FEASIBILITY OF ARTIFICIAL RECHARGE TO THE OAKES AQUIFER, SOUTHEASTERN NORTH DAKOTA: EVALUATION OF EXPERIMENTAL RECHARGE BASINS

By William M. Schuh
and Robert B. Shaver

Water Resources Investigation No. 7
North Dakota State Water Commission

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INTRODUCTION

In 1957, the U. S. Bureau of Reclamation redesigned the Pick–Sloan Missouri River Basin Plan enacted by Congress in the Flood Control Act of 1944. Under the redesigned plan, 1,007,120 acres of land were to be irrigated in central and eastern North Dakota using Missouri River water diverted eastward from the Garrison Reservoir. The plan designated 108,000 acres of land to be irrigated in the Oakes area, southeastern North Dakota.

In 1965, Congress enacted legislation to authorize construction of the 250,000–acre Garrison Diversion Unit as the initial stage of the ultimate 1,007,120–acre project. The 1965 authorization designated 45,980 acres to be irrigated in the East and West Oakes irrigation development tracts of the Garrison Diversion Unit. Missouri River water would be diverted eastward to the James River via the McClusky canal, Lonetree Reservoir, New Rockford canal, and the James River feeder canal. Because channel capacity of the James River was insufficient to meet peak irrigation demands for the East and West Oakes irrigation development tracts, the U. S. Bureau of Reclamation proposed construction of Lake Taayer Reservoir.

The Garrison Diversion Unit, as authorized in 1965, raised significant issues of environmental, economic, and international concern. As a result, in accordance with Public Law 98–360, sec. 207, enacted by Congress July 16, 1984, a 12–member commission was appointed by the Secretary of the Interior to "examine, review, evaluate, and make recommendations with regard to the contemporary water development needs of the State of North Dakota." Concerning irrigation in the Oakes area, the Garrison Diversion Unit Commission recommended the following in December 1984:

1) Reduce the 45,980 acres to be irrigated under the 1965 authorization to 23,660 acres (West Oakes = 19,660 acres; West Oakes extension = 4,000 acres);

2) deauthorize construction of Lake Taayer Reservoir; and

3) initiate a feasibility study to assess artificial recharge to the Oakes aquifer as an alternative to a surface reservoir (Garrison Diversion Unit Commission, 1984).

Based on recommendations of the Garrison Diversion Unit Commission, the Congress of the United States passed the Garrison Diversion Unit Reformulation Act of 1986. The act directed the Secretary of the Interior to submit a comprehensive report to Congress no later than the end of fiscal year 1988. The report would include the results of an artificial recharge feasibility study for the Oakes aquifer. Under the proposed artificial–recharge plan, the Oakes aquifer would function as a storage reservoir. Water would be diverted from the Missouri River to the James River and then into recharge facilities at selected sites in the aquifer. Withdrawals for irrigation would be from wells completed in the Oakes aquifer.

In July 1985, the North Dakota State Water Commission and the U.S. Geological Survey entered into a cooperative agreement with the U.S. Bureau of Reclamation to investigate the feasibility of artificial recharge to the Oakes aquifer. The feasibility study was divided into three phases. Phase I defines the geometric, hydraulic, and hydrochemical properties of the Oakes aquifer. Field work was initiated in August 1985 and completed in April 1986. Results of phase I of the artificial–recharge feasibility study are described in North Dakota State Water Commission Water–Resources Investigations Nos. 5 and 6. Investigation No. 5 (Shaver and Schuh, in preparation) describes the hydrogeology of the

Oakes aquifer. Investigation No. 6 (Shaver and Hove, in preparation) presents the ground–water data, which consists of lithologic logs of test holes and wells (volume 1), water–level measurements (volume 2), and water–quality analyses (volume 2).

Phase II of the artificial–recharge feasibility study describes the selection, construction, maintenance, and performance evaluation of surface–recharge test facilities in the Oakes aquifer. Water used to perform the recharge tests was diverted from the James River. Field work was initiated in May 1986 and completed in November 1987. Results of phase II of the artificial–recharge feasibility study are presented in North Dakota State Water Commission Water–Resources Investigation No. 7 and a U.S. Geological Survey report. Investigation No. 7 (this report) describes infiltration through recharge basins, physical processes that affected infiltration, and operational and maintenance techniques used to enhance infiltration rates. The report prepared by the U.S. Geological Survey describes the chemical and biological processes operative during basin recharge.

Phase III of the artificial recharge feasibility study (Shaver, in preparation, North Dakota State Water Commission Water–Resources Investigation No. 8) describes a preliminary cost analysis of a full project–scale and pilot–scale well field and artificial–recharge facilities for the Oakes aquifer.

PURPOSE AND SCOPE

The purpose of this study was to: 1) measure temporal changes in infiltration rate in recharge basins; 2) determine processes that control infiltration rate; and 3) evaluate selected design criteria and operational procedures that enhance infiltration rate.

Five recharge tests were conducted in a 1.2 m (4 ft.) deep, 15.2 by 15.2 m (50 by 50 ft.) square basin located in southeastern Dickey County, southeastern North Dakota (Fig. 1). One recharge test was conducted in a 1.2 m (4 ft.) deep, 3 by 6 m (10 by 20 ft.) rectangular basin located about 400 feet southeast of the large test basin. James River water was conveyed to the recharge basins for each test using a surface pipeline.

For each test, discharge into the basin and basin stage were measured. Discharge was periodically adjusted to maintain a constant basin stage. Discharge and stage measurements were used to calculate temporal infiltration rates within each basin.

Double–ring infiltrometers and tensiometer nests were installed at selected sites along the basin floor. Prior to basin flooding, short–term infiltration tests were conducted at these sites to develop functional relationships between unsaturated hydraulic conductivity and moisture content and to determine saturated hydraulic conductivity at selected depths below the basin floor. Tensiometric data was periodically collected at the tensiometer nests throughout each recharge test. The tensiometric data and pre–test saturated/unsaturated hydraulic conductivity measurements were used to measure temporal fluctuations in infiltration rate and characterize the growth and extent of clogging.

Physical properties were also measured at selected depths below the basin floor to assess the depth of clogging. USDA texture, wet combustion organic carbon, bulk density, and moisture retention curves were determined for selected tests before and after recharge.

