget. A modified form of these equations is

$$dW = RF + CS - OF - C_eEP \tag{10}$$

Methods are described in the following paragraphs to measure all the terms in Equation 10 except the evaporation efficiency, C_e. Thus, these methods provide a means of determining C_e.

31. Lysimeters, instruments that isolate some of the dredged material from its surroundings, provide a simple method for quantifying the water budget of Equation 10. The lysimeters used here were designed so that both CS and OF were zero. Thus, measuring dW in the lysimeters provided a simplified means of solving Equation 10 for C_e. This method proved to be particularly important because of difficulties encountered in measuring OF (these difficulties are described in paragraph 36).

32. As a check on the water budget approach, another method was also used to determine C_e. The total potential soil evapotranspiration was calculated using the Thornthwaite-Mather method (Dunne and Leopold 1978, Thornthwaite and Mather 1957). The only parameters required to perform these calculations are the mean temperature for a month, an "annual heat index," and the average mean temperature for the period of record for the month in question. Temperature data were obtained from National Weather Service records for the meteorological station at the Wilmington Airport (located about 6 miles southwest of the study area). Historical climatic data needed to calculate the heat index and the average monthly temperature were obtained from Ruffner (1985). These data were used to calculate E, the monthly moisture losses from the crust due to evapotranspiration. Because the Class A pan evaporation, EP, was also measured on the site, the evaporation efficiency could be readily obtained from the relationship $E = C_eEP$.

33. Although the Thornthwaite-Mather method is not strictly formulated for calculating soil moisture losses from a desiccating dredged material, the

field conditions at the Wilmington Harbor containment area closely approximate proper conditions for applying the Thornthwaite-Mather approach. These conditions include abundant vegetation and abundant soil moisture. Thus, the Thornthwaite-Mather method should provide reasonable estimates which may be used to test results obtained from the water budget.

Drainage Efficiency

34. A further modification of the rainfall and the overland flow terms in the water budget leads to

$$RF - OF = (1 - C_d)RF \tag{11}$$

Thus, by simply measuring the rainfall and overland flow, the drainage efficiency may be calculated; methods for measuring rainfall and overland flow are presented below.

Rainfall and Class A Pan Evaporation

35. Original plans called for measuring the rainfall at the containment area. However, due to difficulties encountered during the relatively short field study period, no rainfall data were collected on site. Therefore, rainfall data provided by the US Weather Bureau for the Wilmington Airport, 6 miles from the containment area, were used in this study. Because there are no orographic barriers or other changes in physiography between the containment area and the Wilmington Airport, rainfall measured at the airport should approximate the actual rainfall at the containment area.

36. A Class A Evaporation Pan (US National Weather Service 1972) was placed on the surface of the containment area near Site 3 (Figure 3). The pan was placed on pallets so that evaporation was not influenced by changes in the ground temperature. Changes in water level within the pan were measured using a hook gage in a stilling basin. Water levels were measured weekly. The changes in the water level of the evaporation pan (dWL) were related to rainfall and evaporation by the relationship

$$EP = RF - dWL \tag{12}$$

Overland Flow

37. The amount of overland flow may be approximated by the amount of water leaving the containment area as surface water runoff. The quantity of runoff may be determined by (a) gaging the weirs using one of several available methods or (b) measuring the height of flow over the weir and using a standard equation to calculate quantities. Standard equations are available for calculating the discharge over either sharp-crested or broad-crested weirs. The weir crests at the Wilmington Harbor containment area are made of irregularly worn pieces of wood which are neither clearly sharp-crested nor broad-crested; thus, standard equations cannot provide accurate estimates of discharge. Therefore, initial plans called for measuring the runoff by gaging the outlet weir at the southern end of the containment area. However, at the beginning of the study, all four weir boxes were open, and only one could be effectively gaged. This situation was remedied early in September, when three of the weir boxes were closed. At this time, the one operational weir was instrumented with a Price Pygmy current meter and a Stevens Type A-71 water level recorder. The water level recorder was installed and its float was placed into a stilling well. Flow rates in the weir box were then calculated by measuring current velocities using the current meter. At least 10 verticals were measured at each water level. The flow rates at a number of water levels were measured, and a rating curve was constructed for the weir. The water level records obtained from the recorder were converted to flow rates using the rating curve.

38. During early October, the boards of the outlet weir were removed weekly. This continually lowered the water level in the weir and continually changed the outlet characteristics of the weir. Thus, the rating curve rapidly became useless and a new rating curve was essentially required every week. Under these conditions, rating the outlet weir became impractical; as a result, no useful runoff measurements could be obtained after the beginning of October.

Moisture Content and Void Ratio

39. The moisture storage term in the water budget equation, dW, was quantified by measuring the moisture content (by weight) of the desiccated

crust. Measurements were made weekly at five locations (Figure 3). A block of the crust was first lifted with a shovel. Then, 1-cm cubes were sampled throughout the crust. Samples were obtained at 1-cm intervals at depths between 0 and 20 cm, at 2-cm intervals at depths between 20 and 30 cm, and at 5-cm intervals below 30-cm. Each cube of soil was placed into a preweighed airtight container. The containers were returned to the lab, dried at 90° C overnight, cooled in a desiccator, and weighed to determine the moisture content of the sample.

40. Once the moisture content was determined throughout the crust, the average moisture content, P_{av}, was obtained by numerically integrating the following equation

$$P_{av} = \frac{1}{L} \int_0^L P \, dz \tag{13}$$

where

P = moisture content by weight at a point

L = thickness of the crust

z = vertical spatial coordinate which is 0 at the ground surface and increases downward

41. Because the other components of the water budget (Equation 10) have units of volume/area (i.e. length), the calculated values of P_{av} needed to be converted to equivalent units of length using Equation 14:

$$W = L \frac{\rho_b}{\rho} \frac{P_{av}}{(1-P_{av})} = L \, G_s \frac{W_w}{W_T} \tag{14}$$

where

W = volume of water contained in the crust per unit crust area

ρ_b = dry bulk density of the soil

ρ = density of water

G_s = specific gravity of solids

W_w = weight of water

W_T = total weight of the soil sample

The change in W, dW, was simply calculated by subtracting the value of W obtained for one sampling period from the value obtained the previous sampling period. The dry bulk density of the soil was measured using the sand cone method, Test D 1556 (American Society for Testing and Materials (ASTM) 1986). The dry density was also determined in conjunction with the void ratio determination (described in paragraph 41).

42. Moisture content data were obtained weekly throughout the entire thickness of the recently deposited dredged material at two of the sites. These data were used to determine the thickness of the desiccated crust. In the dense upper 20 cm of the dredged material, samples were obtained using the methods described in paragraph 38. Below the upper crust, an Eikjelkamp 2.5-cm-diam hand-driven coring tube was pushed into the dredged material to obtain a continuous sample. Samples were removed at 5-cm intervals and the moisture content determined as described above. In addition, several precisely measured cylinders of sediment 2 cm in length were obtained from the coring tube at different times. Because the volume of these samples was known, the dry bulk density could be calculated as part of the procedure for determining the moisture content. Once the dry bulk density was obtained, the void ratio, e, of these samples could be calculated by

$$e = \frac{\rho_s}{\rho_b} - 1 = \frac{G_s \gamma_o}{\gamma_{dry}} - 1 \qquad (15)$$

where

ρ_s = density of the soil particles

γ_{dry} = dry unit weight of dredged material

γ_o = unit weight of water at reference temperature, 4°C

The value of ρ_s was assumed to be 2.65 g/cc, a reasonable value for many common rock-forming and clay minerals (Hurlbut 1971). Cargill (1985) used a similar value of 2.60 g/cc in his studies of several containment areas.

43. For samples obtained below the water table, pores are by definition completely filled with water. Under these conditions, the void ratio may be calculated from measured moisture content values by

$$e = \frac{\rho_s}{\rho}\left(\frac{P}{1-P}\right) = 100\ \omega_c\ G_s \qquad (16)$$

where

w_c = weight of water divided by the weight of solids (in decimal form)

Water Supplied From Below the Crust

44. The moisture supplied to the crust from below is represented by the term CS in the water budget (Equation 10). A method for calculating CS may be obtained by defining dW' as the change in moisture in a desiccated crust where CS is zero. From this definition

$$CS = dW - dW' \qquad (17)$$

Methods have been presented above to calculate dW, and potentially dW'. Thus, if a method can be developed to ensure that CS is zero in part of the crust, the value of CS for the remaining crust can be calculated using Equation 17.

45. Lysimeters represent the usual means of isolating part of a body of soil for making soil moisture measurements. Originally, the plan was to install large lysimeters constructed with devices to collect vertical drainage similar to standard lysimeters described in the literature (Mather 1984). However, because the desiccated crust had formed, cracked, and become vegetated by the beginning of the study, large lysimeters could not be installed without destroying the existing crust and vegetation. Therefore, small lysimeters were installed at each of the five sites illustrated in Figure 3. Initially, large cracked blocks (typically about 50 by 50 cm) were lifted out of the crust, trimmed if necessary, and the sides and bottom were wrapped in clear plastic. The plastic was carefully trimmed even with the upper surface of the block; then the plastic was fastened to the upper surface of the block using pins. The plastic was fastened tightly to the edge of the block so surface water could run off of the upper surface of the block and into the cracks which surround the block.

46. After the end of August, another type of lysimeter was required because (a) the dense mat of vegetation made removing cracked blocks difficult and (b) the amphibious vehicle used to trample the vegetation tended to

fracture the soil into blocks that were too small to wrap. Thus, new lysimeters were used from September through December. These consisted of aluminum pots approximately 30 cm in diameter and 20 cm deep. A cylinder of the desiccated crust was cut as precisely as possible to the shape of the lysimeter, lifted out of the ground, and placed into the lysimeter. Now filled with soil, the lysimeter was then placed into the hole cut into the crust with the top of the instrument flush with the ground surface.

47. As discussed in paragraph 45, lysimeters should generally be equipped with devices to drain and collect infiltration. This is needed to maintain the moisture content of the material within the lysimeter similar to that of the surrounding soil. Adequate drains could not be designed for the small lysimeters used in this study. Therefore, these lysimeters provided reliable data for short periods only, when (a) no rainfall occurred and (b) the moisture content of the soil within the lysimeter did not deviate substantially from that of the surrounding soil. As a result, the soil in the lysimeters was replaced weekly or both before and after every rainfall (if possible). The moisture content of the lysimeter soil was measured using the same methods described above for measuring the moisture content of the surrounding soil. Because the bottoms of the lysimeters were impermeable, CS was zero for the soil in the lysimeters; therefore, these devices provided a means of measuring dW'. It should be noted that these lysimeters require frequent tending, particularly during periods of frequent rainfall, and therefore they are a highly labor-intensive means of determining dW'.

Measuring the Percent Saturation of the Dried Crust

48. The percent saturation of the dried crust, PS, may be calculated from measurements of moisture content; the frequency, width, and depth of cracks, and the void ratio.

49. The geometry of the cracks was measured by laying a 50-m tape along the surface of the dredged material. The tape was used to determine the location of each crack intersected by the tape. In addition, the width and depth of each crack was measured using a meter stick. These data provide the basis for calculating P_c, the percentage of the dried crust occupied by cracks, as

$$P_c = \sum_{i=1}^{n} \frac{Ai}{RL} \tag{18}$$

where

A_i = cross-sectional area of crack i (measured in a vertical plane)

n = number of cracks encountered in a survey of length R

L = thickness of the desiccated crust

The area of crack i is defined by

$$A_i = w_i D_i SF \tag{19}$$

where

w_i = width of crack i

D = depth of crack i

SF = crack shape factor which equals 1 for a rectangular crack and 1/2 for a triangular crack

Because detailed measurements of crack morphology were not obtained, an intermediate value of 0.75 was used for SF. The thickness of the desiccated crust in Equation 18 is also difficult to determine precisely. A nominal value was defined by adding the mean and standard deviation of the crack depths for each survey.