Various operational and maintenance techniques were used to enhance infiltration rate within the 15.2 by 15.2 m (50 by 50 ft.) square test basin. These included:

1) desiccation of basin floor,
2) changing basin stage,
3) excavation of the clogged surface layer on the basin floor, and
4) placement of an organic mat (partially decomposed sunflower seed hulls) over the basin floor.

All products and manufacturer names cited in this report are given for information purposes only, and do not imply endorsement by the North Dakota State Water Commission.

ACKNOWLEDGEMENTS

Thanks are due to the following North Dakota State Water Commission personnel: Michael Hove for assistance in the construction and operation of each of the infiltration tests; Garvin O. Muri for suspended solids analyses of James River water samples; and Milton O. Lindvig for scheduling field activities. Thanks are due also to John Thiel, technician, U. S. Bureau of Reclamation, for assistance in the construction and operation of each of the basin tests; and to Berril Gold for supervision of the soil laboratory analysis. Recognition is due to Ambrose Roerick, Byron Wilkerson, and Jerome Jungling, all with the U. S. Bureau of Reclamation, for excavating the recharge basins, setting surface pipeline and installing the pump. Thanks are due also to Emory A. Visto, Oakes, North Dakota who provided land for the infiltration tests.

LOCATION AND NUMBERING SYSTEM

The location and numbering system used in this report is based on the public land classification system used by the U. S. Bureau of Land Management. The system is illustrated in Figure 1. The first number denotes the township north of a base line, the second number denotes the range west of the fifth principal meridian, and the third number denotes the section in which the well or test hole is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter–quarter section, and quarter–quarter–quarter section (10–acre tract). For example, well 130–059–15DAA is located in the NE 1/4 NE 1/4 SE 1/4 sec. 15, T. 130 N., R. 59 W. Consecutive terminal numerals are added if more than one well or test hole is located within a 10–acre tract.

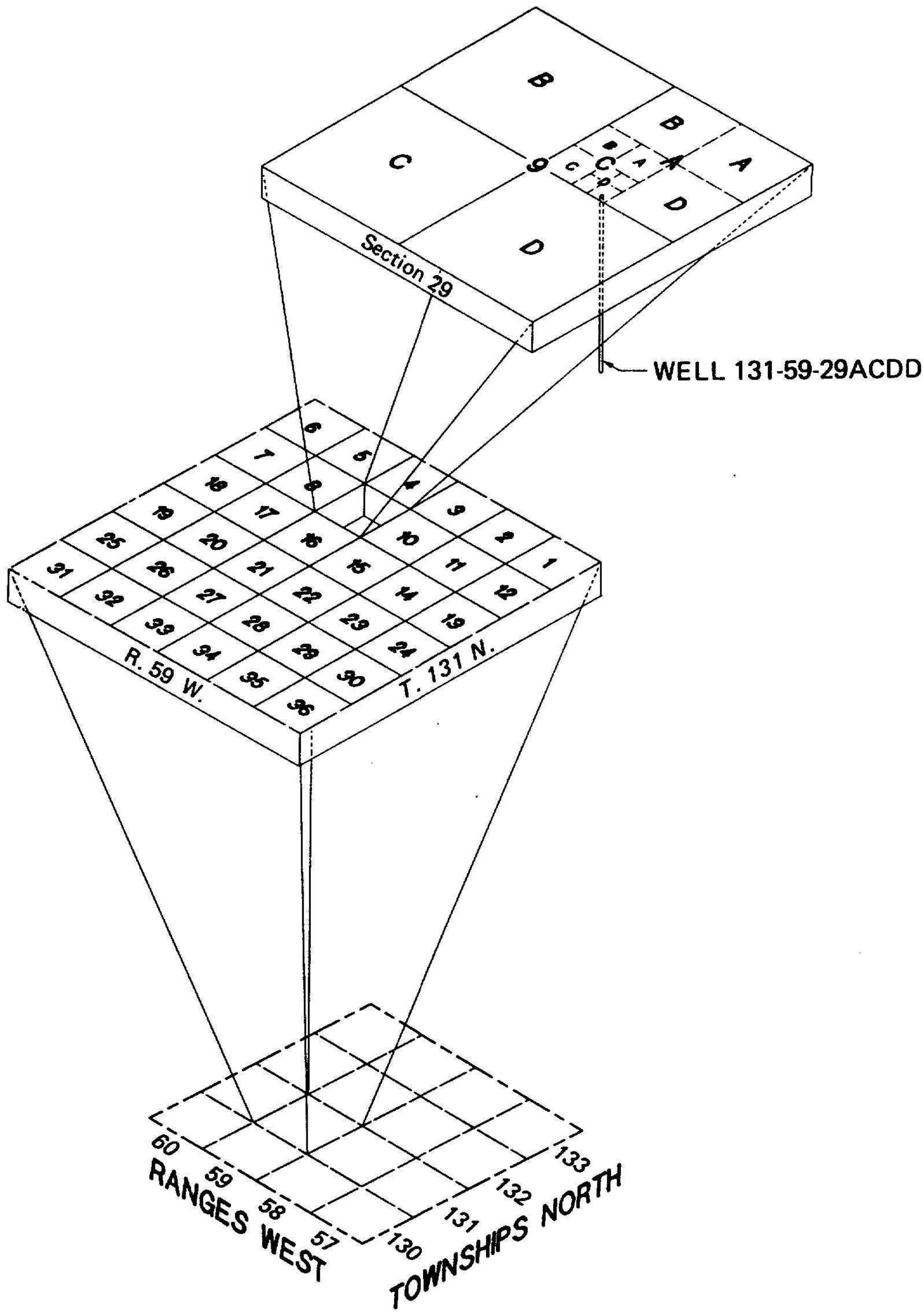


Fig. 1 Location and numbering system of lithostratigraphic logs.

PREVIOUS WORK IN THE OAKES AQUIFER STUDY AREA

The geology and water resources of the Edgeley and LaMoure areas are described by Hard (1929). Rasmussen (1947) and the U. S. Bureau of Reclamation (1953a, 1953b) described the geology and ground–water resources of the glacial Lake Dakota area in Dickey and Sargent Counties. Soil surveys of the study area were completed by Larsen et al. (1964) and Thompson and Sweeney (1971).

The geology and ground–water resources of Dickey and LaMoure Counties are described in a three–part report. Part I (Bluemle, 1979a) describes the geology of Dickey and LaMoure Counties, part II (Armstrong and Luttrell, 1978) presents the ground–water data, and part III (Armstrong, 1980) describes the ground–water resources.

The geology and ground–water resources of Ransom and Sargent Counties also are described in a three–part report. Part I (Bluemle, 1979b) describes the geology of Ransom and Sargent Counties, part II (Armstrong, 1979) presents the ground–water data, and part III (Armstrong, 1982) describes the ground–water resources.

Williams (1984) described the hydrogeochemistry of a closed topographic trough in the Oakes aquifer southeast of Oakes.

The hydrogeology of the Oakes aquifer is described in a two–part report prepared for phase 1 of the artificial recharge feasibility study. Part I (Shaver et al., in preparation) describes the hydrogeology of the Oakes aquifer. Part II (Shaver and Hove, in preparation) presents the ground–water data.

METHODS OF ARTIFICIAL RECHARGE

There are six general methods of artificial recharge: 1) basins, 2) ditches and furrows, 3) flooding, 4) use of natural stream channels, 5) pits and shafts, and 6) injection wells (Bianchi and Muckel, 1970). Basins are the most common method of artificial recharge. If surface or near surface impeding layers (clay and silt) are absent, basins are formed by the construction of levees. If surface or near surface impeding layers occur, basins are formed by shallow excavations generally less than five feet deep. The objective of the basin–type project is to obtain the maximum ratio of wetted area to gross land area, commensurate with efficient operation and maintenance (Bianchi and Muckel, 1970). Standby basins commonly are used for continuous recharge projects when other basins are removed from operation for maintenance and rehabilitation. Natural desiccation, scarifying, discing, and excavation are common maintenance methods used to rehabilitate basins.

Advantages of basins include (Richter and Chun, 1959):

1) Basins utilize the maximum area for spreading with only the tops of the levees being unproductive. This is particularly important where suitable locations are scarce, or where land values are extremely high.
2) Irregular and gullied surfaces can be used with a minimum of preparation.
3) Silt–laden waters can be used, particularly if the upper basins are utilized for desilting and are periodically cleaned.
4) Considerable surface storage capacity is available in basins which can be used to store a portion of the water from flash floods for later slow percolation into the ground–water reservoir.
5) In general, local materials can be used for construction of dikes and levees.

There are three basic types of ditch and furrow recharge methods: 1) contour, where the ditch follows the ground contour, 2) tree–shaped, where the main canal successively branches into smaller canals and ditches, and 3) lateral, where a series of small ditches extends laterally from the main canal. The ratio of wetted to gross area is usually low, averaging about 10 percent. This method may combine well with the basin method where the natural ground slopes are too steep for economical stepped–basin construction. The width of ditches generally range from 0.3 m to 1.8 m (1 to 6 ft.), depending on the terrain and flow velocity. An advantage of the ditch system is that the ratio of the perimeter to wetted area is large, thereby permitting more lateral flow than in a basin system. Where infiltration is retarded by substrata of lower hydraulic conductivity than the surface soils, the same total recharge to the ground water may be obtained with a system of ditches occupying far less surface area than with a basin system occupying 100 percent of the surface (Bianchi and Muckel, 1970).

Water may be diverted to spread evenly over a large area of relatively flat topography by flooding. Canals or ditches are used to release water into the area to be flooded. It is desirable to form a thin sheet of water over the land moving at low velocity to avoid soil erosion. Highest infiltration rates occur on areas with undisturbed vegetation and soil covering (Todd, 1980). In comparison to other recharge methods, flooding costs are low in terms of both land preparation and operation.

Stream channels offer another method of artificial recharge. Infiltration through stream channels is enhanced by increasing: 1) the period of time water is available for seepage, and 2) the wetted area of the stream channel (Bianchi and Muckel, 1970). The period of time available is increased by the construction of dams for reservoirs along the stream channels. Increasing the wetted area of a stream channel is accomplished by widening, scarifying, or ditching. Advantages of using stream channels are: 1) land acquisition costs are low, and 2) recharge is over a long, narrow strip which is an efficient recharge method in areas where shallow layers of low hydraulic conductivity occur.

Pits and shafts are commonly used recharge methods in areas where low hydraulic conductivity surface deposits occur. Because excavation costs can be high, abandoned excavations such as gravel pits are used. Infiltration is enhanced by steep–walled excavations because sediment clogging is much greater along pit floors than along sidewalls. Shafts are applicable in areas where silt–free water is available and where biologic clogging is minimal. If sediment and biologic clogging are significant rehabilitation may be prohibitive.

Injection wells are practical where deep, confined aquifers must be recharged, or where economy of space, such as in urban areas, is an important consideration (Todd, 1980). Recharge rates are difficult to maintain because of sediment clogging, bacterial and algae growths, air entrainment, rearrangement of soil particles, and deflocculation caused by reaction of high sodium water with the aquifer matrix. Successful injection wells require water treatment to reduce suspended loads and growth of bacteria and algae. In addition, periodic well redevelopment is required.

Three methods of recharge are practical for the Oakes aquifer. These include: 1) basins, 2) surface flooding, and 3) canals. The importation of sediment–laden water from the James River to recharge facilities in the Oakes aquifer will require special operation and rehabilitation techniques to maintain adequate infiltration rates. Basin, surface flooding, and canal facilities are best suited for periodic removal of accumulated sediment (filter cake). Depending on long–term infiltration rates, basin recharge and surface flooding can require large land areas. The land in the proposed project area is agricultural and is used primarily for pasture.

Canals may be practical on a limited scale in areas overlying the outwash channel where low hydraulic conductivity surface deposits are between 1.5 m (5 ft.) and 3 m (10 ft.) thick. In these areas, perched ground–water mounds may control infiltration rates. To minimize the height of perched ground–water mounds, lateral flow components should be maximized. This is achieved with canals because the ratio of the perimeter to the wetted area is large.

The James River is not in direct hydraulic connection with the Oakes aquifer. In addition, there are no intermittent streams overlying the Oakes aquifer. Therefore, stream–channel infiltration is not a practical artificial recharge method for the Oakes aquifer.