50. The data described in the preceding paragraphs lead to a method for calculating the percent saturation (PS) of the desiccated crust (including cracks):

$$PS = \left\{ \left[\frac{\rho_s}{(1+e)\rho} \right] \left[\frac{P}{(1-P)} \right] (1-P_c) + P_c P_w \right\} \left[\frac{1}{\frac{e}{1+e} \quad (1-P_c) + P_c} \right] \tag{20}$$

where

P_w = water content (by weight) of the crack itself

Generally, P_w should be zero for the desiccated crust.

Measuring the Depth to the Water Table

51. Observation wells were installed at each of the five sites illustrated in Figure 3. These observation wells were constructed of 4-in.-diam-polyvinyl chloride pipe. The lower half of each tube was slotted, and the slots were covered with fine cloth to keep the wells from filling with soft dredged material. The wells were pushed down through the entire thickness of the recently deposited material and were then capped. The distance from the top of the observation well to the water table and to the ground surface were measured weekly.

PART V: RESULTS

Climatic Conditions During the Study

52. Climatic data for the period of the study are summarized in Table 2. The monthly average temperature for August and September was very similar to the long-term average temperatures for these months. October was slightly cooler than average, and November was slightly warmer than average. August precipitation was equal to the long-term average, while precipitation for September was greater than average. Precipitation for October was lower than average, with precipitation for November slightly greater than average. Overall, total precipitation during the study was slightly greater than the long-term average precipitation for these months.

Table 2

Monthly Mean Temperature, Rainfall, and Potential Evapotranspiration During the Study

Month	Mean Temperature °C	Mean Temperature, Period of Record* °C	Rainfall cm	Ave. Rainfall, Period of Record* cm	Potential Evapotranspiration (Thornthwaite-Mather Method)
August	23.8	23.7	10.20	10.20	11.39
September	20.2	19.9	12.32	9.12	9.23
October	11.4	13.5	5.74	7.34	4.16
November	8.9	7.6	8.89	8.46	2.60
Total			37.15	35.12	27.38

* 29 years at the Wilmington Airport.

Evaporation efficiency

53. The values of the evaporation efficiency, calculated from the water budget, are plotted as a function of time in Figure 4. Considerable variation is apparent; the values range from close to 1.0 to as small as 0.1, without any clear pattern of temporal dependence.

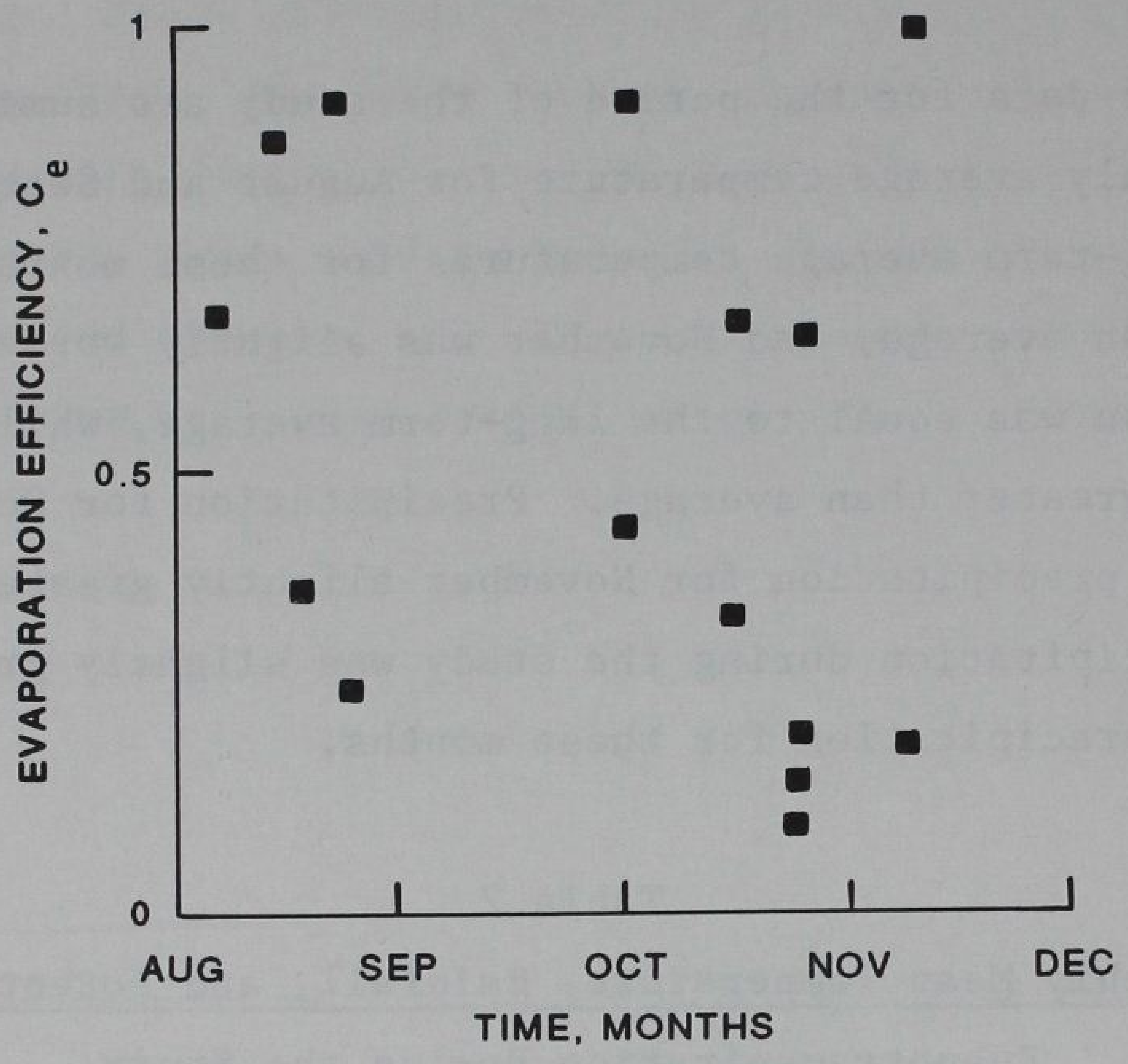


Figure 4. Evaporation efficiency (calculated from the water budget) as a function of time during the study

54. Figure 5, however, illustrates that the amount of soil moisture loss (evapotranspiration) and the measured pan evaporation are closely related. To develop Figure 5, pan evaporation was measured, and these values were used in Equation 1 to obtain corresponding values of soil moisture loss; these data are plotted as solid squares in Figure 5. The Thornthwaite-Mather method was then used to calculate soil moisture loss (evapotranspiration); these values were used in Equation 1 to calculate pan evaporation, and the corresponding values are plotted as open circles in Figure 5. The equation of the regression line of Figure 5 is

$$E = 0.722EP - 0.0349 \qquad (21)$$

Equation 21 has a correlation coefficient (r^2) of 0.74. These results suggest that the evaporation efficiency can be reasonably represented by a constant for the period of the study, and the constant value of the evaporation efficiency is the slope of the regression curve (Equation 21). Thus, a constant

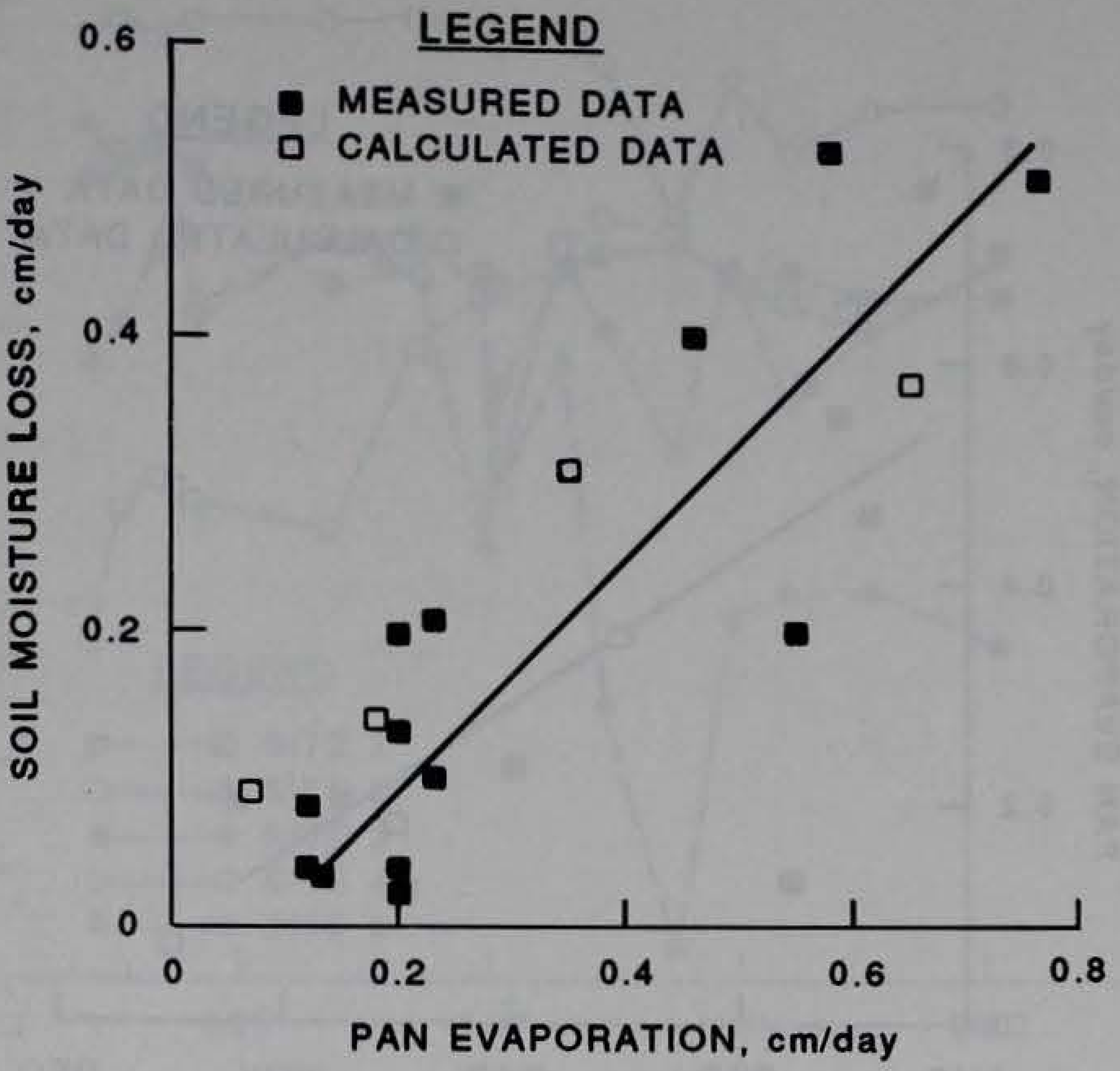


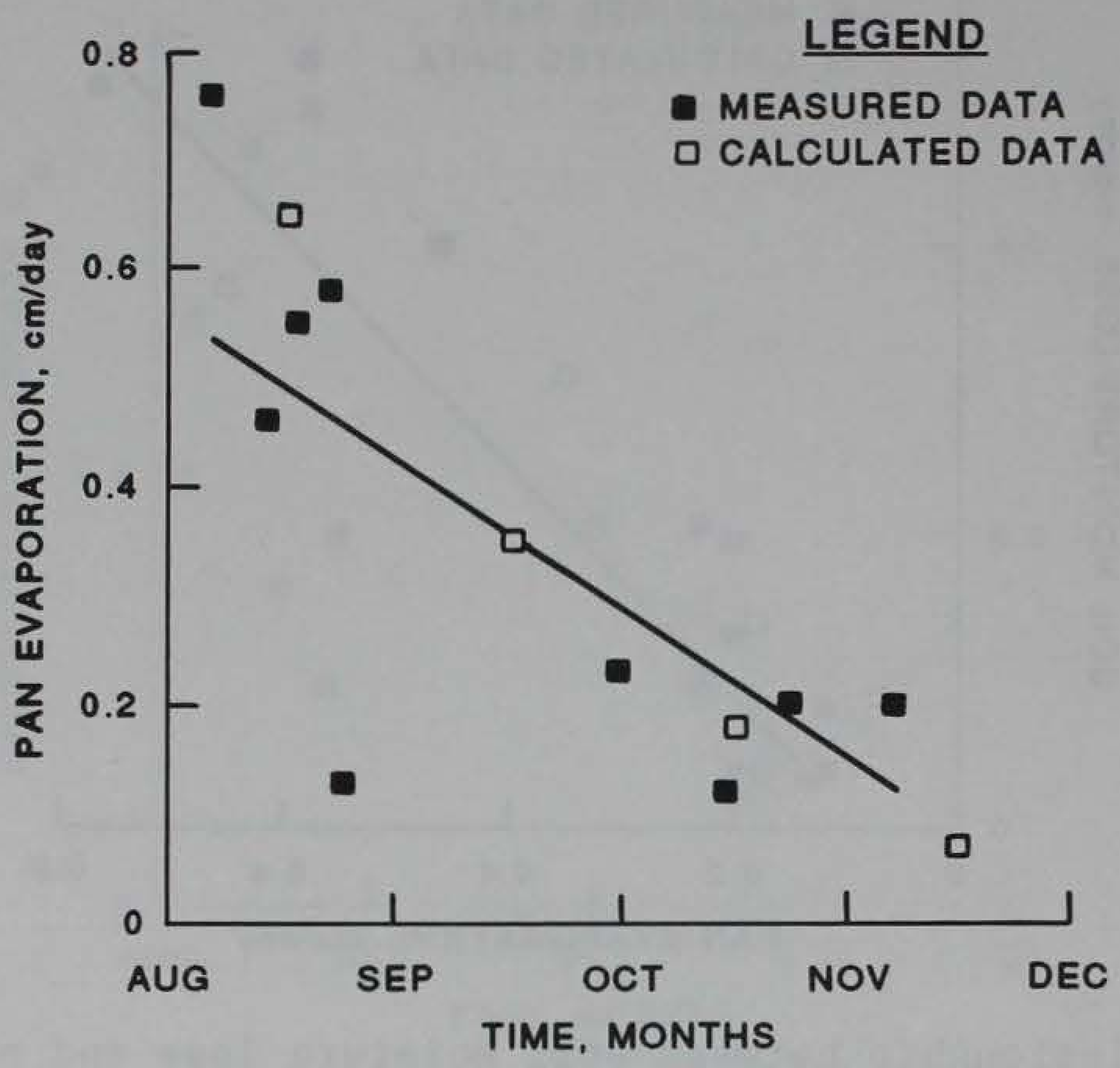
Figure 5. Relationship between soil moisture loss and pan evaporation with open squares indicating soil moisture loss estimates obtained using the Thornthwaite-Mather method

value of 0.72 is a good estimate for the evaporation efficiency for the entire period of the study.

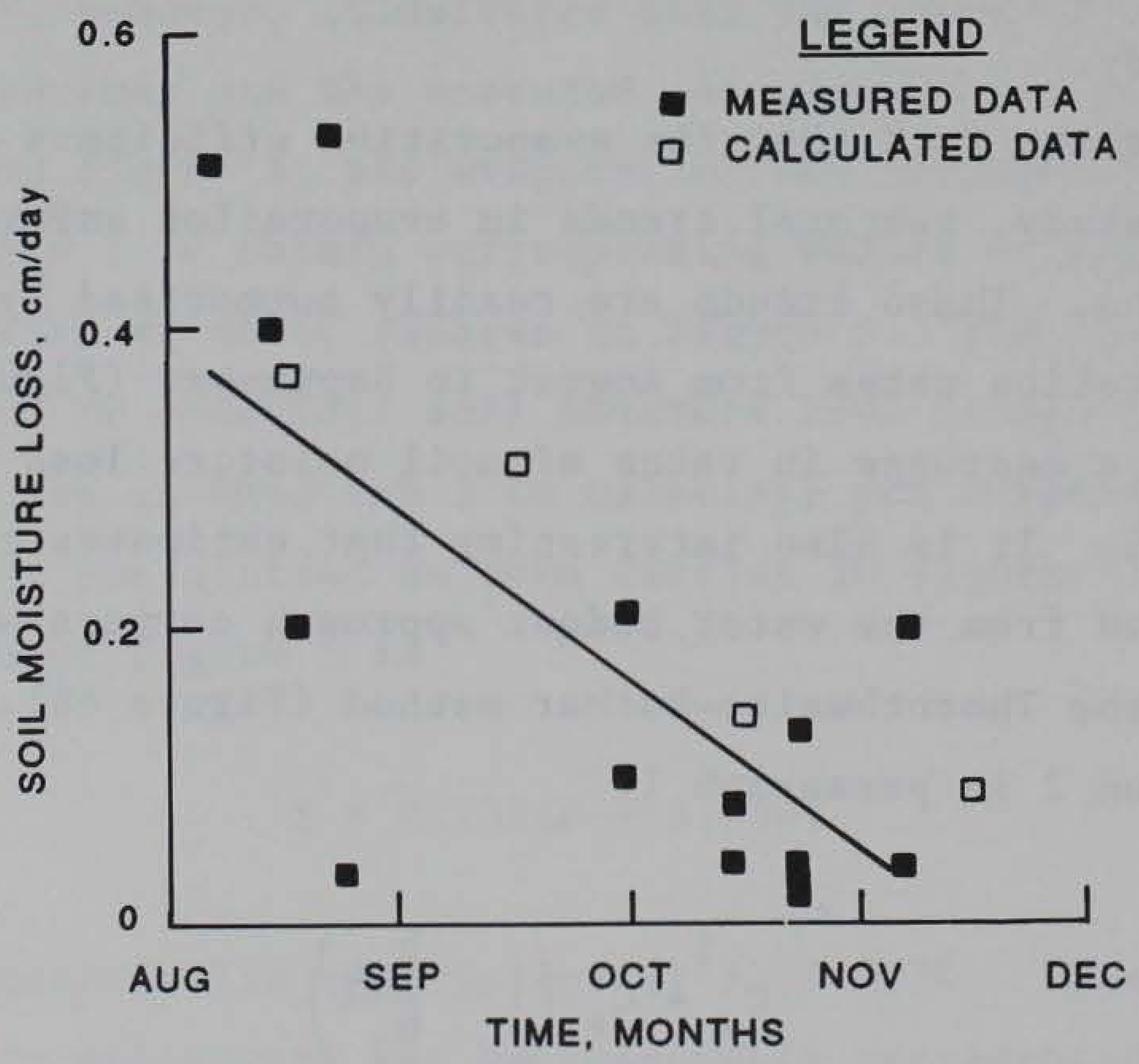
55. Despite the fact that the evaporation efficiency was nearly constant during the study, temporal trends in evaporation exist due to seasonal climatic variations. These trends are readily summarized by a decrease in Class A pan evaporation rates from August to September (Figure 6a), which are also reflected in a decrease in rates of soil moisture loss during the same period (Figure 6b). It is also interesting that estimates of soil moisture loss rates obtained from the water budget approach compare well with estimates calculated using the Thornthwaite-Mather method (Figure 6b).

56. Equation 2 in paragraph 11

$$C_e = C'_e \left(1 - \frac{h_{wt}}{h_2}\right) \qquad \text{(2 bis)}$$



a. Pan evaporation



b. Soil evaporation

Figure 6. Pan evaporation and soil evaporation as a function of time during the study

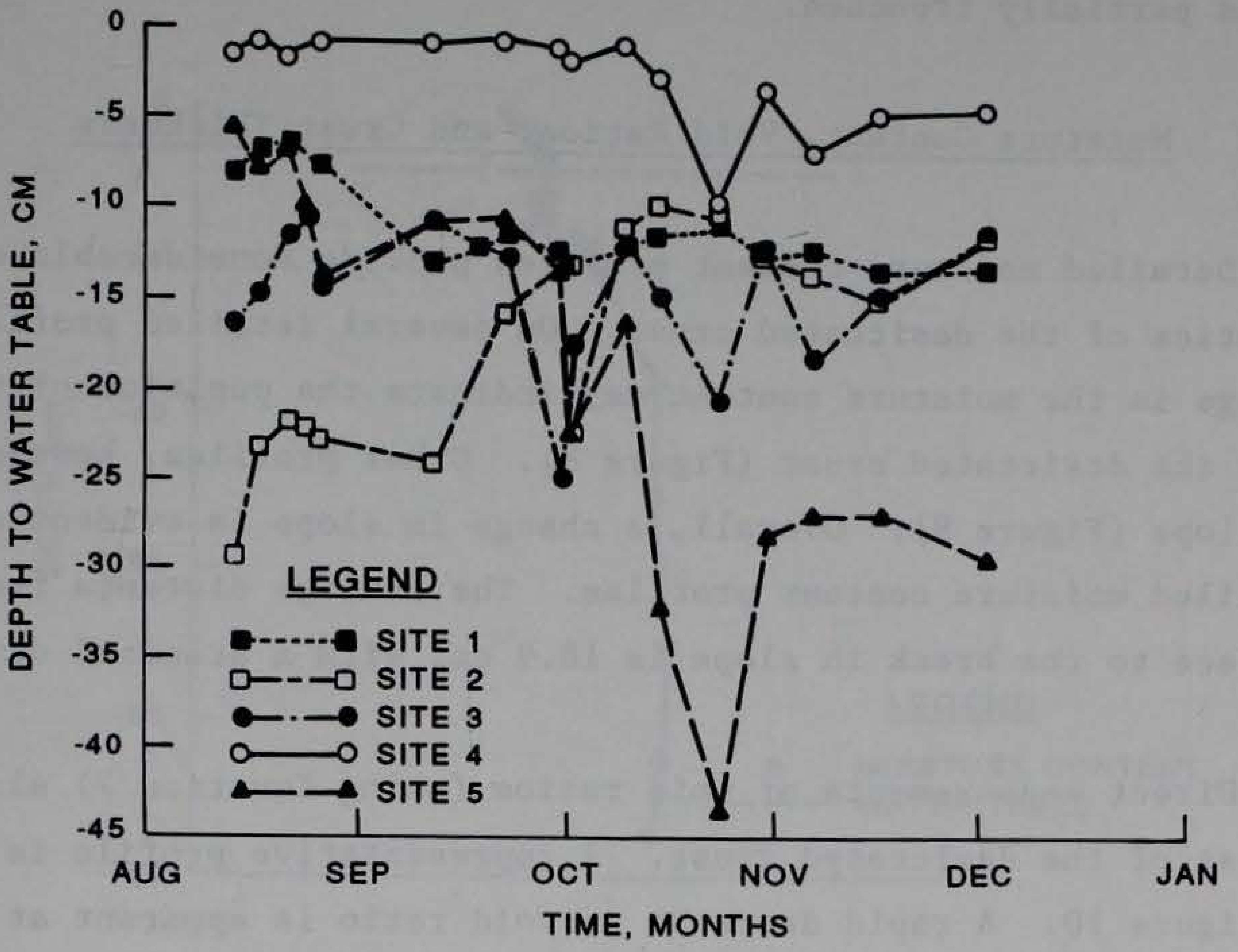


Figure 7. Water level records from observation wells at the five study sites

suggests that trends in the evaporation efficiency should be related to changes in the elevation of the water table. This model is partly based on the assumption that the water table should slowly fall as the dredged material desiccates. Water level records from the piezometers, however, present a more complex picture (Figure 7). At Sites 1, 4, and 5 the water level fell by varying amounts relative to the surface of the dredged material. At Site 3 little change was observed in the distance from the material surface to the water table. At Site 2, the water table actually rose toward the ground surface. During these changes, however, the evaporation efficiency showed no discernible change. Thus, Equation 2 is a poor model for predicting the evaporation efficiency at the Wilmington Harbor site.