There are no major abandoned pits or shafts in the Oakes aquifer study area. Pits and shafts are used to penetrate surficial deposits of low hydraulic conductivity. Low hydraulic conductivity deposits below 1.5 m (5 ft.) are not widespread in the proposed project area. Maintenance and rehabilitation techniques for pits and shafts generally are cost prohibitive, particularly if sediment–laden water is used for recharge. Therefore, pits and shafts are not practical methods of artificial recharge in the Oakes aquifer.

Since 1) basins are the most common method of artificial recharge; 2) basins are practical in the Oakes aquifer; and 3) time and economic constraints preclude an adequate investigation of all practical methods of artificial recharge to the Oakes aquifer, a comprehensive investigation of basin recharge was initiated.

SELECTION OF A RECHARGE BASIN TEST SITE

Four requirements were necessary to select a recharge basin test site in the Oakes aquifer:

1) The water table should be of sufficient depth to preclude the intersection of a water–table mound with the basin floor. The intersection of a water–table mound with the basin floor directly results in lower infiltration rates. In addition, fully saturated conditions in the subbasin soil caused by mound growth can alter soil physical, chemical, and biological processes that affect infiltration rates. Conditions in the proposed artificial recharge project area are such that with proper management, water–table mound intersection with the basin floor would not be expected.

2) Layers of low hydraulic conductivity (silt and clay) should not be prevalent in the soil beneath the test basin. Perched ground–water mounds can develop above layers of low hydraulic conductivity and can intersect the basin floor. Such areas will be avoided when selecting the final project area.

3) The recharge test facility should be located as close as possible to the James

River to minimize water conveyance costs.

4) Initial infiltration rates in the test area should be similar to those in the proposed final project area, based on similarity of soils and on previous infiltration measurements made in the Oakes area (Shaver et al., in preparation).

It was determined from phase I of the Oakes artificial recharge feasibility study that the best potential for a large–scale artificial recharge–irrigation project is in the area overlying the outwash channel along the eastern margin of the Oakes aquifer. This area was not selected as the test basin site because the depth to water table is generally less than 3.1 m (10 ft.) below land surface and the James River is about 13.4 km (8 mi.) to the west.

The SE 1/4 SE 1/4 of Section 29, Township 131 North, Range 59 West was selected as the test basin site (Fig. 2). Depth to water table below land surface ranged from 4.6 m (15 ft.) to 6.1 m (20 ft.) and there were no continuous low hydraulic conductivity layers (clay and silty clay) in the test area. The test area is located about one mile east of the James River. A U. S. Bureau of Reclamation pilot drain is located along the southern border of Section 29 and extends west to the James River. Surface pipe used to convey James River water to the test area was installed along the drain right–of–way. Therefore, pipeline easements were not required. The SE 1/4 of Section 29 was not being farmed and, as a result, an easement to construct and operate a test basin in this area was readily obtainable at low cost.

DESCRIPTION OF THE TEST AREA

Physiography

The test area is located on the western flank of the lake plain of ancestral glacial Lake Dakota. The lake plain is flat with relief generally less than 3.0 m (10 ft.) per mile.

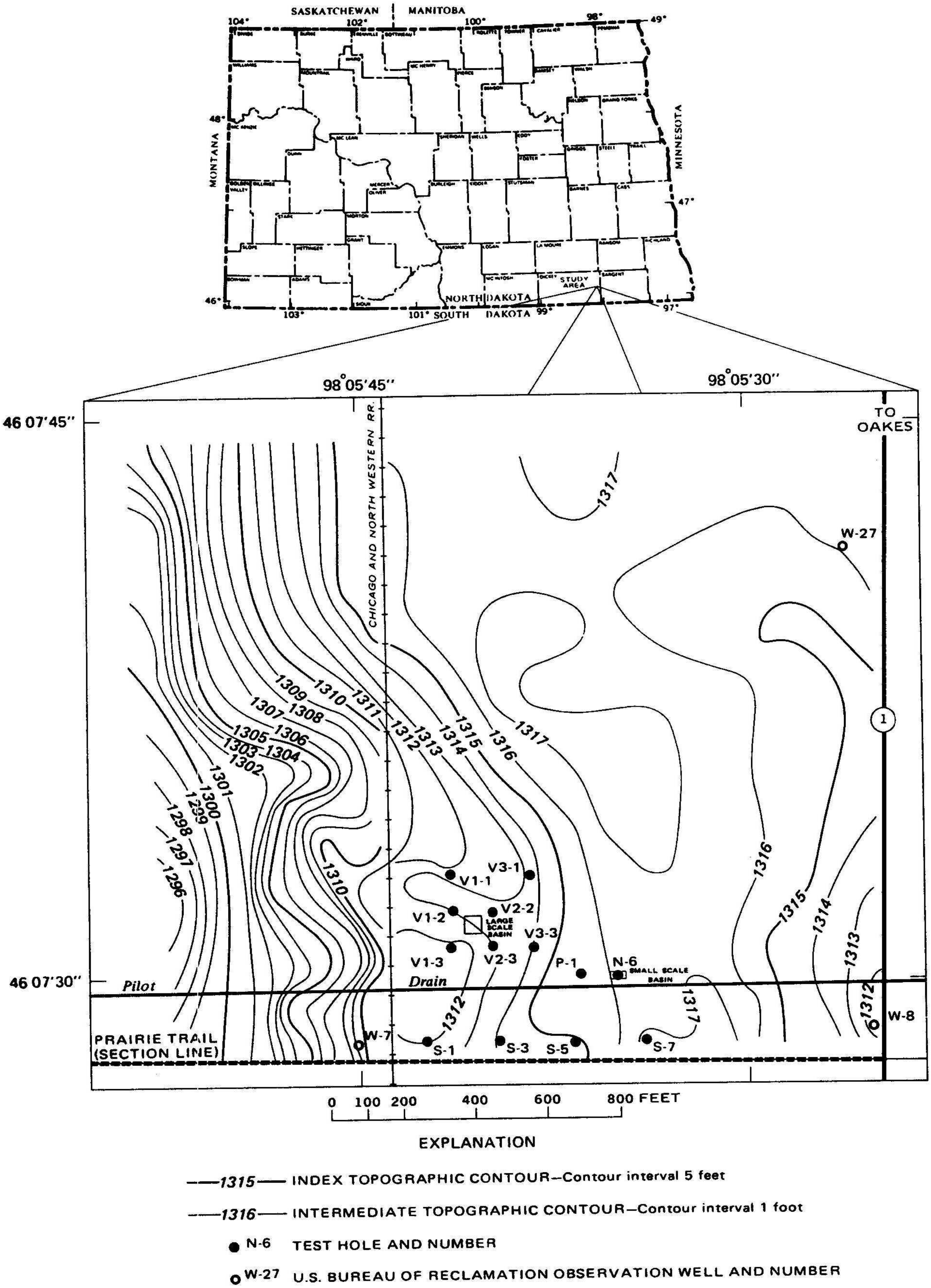


Fig. 2 Part of SE 1/4, section 29, T.131N., R.59W., and location of test holes, observation wells, and test basins.