Drainage efficiency

57. Only three estimates of the drainage efficiency could be made because of the difficulty of measuring surface water runoff from the containment area. During the period when the outlet weir was effectively gaged, rainfall events of 0.51 cm, 2.16 cm, and 0.76 cm occurred. These rainfall events yielded estimates of the drainage efficiency of 0.24, 0.17, and 0.21,

respectively. These results were obtained when the surface of the dredged material was partially trenched.

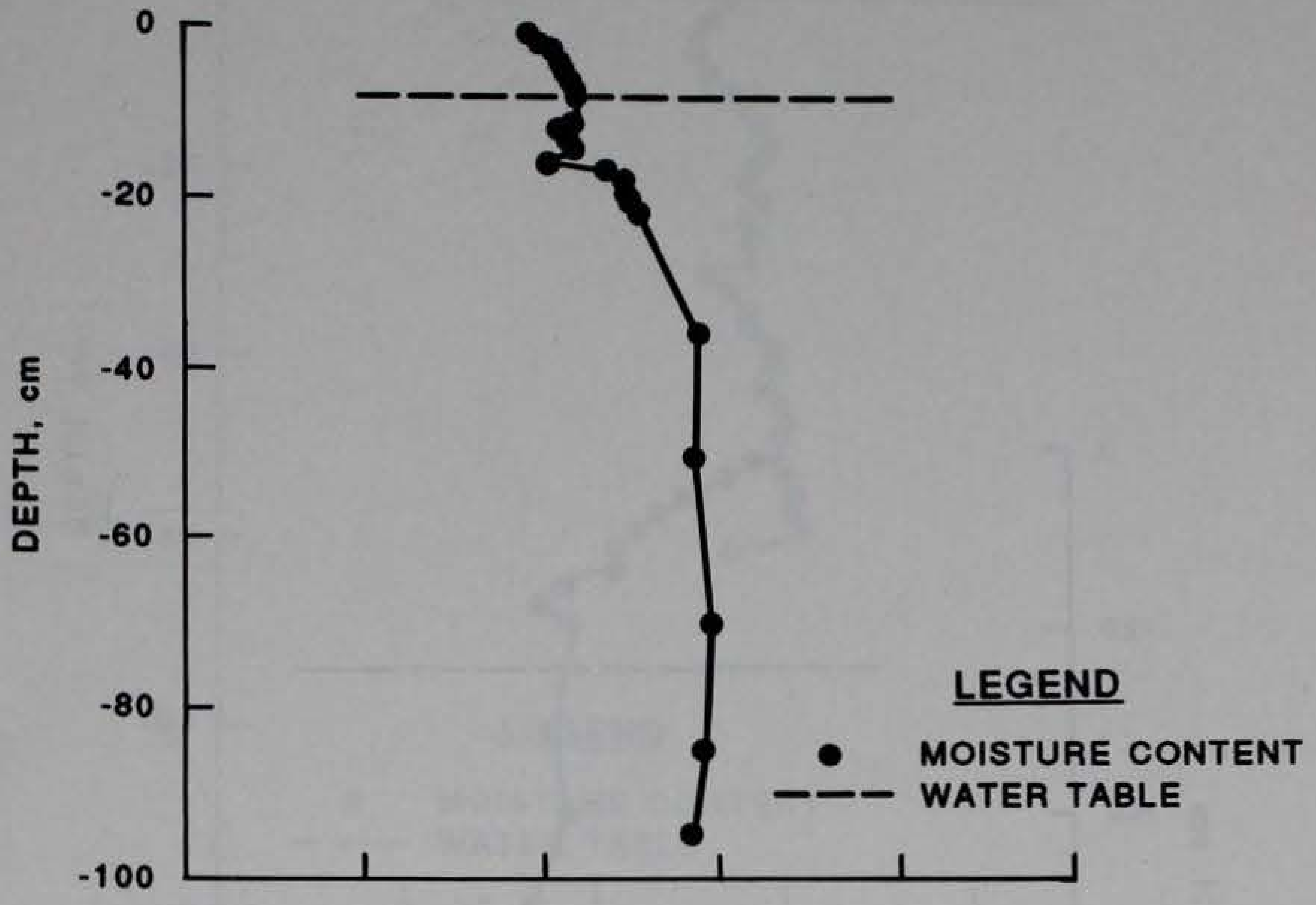
Moisture Content, Void Ratios, and Crust Thickness

58. Detailed moisture content profiles provide considerable data on the characteristics of the desiccated crust. On several detailed profiles, an abrupt change in the moisture content may indicate the position of the lower boundary of the desiccated crust (Figure 8). Other profiles, however, show no change in slope (Figure 9). Overall, a change in slope is evident on 14 of 17 of the detailed moisture content profiles. The average distance from the ground surface to the break in slope is 18.9 cm, with a standard deviation of 6.5 cm.

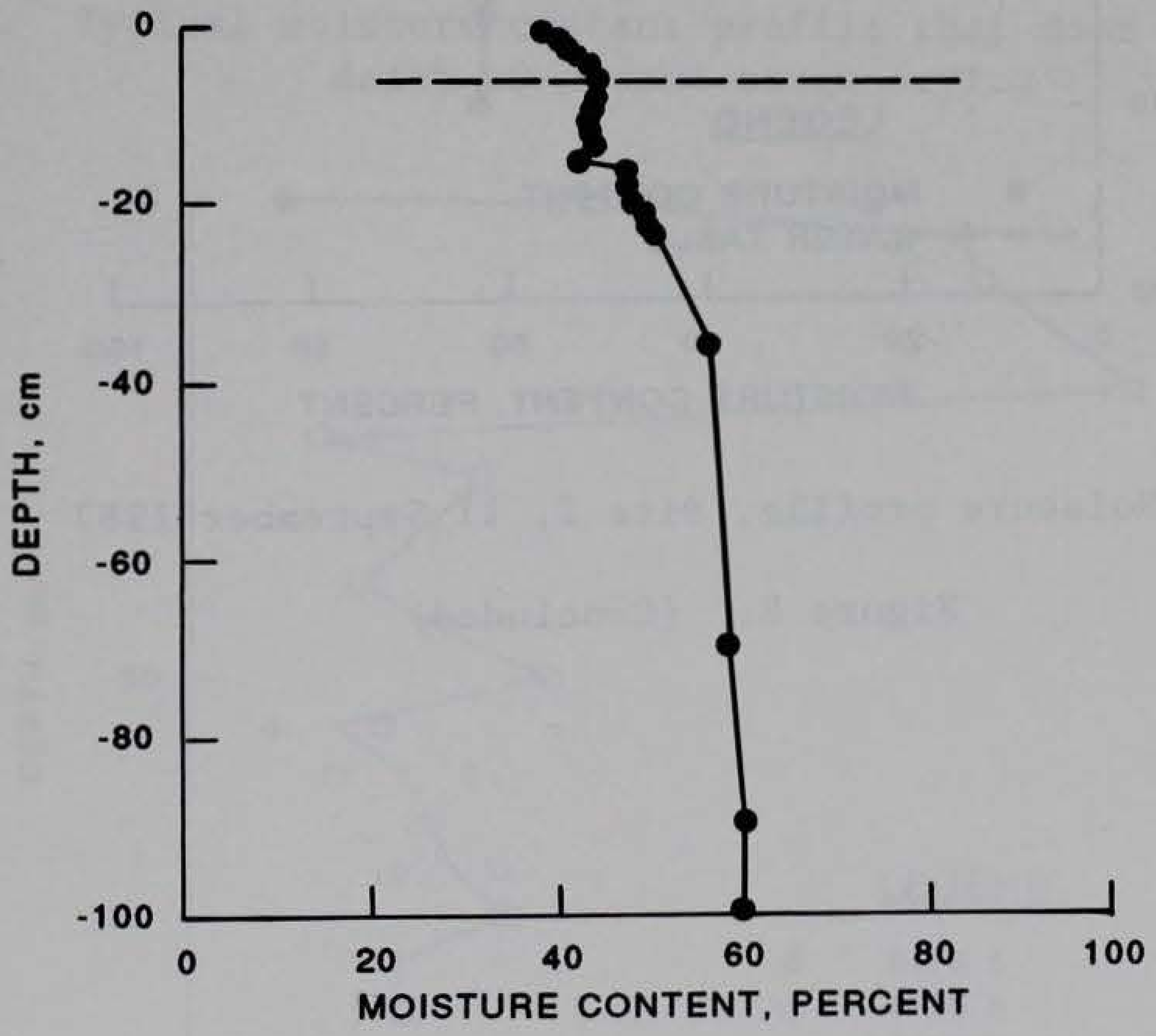
59. Direct measurements of void ratios (using Equation 7) also indicate the thickness of the desiccated crust. A representative profile is illustrated in Figure 10. A rapid decrease in void ratio is apparent at a depth of approximately 20 cm, suggesting that the base of the desiccated crust is near this depth. In addition, these data also suggest a mean value of the desiccation limit of 2.69, with a standard deviation of 0.61; this value was obtained by averaging 40 direct void ratio measurements within the upper 20 cm of the dredged spoil material.

60. At Site 4, the water table remained near the ground surface during most of the study. Several detailed moisture content profiles provide an additional means of calculating void ratio profiles (Figure 11). These profiles do not clearly provide an obvious indication of the thickness of the desiccated crust. However, because the water table has remained close to the surface, the void ratio under these conditions may be close to the saturation limit. Averaging all void ratios determined at Site 4 and also at other sites when the water table was at or very near the surface (a total of 30 different measurements of void ratio) yields a mean value of 3.02 for the saturation limit, with a standard deviation of 0.25.

61. Measurements of the depth of cracks in the surface of the dredged material provide an additional estimate of the depth of the dried crust. Data obtained at Sites 1 and 2 (Figure 12) indicate maximum depths of cracking of 18 and 22 cm, respectively.

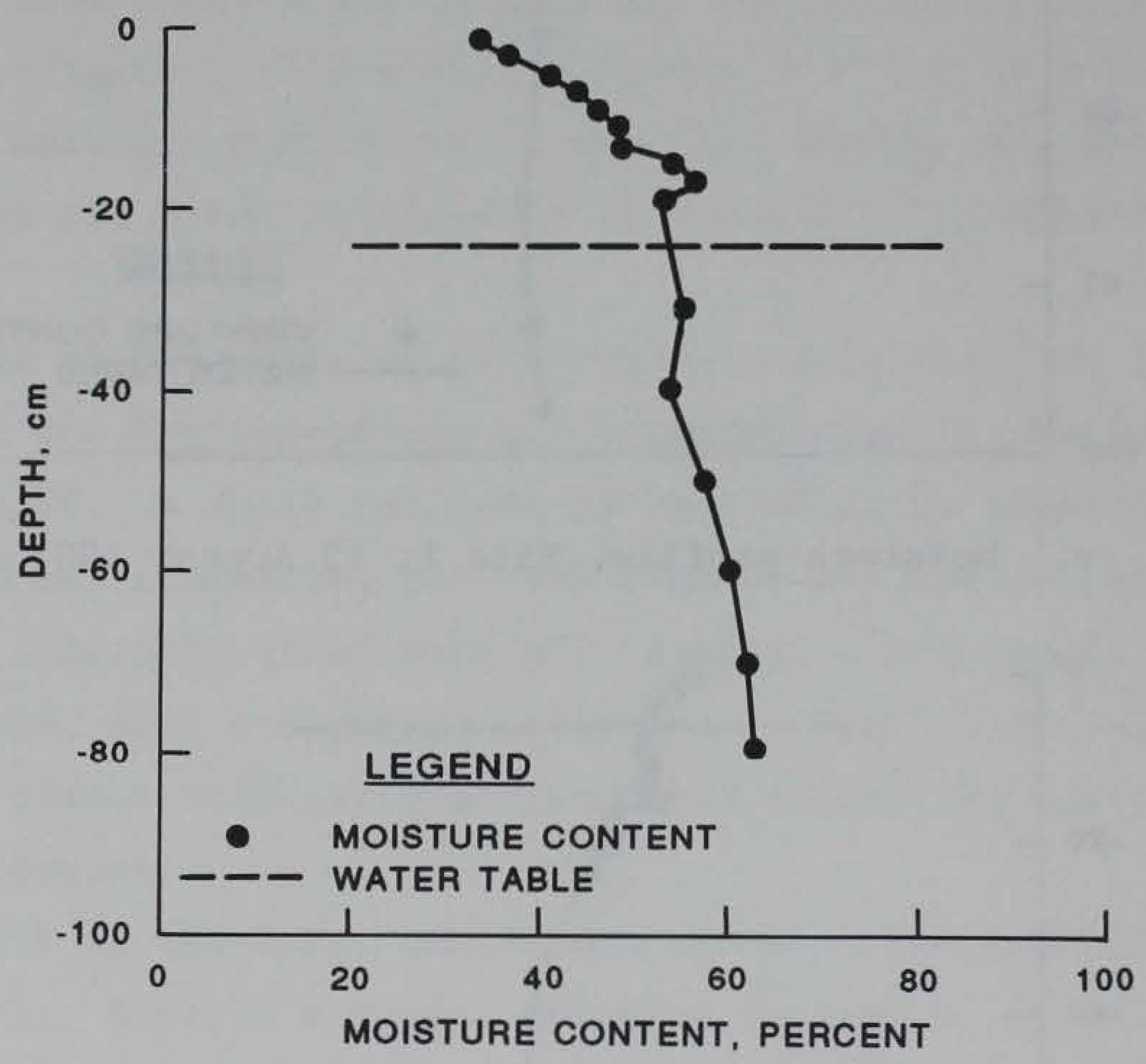


a. Moisture profile, Site 1, 13 August 1987



b. Moisture profile, Site 1, 21 August 1987

Figure 8. Detailed moisture content profiles that provide data on the depth of second-stage drying (Continued)



c. Moisture profile, Site 2, 11 September 1987

Figure 8. (Concluded)

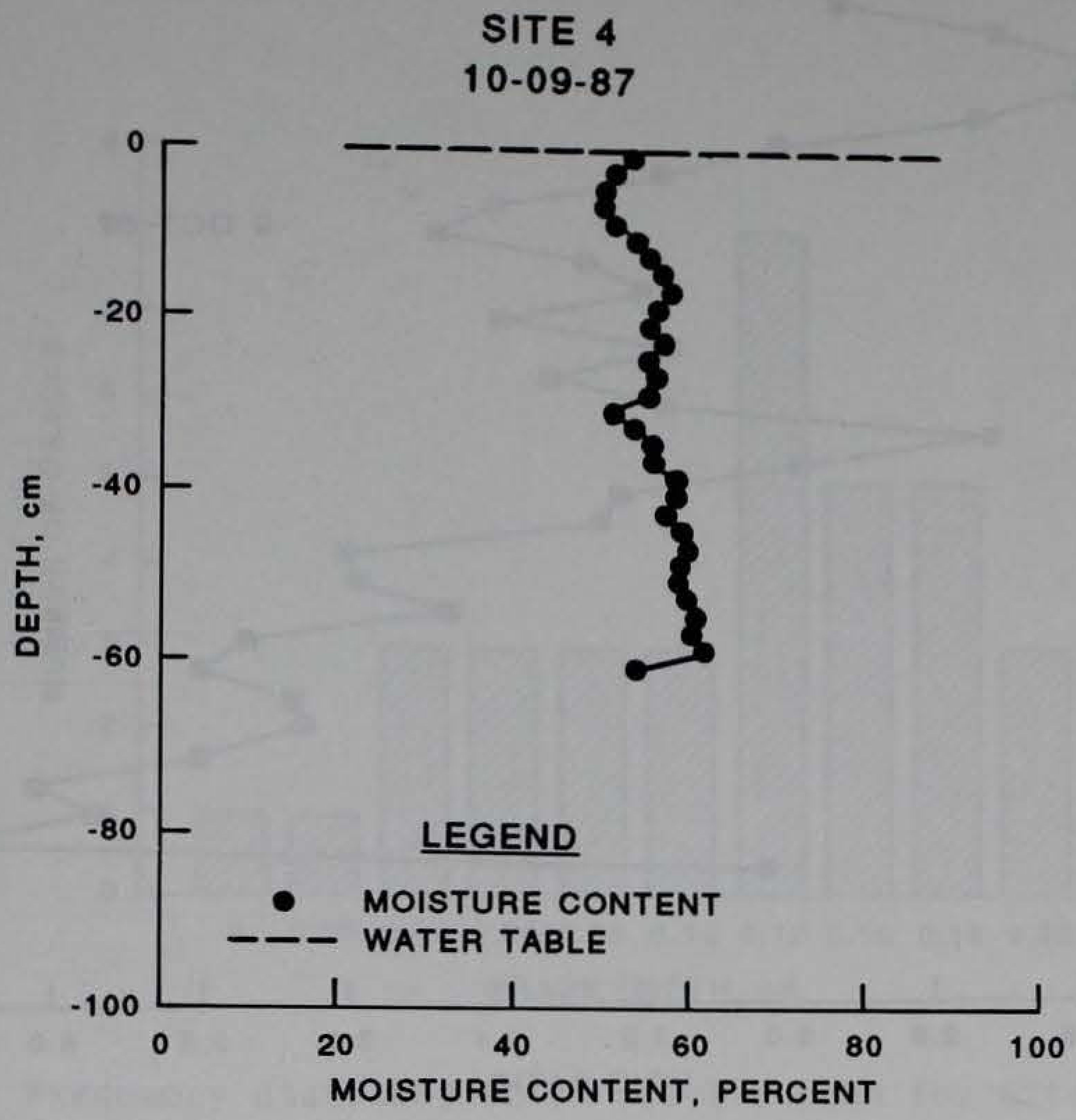


Figure 9. Typical moisture content profile that does not indicate the depth of second-stage drying