Runoff from the lake plain is minor as indicated by the lack of surface drainage. The lake plain is truncated by recent flood–plain deposits of the James River about 182 m (600 ft.) west of the large test basin (Fig. 2). This accounts for the increased relief in the western part of the test area.

Climate

Climate of the study area is semiarid to subhumid. Mean annual precipitation at Oakes from 1931 through 1974, less 1949 and 1950, is 48.8 mm (19.21 in.) (U.S. Department of Commerce, Weather Bureau, 1960, 1965; U.S. Department of Commerce, Environmental Data Service, 1962–75). Annual precipitation ranged from 23.2 mm (9.14 in.) in 1936 to 75.3 mm (29.64 in.) in 1960. From 1975 to 1986, annual climatologic data for the Oakes station are incomplete. Most of the missing data are for November through April. About 70 percent of the precipitation generally falls from April through August (Fig. 3) when it is most needed for germination and growth of crops. Most summer precipitation is from thunderstorms and is extremely variable (Armstrong, 1980).

Mean annual temperature at Oakes from 1951 through 1980 was 4.9 ^{o}C (40.9^{o}F) (U.S. Department of Commerce, Environmental Data Service, 1982). From 1931 through 1984, the maximum recorded temperature was 46.1^{o}C (115^{o}F) on July 6, 1936, and the minimum recorded temperature was –43^{o}C (–46^{o}F) on February 16, 1936. The average number of days between the last freeze 0^{o}C (32^{o}F) in the spring and the first freeze in the fall ranges from about 120 to 130 (Armstrong, 1980).

Geology

Surficial Geology

The test area is located on the lake plain of ancestral glacial Lake Dakota. Glacial Lake Dakota flooded part of southeastern Dickey and southwestern Sargent Counties when

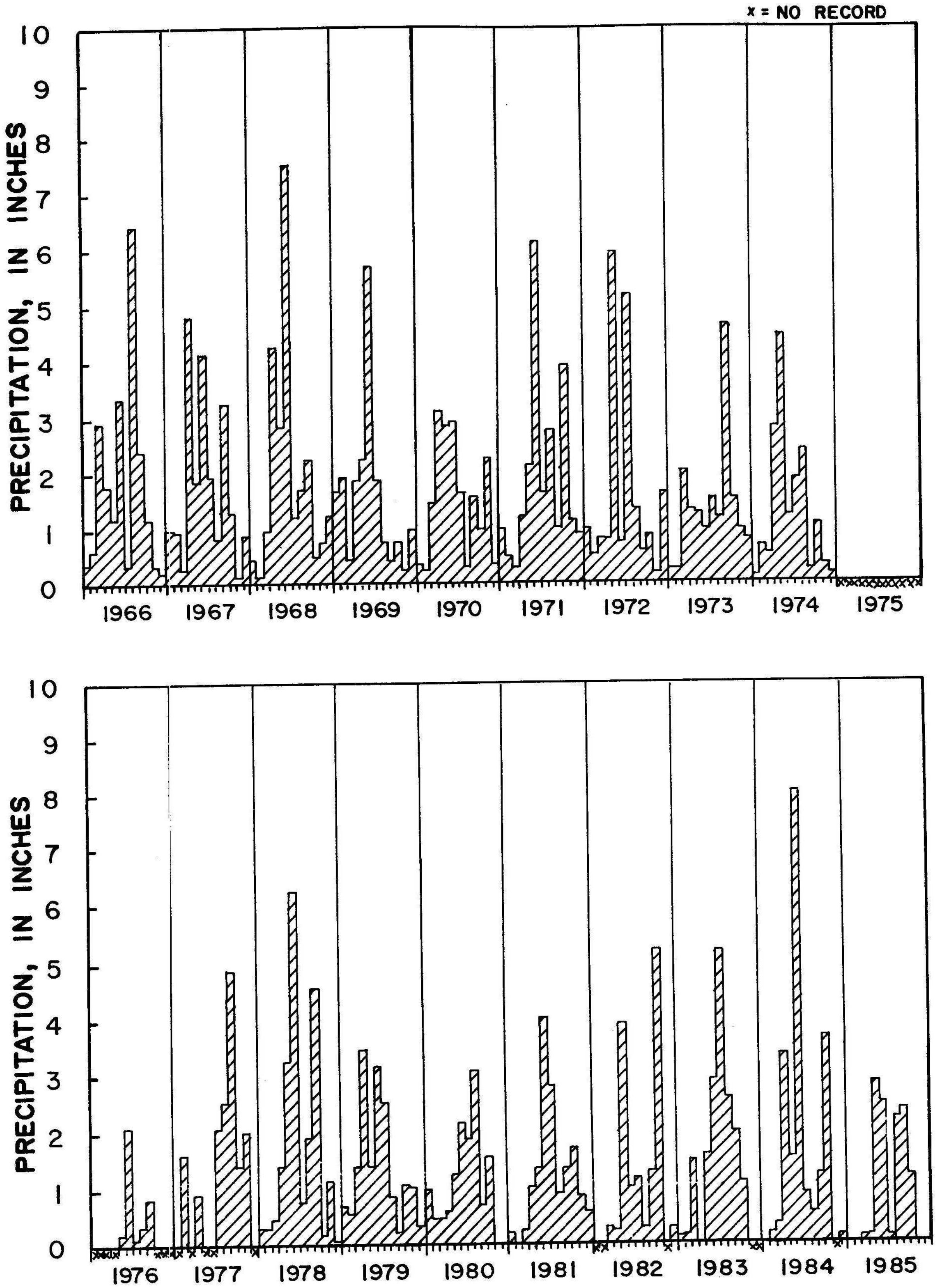


Fig. 3. Monthly precipitation at Oakes, 1966 to 1985.

the late–Wisconsin glacier moved from the area (Bluemle, 1979a, 1979b).