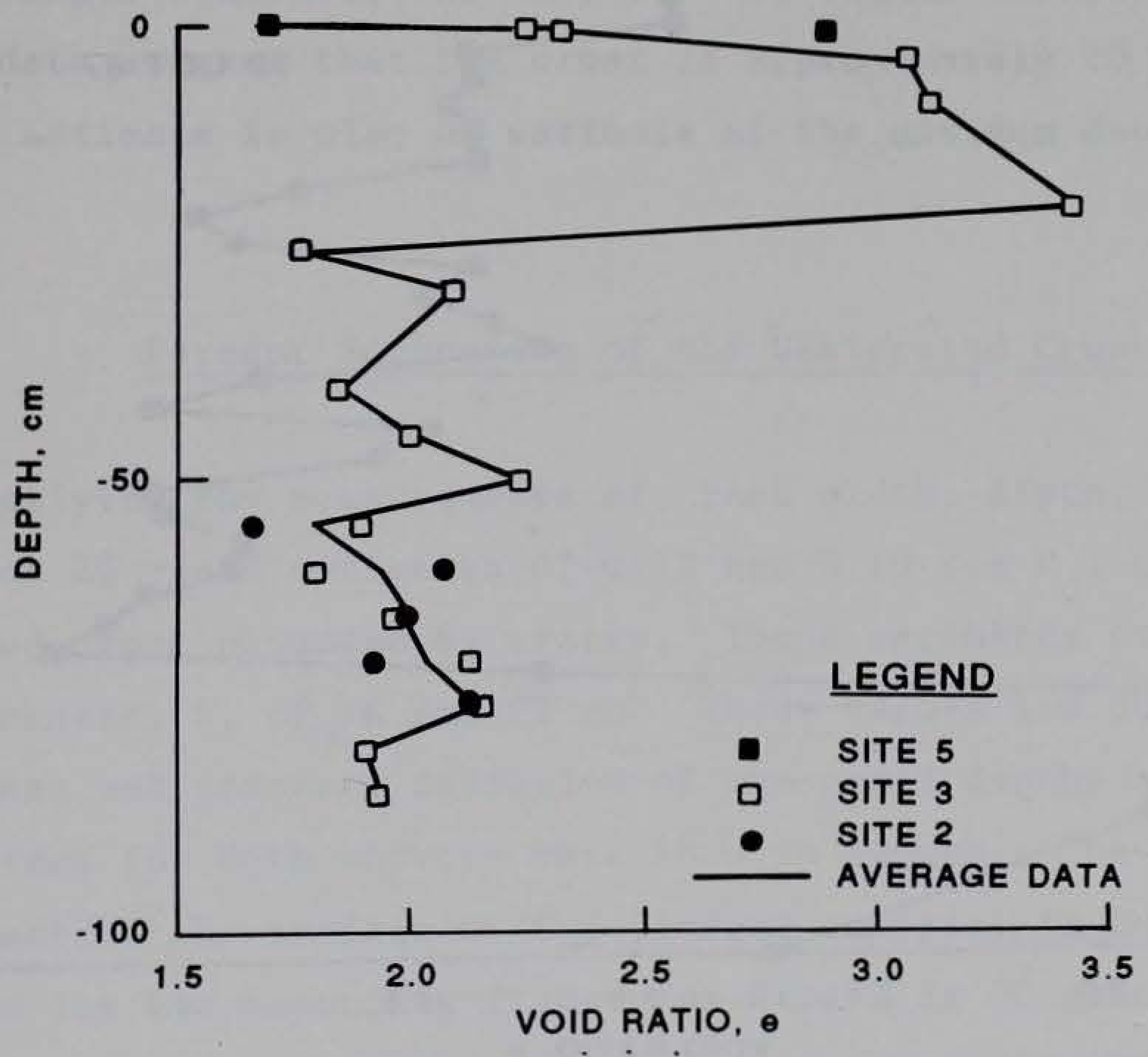


Figure 10. Void ratio profiles for three sites and the averaged profile

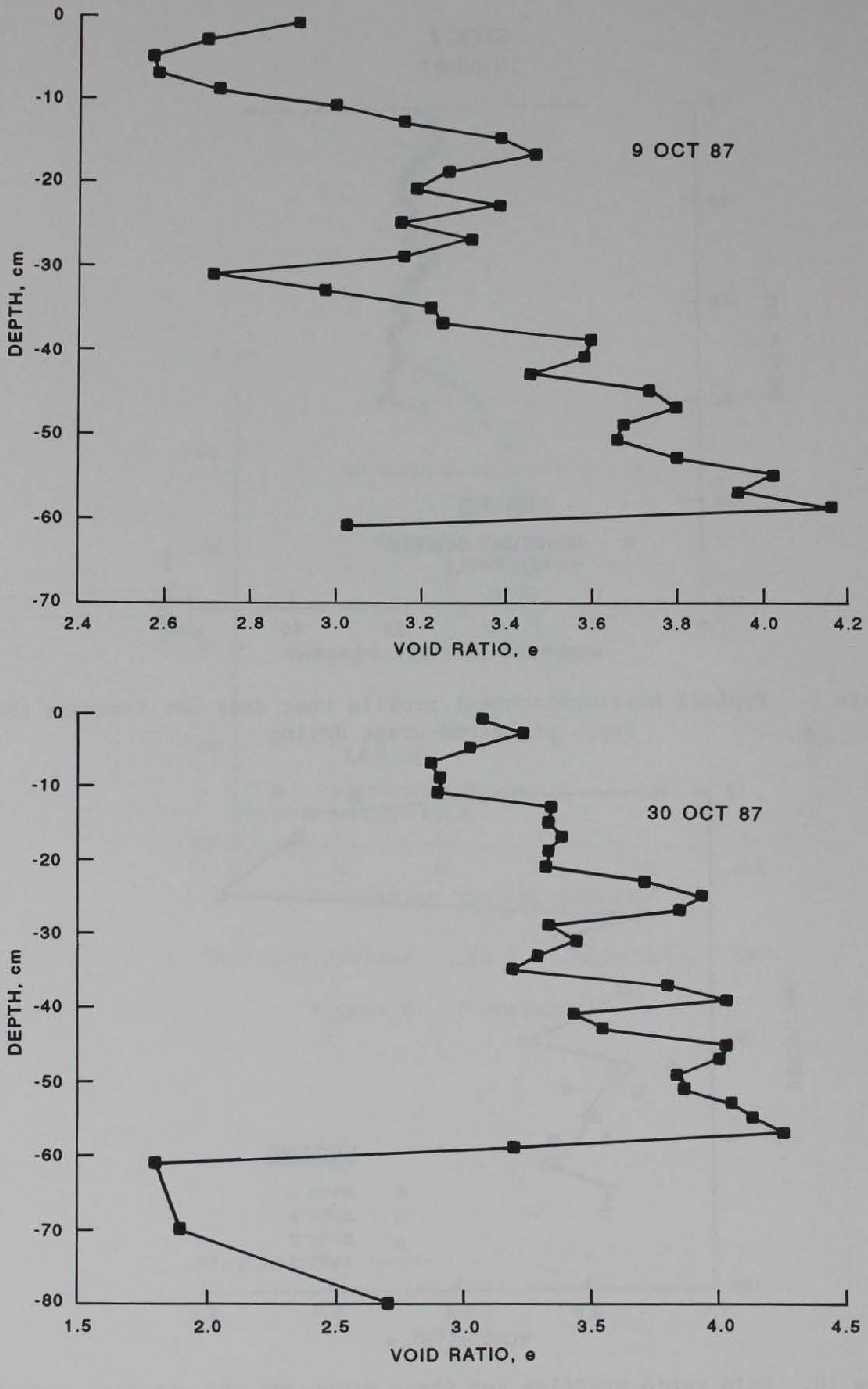


Figure 11. Void ratio profiles calculated from moisture content profiles on two dates at Site 4

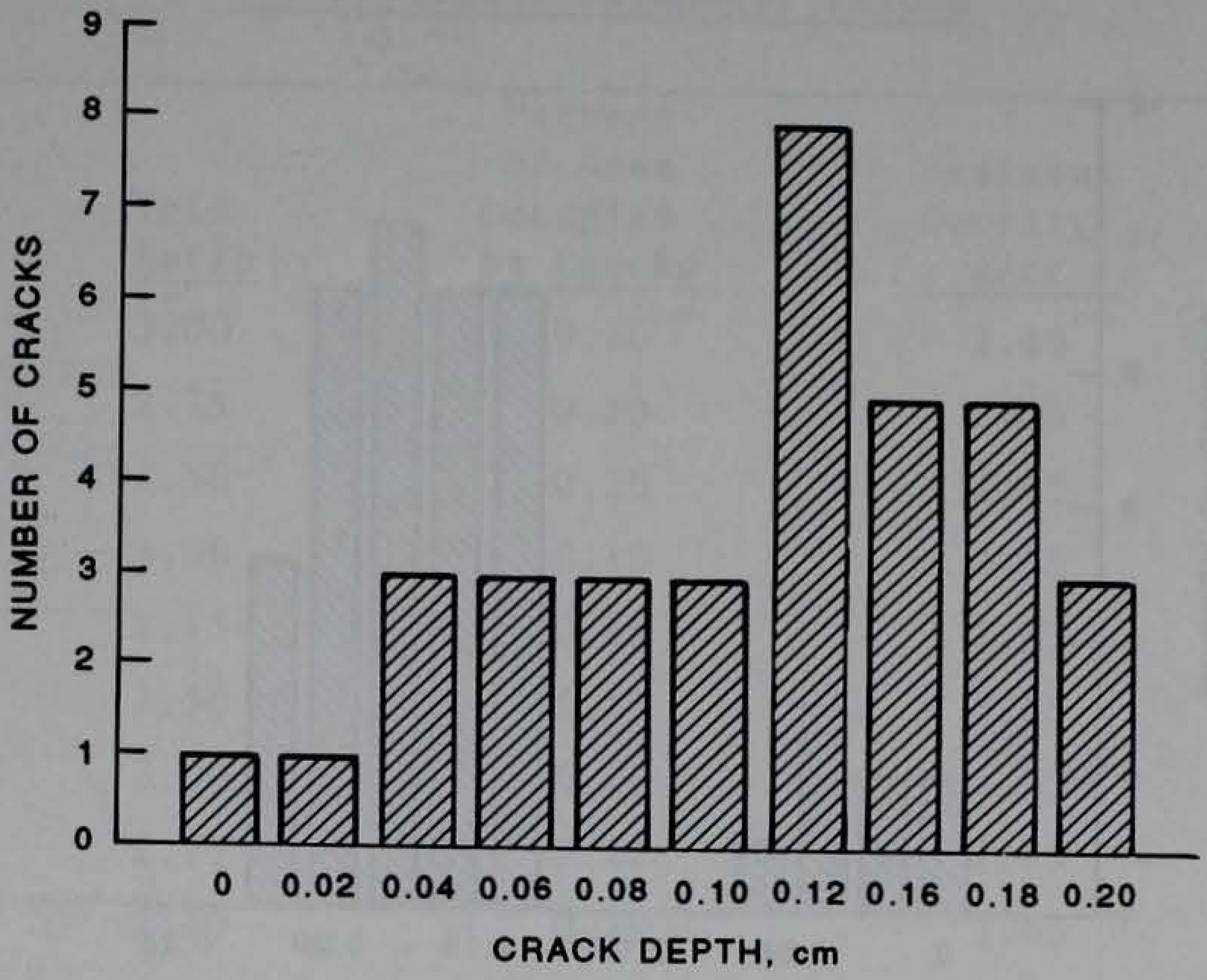


Figure 12. Frequency distribution of crack depths for Site 1, 24 July 1987

62. The estimates quoted in Figure 12 for the thickness of the desiccated crust differ somewhat, but they are all within a relatively narrow range. The data suggest that the crust is approximately 20 cm thick. Of course, this estimate is also an estimate of the maximum depth of second-stage drying.

Percent Saturation of the Desiccated Crust

63. Applying the measurements of crack width, depth, and spacing and using Equation 20 yield estimates of 0.12 and 0.19 for P_c, the percentage of the desiccated crust occupied by cracks. These estimates are based on values of crust thickness, L, of 16 and 22 cm. These values are obtained from the sum of the mean and standard deviation of the crack depths at each survey. The survey lines for both surveys were 10 m in length. The data also indicate that 21 percent of the surface of the dredged material is covered by cracks at Site 1, while the corresponding figure for Site 2 is 30 percent (Figure 13).

64. The values of percent saturation of the desiccated crust calculated for different physical properties are presented in Table 3. Clearly, the

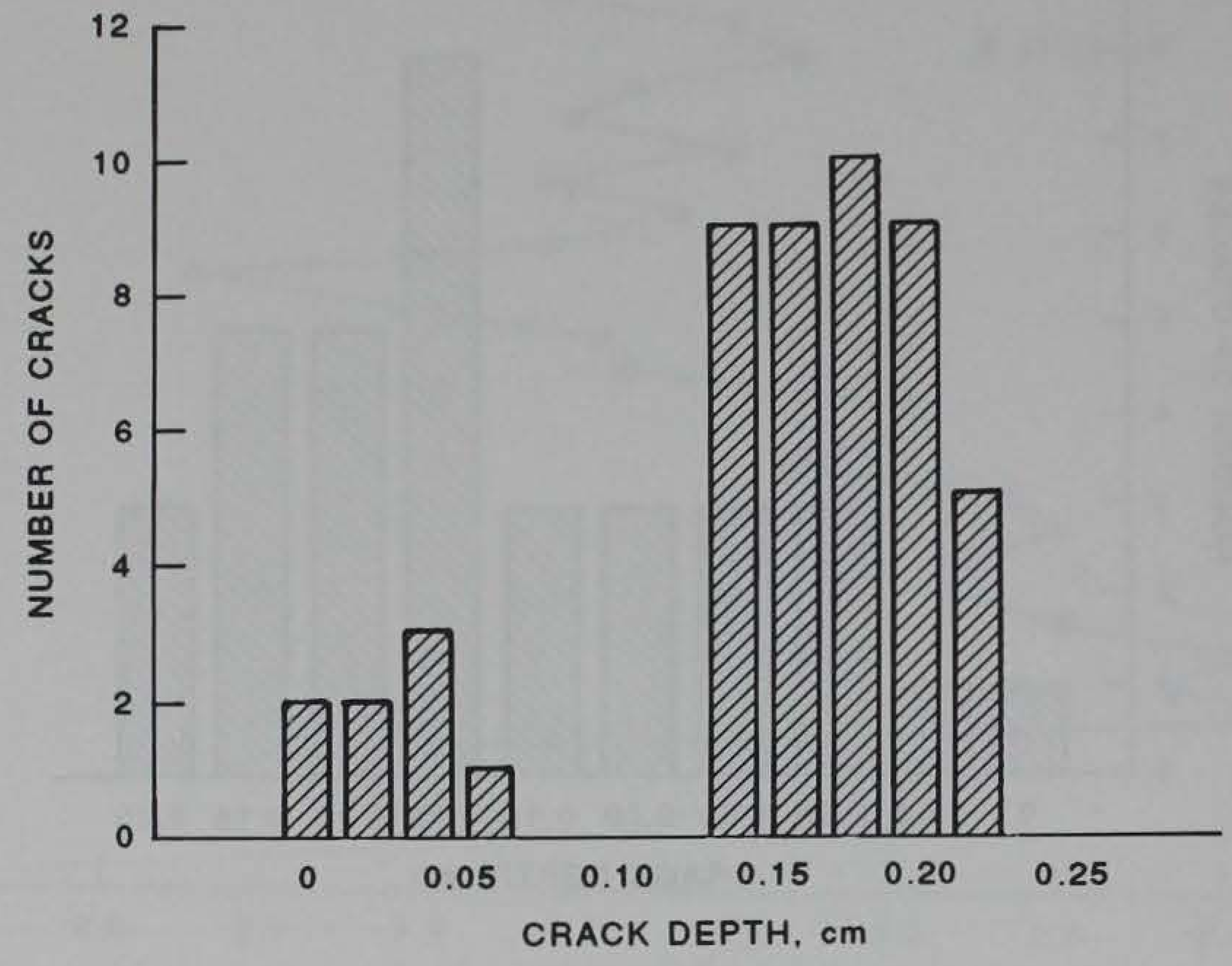


Figure 13. Frequency distribution of crack depths for Site 2, 5 August 1987

calculated values of PS are related to variations in moisture content, void ratio, and the percentage of the crust occupied by cracks. The calculations in Table 2 suggest that a reasonable average estimate of PS is approximately 0.60, with a standard deviation of about 0.10.

Table 3

Percent Saturation Estimates for Desiccated Crust for Different Parameter Values

Moisture Content	Void Ratio	Percent of Area Occupied by Cracks	Sediment Density g/cc	Percent Saturation PS*
0.45	3.00	0.20	2.65	0.54
0.45	2.75	0.20	2.65	0.59
0.45	2.50	0.20	2.65	0.64
0.45	3.00	0.15	2.65	0.59
0.45	2.75	0.15	2.65	0.64
0.45	2.50	0.15	2.65	0.70
0.55	3.00	0.20	2.65	0.81
0.55	2.75	0.20	2.65	0.88
0.55	2.50	0.20	2.65	0.96
0.55	3.00	0.15	2.65	0.87
0.55	2.75	0.15	2.65	0.95
0.55	2.50	0.15	2.65	1.04**
average				0.74 ± 0.16

---

* Calculated using Equation 20 assuming that $P_w = 0$.

** Not used to calculate average.

PART VI: DISCUSSION AND INTERPRETATION

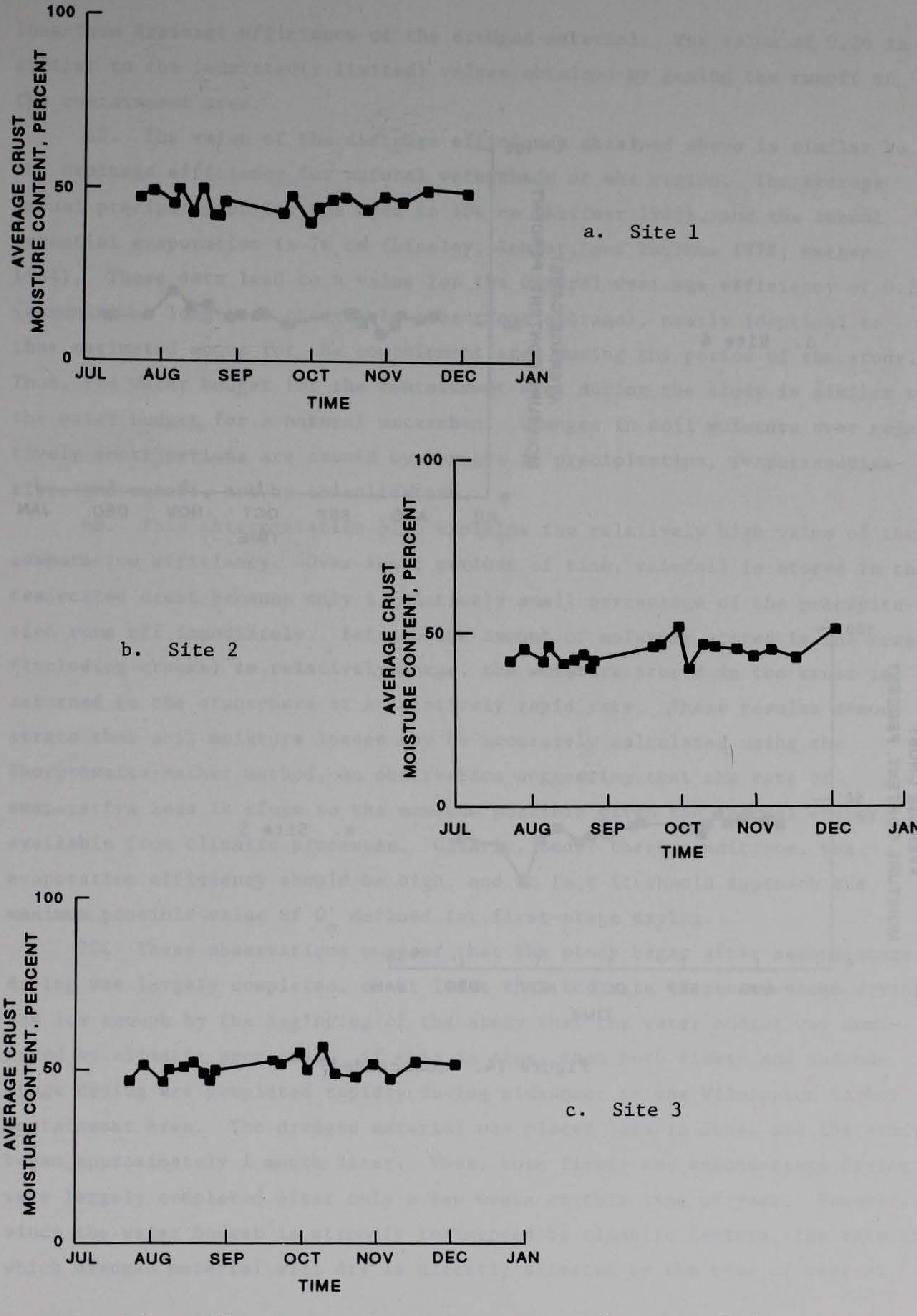
65. The results presented do not clearly fit the two-stage desiccation model described in Part I. The evaporation efficiency does not decrease exponentially as expected; rather, it is approximately constant during the study. Furthermore, the average value of 0.72 for the evaporation efficiency is rather high. A lower value of the evaporation efficiency would be expected during the latter stages of desiccation and consolidation. Furthermore, the drainage efficiency is much lower than expected. The average value of 0.21 is much lower than values near 1.00 used by Cargill (1985).

66. These discrepancies may be understood by considering the water budget for the desiccated crust for the entire period of study. The clearest indication of the state of the long-term water budget is provided by temporal trends in the average moisture content of the desiccated crust for the five study sites (Figure 14). These data clearly indicate that the moisture content of the desiccated crust did not change significantly during the study. This conclusion is supported by temporal trends in the elevation of the water table of the five sites. Although the water table declined slightly at three of the sites (Figure 7), no change in the elevation of the water table was observed at one of the other sites, and the water table actually increased in elevation at another site.

67. The evidence presented clearly indicates that the water budget for the desiccated crust during the study represents storage and transport of moisture derived from precipitation, not moisture derived from consolidation of the dredged material. This conclusion, which is required by the moisture content data presented in Figure 14, also explains the seemingly anomalous values of the evaporation efficiency and the drainage efficiency. Consider the long-term water budget for the dredged material suggested by the moisture content data,

$$0 = RF - E - OF \qquad (22)$$

During the study, 37.2 cm of rainfall fell on the containment area (Table 1). The potential evapotranspiration calculated using the Thornthwaite method for the period of the study is 27.4 cm. These quantities, when inserted into Equation 22, yield 9.8 cm of runoff, which gives a value of 0.26 for the