The Oahe Formation is exposed within the test area. The Oahe Formation is of Holocene age and consists of clay, silt, sand, and gravel deposits. Three main textural facies are included in the formation (Bluemle, 1979a, 1979b): 1) clay, 2) bouldery–gravelly clay, and 3) sand and silt. The sand and silt facies predominate in the test area. Sand, silt, and clay flood–plain deposits of the James River occur in the western part of the test area. Windblown fine–silty sand deposits occur in the eastern part of the test area.

The soil of the test site was a Maddock sandy loam (sandy–mixed Udorthentic Haploboroll), while those of the designated area for construction of a full scale facility consist of a mixture of Hecla (sandy–mixed Pachic Udic Haploboroll), Ulen (coarse–loamy mixed frigid Aeric Calciaquoll), and Maddock soils. Soil survey permeability ranges for subsoils of the Hecla and Maddock series are similar (Thompson and Sweeney, 1971). The soils of the selected test site were thus similar to those of the area proposed for a full scale facility.

Subsurface Geology

The Coleharbor Group underlies surficial deposits of the Oahe Formation in the test area. The Coleharbor Group is of Pleistocene age and consists of three main textural facies (Bluemle, 1979a, 1979b): 1) till, 2) silt and clay, and 3) sand and gravel. The sand and gravel facies underlies the Oahe Formation in the eastern part of the test area. The stratified sand and gravel deposits are part of a deltaic deposit that extends to a depth of about 20 m (65 ft.). The deltaic deposits are composed of quartz, shale, lignite, shield silicates, and carbonates.

The till facies of the Coleharbor Group underlies the sand and gravel facies in the test area. The Niobrara Formation of Cretaceous age unconformably underlies the till. Deeper test holes were not completed in the test area and as a result, the thickness of the till and the depth to the top of the Niobrara Formation were not determined.

Thirteen test holes (V1–1 to V3–3, S–1 to S–7, P–1, and N–6) were drilled to the top of the water table in the test area (fig. 1). The test holes were drilled using a hydraulic probe and a truck–mounted solid–stem spiral auger. Lithologic logs for each of the 13 test holes are found in supplements 1–13. Land surface elevations were determined at each drilling site and ranged from 399.5 to 401.3 m (1310. 8 to 1316.3 ft.) above sea level.

Nine observation wells and two sampling wells were also completed near the top of the water table in the test area. Six observation wells were completed in the unsaturated zone to monitor growth of perched ground–water mounds. Lithologic logs for each of the 15 observation wells and two sampling wells are found in supplements 14–29.

The lithologies below the topsoil layers range from very fine silty sand to very fine to very coarse gravelly sand (Fig. 4). Clay layers for the most part are absent. The sediment sequence is well stratified at all drilling sites.

GROUND–WATER HYDROLOGY OF THE TEST AREA

General Statement

The stratified sand and gravel deposits of the Coleharbor Formation that occur in the eastern part of the test area are part of the Oakes aquifer. The Oakes aquifer, named by Armstrong (1980), consists of four depositional facies that are grouped together into one hydrostratigraphic unit. The depositional facies include: 1) deltaic sand and gravel (test area), 2) lacustrine sand, 3) channel–fill sand and gravel, and 4) eolian sand. A detailed description of the ground–water hydrology of the Oakes aquifer is found in Shaver et al. (in preparation).

Occurrence and Movement of Ground Water

The Oakes aquifer is unconfined in the test area. Depth to water table below land surface is about 4.6 to 6.1 m (15 to 20 ft.). Regional ground–water flow in the Oakes