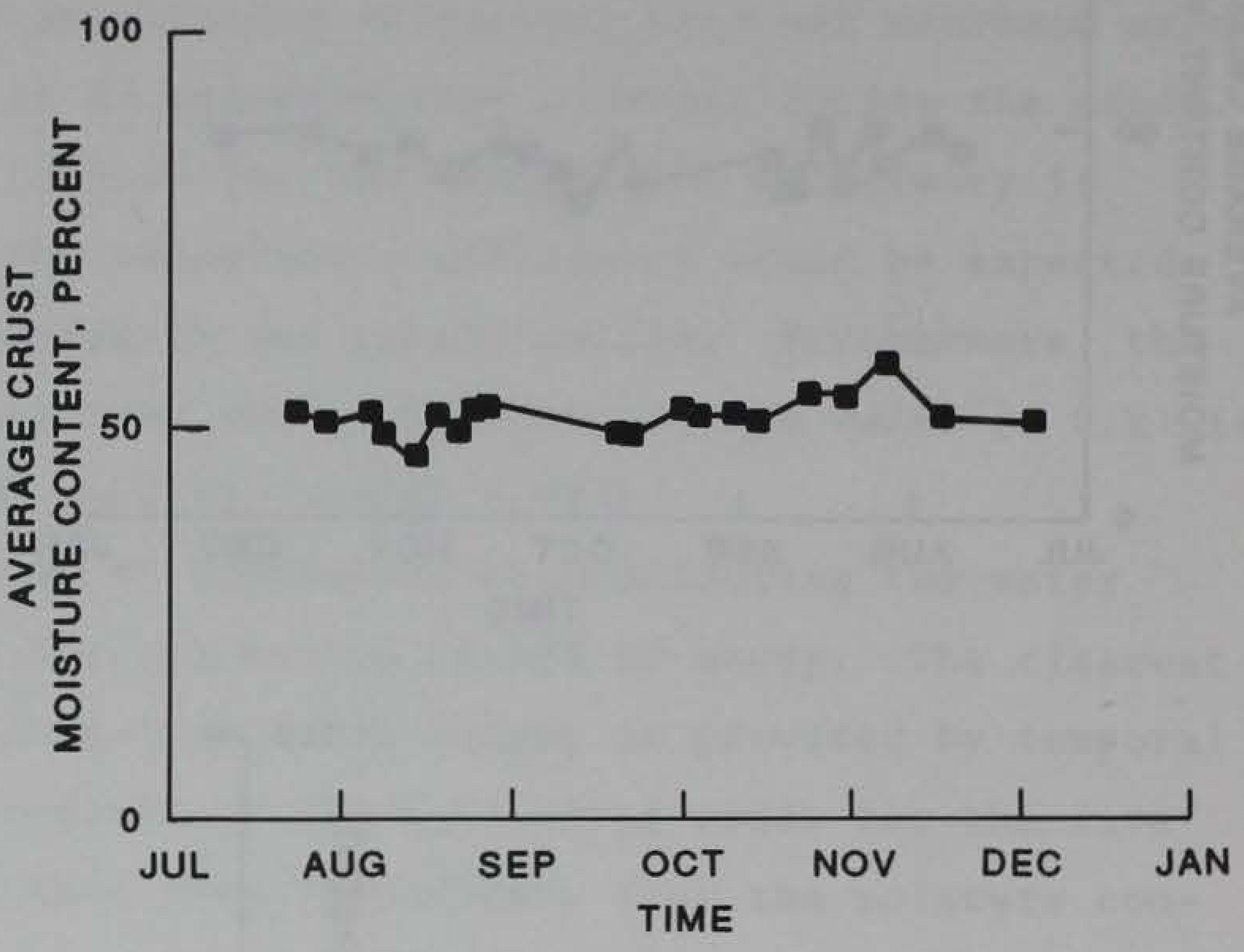


a. Site 1

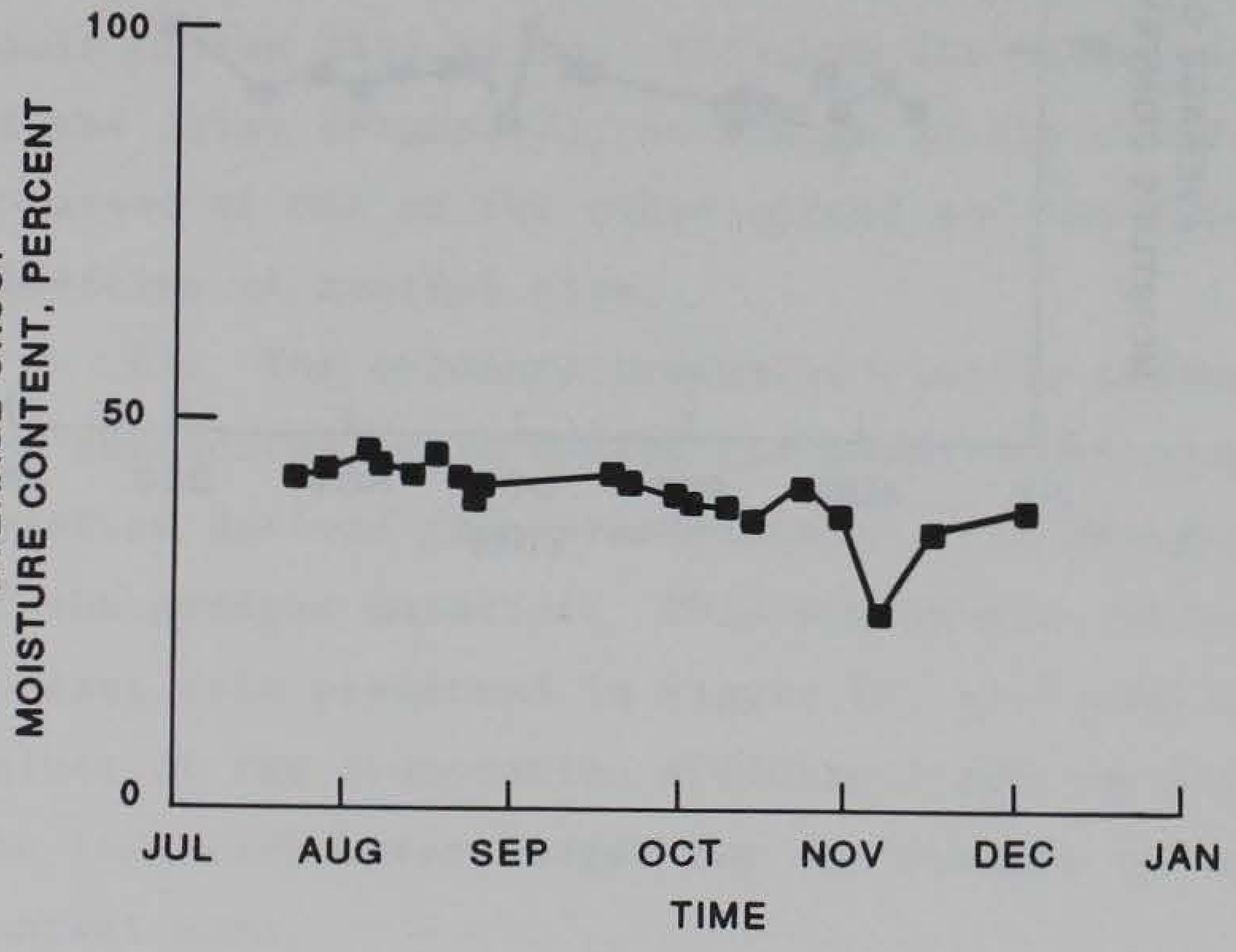
b. Site 2

c. Site 3

Figure 14. Crust moisture content as a function of time for the five sites (Continued)



d. Site 4



e. Site 5

Figure 14. (Concluded)

long-term drainage efficiency of the dredged material. The value of 0.26 is similar to the (admittedly limited) values obtained by gaging the runoff at the containment area.

68. The value of the drainage efficiency obtained above is similar to the drainage efficiency for natural watersheds of the region. The average annual precipitation for the area is 104 cm (Ruffner 1985), and the annual potential evaporation is 76 cm (Linsley, Kohler, and Paulhus 1978; Mather 1984). These data lead to a value for the natural drainage efficiency of 0.27 (assuming no long-term changes in subsurface storage), nearly identical to that estimated above for the containment area during the period of the study. Thus, the water budget for the containment area during the study is similar to the water budget for a natural watershed. Changes in soil moisture over relatively short periods are caused by changes in precipitation, evapotranspiration, and runoff, not by consolidation.

69. This interpretation also explains the relatively high value of the evaporation efficiency. Over short periods of time, rainfall is stored in the desiccated crust because only a relatively small percentage of the precipitation runs off immediately. Because the amount of moisture stored in the crust (including cracks) is relatively large, the moisture stored in the crust is returned to the atmosphere at a relatively rapid rate. These results demonstrate that soil moisture losses may be accurately calculated using the Thornthwaite-Mather method, an observation suggesting that the rate of evaporative loss is close to the maximum possible given the thermal energy available from climatic processes. Clearly, under these conditions, the evaporation efficiency should be high, and in fact it should approach the maximum possible value of C'_e defined for first-stage drying.

70. These observations suggest that the study began after second-stage drying was largely completed, or at least that the rate of second-stage drying was low enough by the beginning of the study that the water budget was dominated by climatic processes. If this is true, then both first- and second-stage drying are completed rapidly during midsummer at the Wilmington Harbor Containment Area. The dredged material was placed late in June, and the study began approximately 1 month later. Thus, both first- and second-stage drying were largely completed after only a few weeks at this time of year. However, since the water budget is strongly influenced by climatic factors, the rate at which dredged material will dry is directly affected by the time of year at

which the material is placed. Therefore, seasonal variations should be expected within the same containment area.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

71. Procedures were established for determining the hydrologic parameters of a desiccating crust in a dredged material containment area; these procedures were established through a field evaluation program at the Wilmington Harbor containment area in the US Army Engineer District, Philadelphia.

72. The procedures utilized in this study at Wilmington Harbor can be employed at other dredged material containment areas to determine quantitative values for the empirical desiccation parameters used in site capacity evaluations. Quantification of the empirical desiccation parameters at individual dredged material containment areas is essential if accurate predictions of site capacity and useful life are to be made for those sites using the computer model PCDDF.

73. A water budget approach was used to calculate desiccation parameters for the dried crust of desiccating dredged material at the Wilmington Harbor Containment Area. Final estimates of the evaporation efficiency, the depth of second-stage drying, the desiccation and saturation limits, and the gross percent saturation of the desiccated crust are presented in Table 3; both mean values and standard deviations are presented. All of the parameters vary considerably over the surface of the dredged material. This variability is certainly to be expected, as the containment area is an uneven topographic surface with widely varying hydrologic properties.

74. The results of this investigation suggest that both first- and second-stage drying are completed very rapidly at the Wilmington Harbor containment area. This may or may not be the case for other types of dredged material and locations of placement. Because contracting inefficiencies caused delay of contract award for this study, the study was initiated approximately 1 month after dredged material placement was completed.

75. The long-term water budget for the desiccated crust evaluated in this study clearly indicates that second-stage drying was largely completed when the study began. Thus, the development of the desiccated crust could not

Table 4

Final Estimates of Desiccation Parameters

Parameter	Value
Evaporation efficiency, C_e	0.72 ± 0.10*
Drainage efficiency, C_d	0.21 ± 0.04**
Depth of 2nd-stage drying, metres	0.20 ± 0.05+
Saturation limit, e_{SL}	3.02 ± 0.25++
Desiccation limit, e_{DL}	2.69 ± 0.61
Percent saturation of crust (including cracks), PS	0.74 ± 0.16

* May be appropriate for first-stage drying

** Based on only three values

\+ Based on crack data, moisture content, and void ratio profiles

++ Indirect estimate based on saturated soil after second-stage drying

be directly observed during the study, and parameters needed to characterize first-stage drying could not be directly quantified.

76. It is imperative that studies to evaluate the desiccation parameters of dredged material be initiated as soon as the ponded water is removed from the site. This will ensure that the entire drying process, including both first- and second-stage drying, is assessed and that the most correct values for each of the empirical desiccation parameters will be obtained.

Recommendations

77. A study is needed to observe and quantify the entire desiccation process. Such a study should begin well before dredged material is placed into a containment area so instruments can be tested and installed before measurements are needed. It is important to continue measurements until second-stage drying is completed. Such a study would provide more complete estimates of desiccation parameters than those reported here; it could also provide valuable insights into the physical processes that control evaporative losses from the desiccating crust. In any such study, the cooperation of the local Corps district office is vital since the disposal site must continue to be operated throughout the study according to prestudy agreements.

78. Better methods and instrumentation would also be desirable. For example, the lysimeters used during the present study require very frequent maintenance and they are only suitable for short-term water budgets. Lysimeters should be designed to inhibit moisture from entering the crust from below, allow moisture to infiltrate through the crust, and allow surface runoff to escape from the lysimeter and into cracks. Furthermore, the instruments must be smaller than the average crack spacing. If cracks develop in soil contained in lysimeters, water in the cracks will not be able to drain as it can from cracks in the surrounding soil. Water stored in cracks in lysimeters could infiltrate and raise the moisture content of the crust in the lysimeter to unreasonably high values.

79. In addition to developing appropriate lysimeters, the weir system should be redesigned to accommodate the dual needs of accurate gaging of runoff and frequent lowering of the outfall level. This could be accomplished by installing a V-shaped weir and perhaps by redesigning the stilling basin behind the weir outlet.

80. Finally, it should be noted that although the water budget method is difficult, it probably represents the only potentially accurate method of quantifying evaporative moisture losses from a cracked, desiccating crust. The obvious alternative would be to directly measure the flux of moisture into the atmosphere from the surface of the dredged material. However, these measurements would include (and frequently be dominated by) evaporation from standing water stored in cracks and occasional small ponds, and therefore such measurements would not directly reflect evaporation from the crust itself. Desiccation parameters obtained by measuring the total evaporative flux into the atmosphere, therefore, would reflect climatic processes and not consolidation and drying of the dredged material deposit.

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APPENDIX A: NOTATION

A	Cross-sectional area of a crack (cm^2)
C_d	Drainage efficiency
C_e	Evaporation efficiency
C'_e	Evaporation efficiency at end of first-stage drying
CS	Water supplied to crust from below (cm)
dW	Change in moisture content of crust (cm)
dW'	Change in moisture in a desiccated crust where CS is zero
dWL	Water level of evaporation pan
D	Crack depth (cm)
e	Void ratio
e_{DL}	Void ratio at desiccation limit of the dredged material
e_{SL}	Void ratio at saturation limit of the dredged material
E	Evaporation (cm)
EP	Class A pan evaporation (cm)
G_s	Specific gravity of the dredged material solids
h_2	Depth to water table after second-stage drying (cm)
h_{wt}	Depth to water table (cm)
L	Crust thickness (cm)
LL	Liquid limit of the dredged material
n	Number of creeks encountered in a survey of length and thickness of desiccated crust
OF	Overland flow (cm)
P	Moisture content by weight (W_w/W_T)
P_{av}	Average value of P for the desiccated crust
P_c	Percentage of the desiccated crust occupied by cracks
P_w	Moisture content of cracks
PL	Plastic limit of the dredged material
PS	Percent saturation of the desiccated crust (including cracks)
R	Length of survey to measure crack morphology
RF	Rainfall (cm)
S	Settlement (cm)
SF	Crack shape factor
w	Crack width (cm)
W	Volume of water in crust per unit crust area

W_s	Weight of solids in the dredged material sample
W_T	Total weight of the dredged material sample
W_w	Weight of water in the dredged material sample
z	Vertical spatial coordinate
ρ	Density of water (g/cc)
ρ_b	Dry bulk density (g/cc)
ρ_s	Density of sediment (g/cc)
ω	Water content of void ratio at condition of interest
ω_c	Water content of dredged material sample $\omega_c = \frac{W_w}{W_s}$
γ_{dry}	Dry unit weight of dredged material
γ_o	Unit weight of water at reference temperature, 4° C