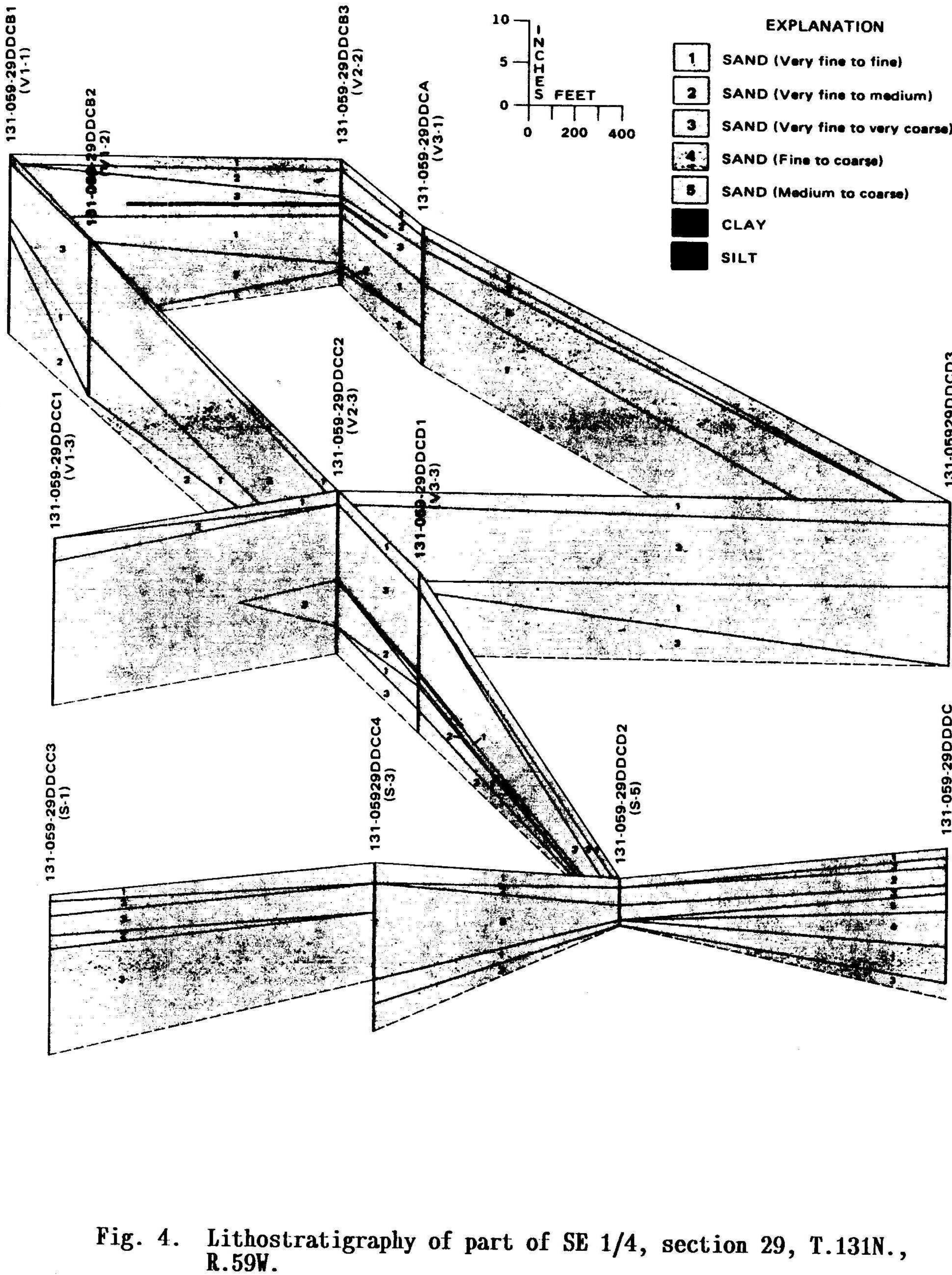


Fig. 4. Lithostratigraphy of part of SE 1/4, section 29, T.131N., R.59W.

aquifer is from east to west toward the James River valley. Within the test area, ground–water flow is essentially north to south and south to north toward the U.S. Bureau of Reclamation pilot drain located along the southern border of Section 29, Township 131 North, Range 59 West.

Hydraulic Properties

The North Dakota State Water Commission conducted an aquifer test in the deltaic sand and gravel deposits located about one mile northeast of the test area at 131–059–28BBA (Shaver et al., in preparation). Transmissivity was 1022 meters squared per day (11,000 feet squared per day), apparent storativity was 0.29, and hydraulic conductivity was 67 meters per day (220 feet per day). The hydraulic conductivity and apparent storativity values are probably representative for the saturated zone in the test area based on similarity of lithologies.

Recharge and Discharge

Recharge to the Oakes aquifer primarily occurs by relatively direct infiltration of precipitation and snowmelt during the spring. Recharge probably is negligible during the summer months because, in most years, potential evapotranspiration exceeds precipitation (Shaver et al., in preparation). Within the test area, the U.S. Bureau of Reclamation pilot drain probably functions as a line source of water during the spring.

Depth to water table in the Oakes aquifer generally is less than 2.4 m (8 ft.) below land surface. As a result, natural discharge to the Oakes aquifer is due primarily to evapotranspiration. Within the test area, depth to water table is about 4.6 to 6.1 m (15 to 20 ft.) below land surface. Therefore, discharge due to evapotranspiration is negligible. Discharge from the test area occurs primarily in the pilot drain which functions as a line sink during the summer months.

WATER QUALITY

Surface Water – James River

Beginning in October, 1982, water quality data from the James River has been collected from a site located 1.67 km (1.0 mi.) west of Oakes near a highway bridge in 131–59–30BAA. Twenty–two samples were collected for analysis between December 1982 and August 1986 (U.S.G.S. Water Resources Data – North Dakota, 1982–1986). The arithmetic mean, minimum, and maximum values of selected cations, anions, and other chemical parameters are shown in Table 1. Lowest dissolved solids concentrations occur during the spring snowmelt periods when discharge is high. Highest dissolved solids concentrations occur during the winter months when discharge is low. The maximum water temperature was 27.5^{0} Celsius on July 12, 1985 and the minimum water temperature is zero degrees Celsius on many days during the winter months.

Under certain conditions, the interaction of dissolved cations and soil particles can cause slaking and dispersion of the soil, resulting in a sealing of the soil surface. Decreased hydraulic conductivity due to high sodium, with low total salinity have been documented by McNeal (1966) and McNeal and Coleman (1966). The average SAR for James River water at Oakes, between 1982 and 1986 is 1.9 (Table 1). On soils tested by McNeal (1966) and McNeal and Coleman (1966) negligible reduction in hydraulic conductivity was found for soils with SAR values as great as 2, even at very low total salt contents. For North Dakota soils, waters with SAR values indicated for the James River represent a low sodium hazard, and can be used on almost all soils with little danger of developing exchangeable sodium problems (Sweeney, 1972). Chances of reduced hydraulic conductivity due to sodium are further reduced by the coarse texture of sediments in the project area and by the relatively high salinity of the James River, which averaged 9.55 dS/cm from 1983 to 1986.

Table 1. Chemical and physical data for the James River near Oakes, ND

CHEMICAL PARAMETERS

	Ca mg/l	Mg mg/l	Na mg/l	SO_4 mg/l	Cl mg/l	Dissolved Solids mg/l	Suspended Solids mg/l	pH	S.A.R.
Mean	77	38	85	181	38	711	136	7.9	1.9
Maximum	170	82	240	460	140	1500	461	9.0	4
Minimum	42	21	33	78	11	340	40	7.6	1

Ground Water

One observation well completed just below the water table was installed adjacent to the small test basin at 131–059–29DDCD5. Another observation well completed just below the water table was installed adjacent to the large test basin at 131–059–29DDCB7. A water sample was collected at each well near the beginning of the recharge tests conducted in September 1986. A water sample was also collected from a U.S. Bureau of Reclamation observation well (W–008) completed in the Oakes aquifer (W–008) on January 28, 1985. This observation well is located about one–half mile east of the test area at 131–059–28CCC.

Ground water in the test area is a calcium–bicarbonate type with dissolved solids concentrations less than 400 mg/l (Fig. 5). Bicarbonate concentrations for the wells adjacent to the large and small test basins were estimated as the anion deficit by assuming a zero percent difference between measured total cations (Ca, Mg, Na, K) and anions (SO_4, Cl).

EXPLANATION

1. 131-059-29 DDCB7
   ADJACENT TO LARGE TEST BASIN
   DISSOLVED SOLIDS = 396 Mg/L

2. 131-059-29 DDCD5
   ADJACENT TO SMALL TEST BASIN
   DISSOLVED SOLIDS = 308 Mg/L

3. 131-059-28CCC
   U.S. BUREAU OF RECLAMATION W-008
   DISSOLVED SOLIDS = 320 Mg/L

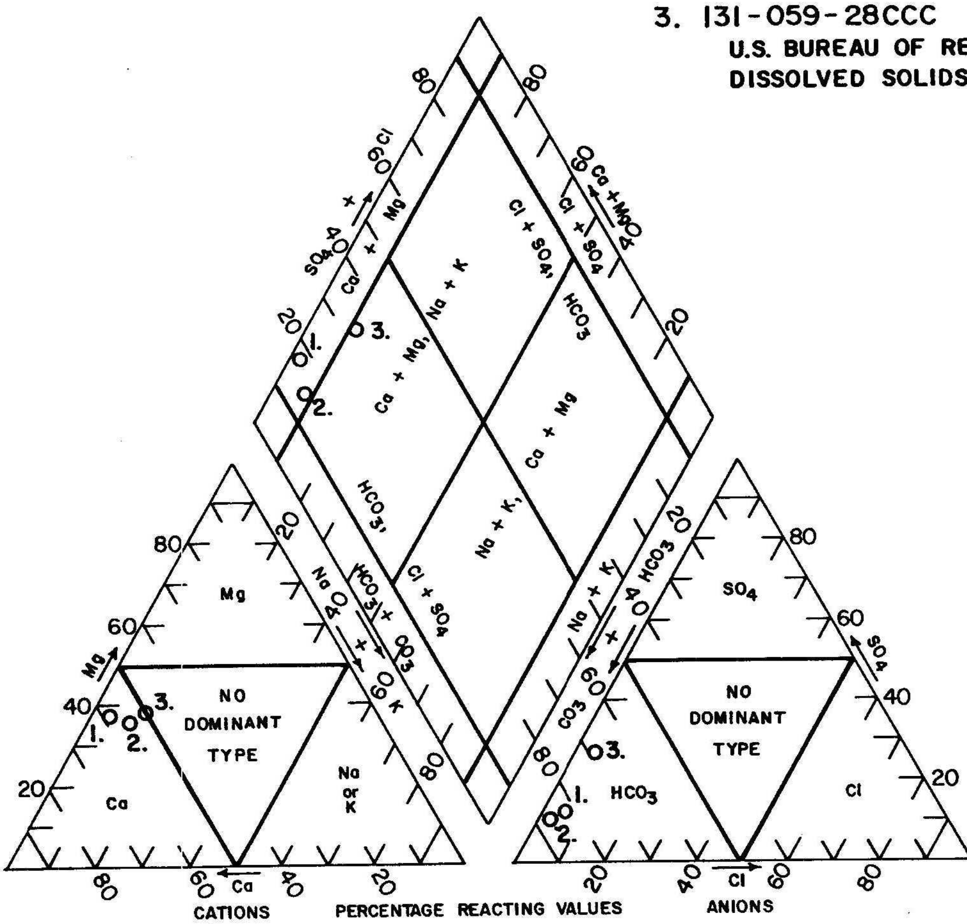


Fig. 5. Hydrochemical facies of ground water in the Oakes Aquifer test area displayed on a Piper diagram.

BASIN RECHARGE – GENERAL DISCUSSION

INFILTRATION

The problem of delivering water through the vadose zone is essentially one of infiltration. For a system defined as a volume of soil with surface and bottom boundaries set at the basin floor and a water table, respectively; and with a semi–infinite lateral boundary, the final steady–state infiltration rate for clean water may be controlled by either vertical or horizontal hydraulic properties of the system. If the ability of the defined system to transmit water laterally is large relative to its ability to conduct water vertically to the water table, then the amount of recharge will be determined by the vertical hydraulic properties of the overlying vadose materials. On the other hand, if the conductive properties and operational constraints (applied head, etc.) are such that the vertical movement to the water table is large in relation to the ability of the aquifer to conduct laterally, then the final steady–state infiltration rate will be determined by lateral constraints, and by the properties of the resulting ground–water mound.

Vertical Constraints

For vertical flow in a homogeneous soil profile, the infiltration rate, i, for any time, t, can be expressed using the equation of Green and Ampt (1911) as

$$i = K\,(H_0 + L + S)\,/\,L \qquad (1)$$

where K is the uniform saturated hydraulic conductivity of the soil between the surface and wetting front, H_0 is the depth of the ponded surface above the infiltration surface, L is the depth of the wetting front beneath the infiltration surface, and S is the soil water suction at the wetting front boundary. In the absence of osmotic pressure, vertical infiltration is controlled by three principle head components: elevation, pressure, and suction head. The relative importance of each of those components at any point in time may vary with the properties of the soil system, the ponded depth imposed, and the time of infiltration during the transient flow phase.

The simplest case is for the advance of a wetting front on a homogeneous soil with semi–infinite depth to the water table, and with uniform soil water suction (S) for each depth at the advancing wetting front. One example would be the case of an agricultural soil at "field capacity" prior to infiltration. When the depth of the wetting front, L, is small, H_0 and S strongly influence infiltration rate. As the wetting front advances, however, L becomes increasingly dominant. If the soil profile is semi–infinite in relation to S and H_0, then the hydraulic gradient approaches unity. Therefore, at quasi–steady state the infiltration rate will be identical to the hydraulic conductivity of the saturated soil profile, and will be insensitive to changes in ponded depth. The resulting time sequence during infiltration is illustrated on Fig. 6, where the final steady–state i value is approached under an increasingly dominant gravitational gradient for the saturated soil profile.

For nonhomogeneous soil profiles, the relationship between flux and individual head components may vary. One simple case, that of a material with a large hydraulic conductivity overlying a deep layer of small hydraulic conductivity, would result in the steady–state infiltration rate approaching the hydraulic conductivity of the limiting layer. For this case, flux would continue to be relatively insensitive to surface head changes. With a surface limiting layer overlying materials of larger hydraulic conductivity, however, the relative importance of individual head components changes . Under such conditions, at quasi–steady state the L component is limited by the depth of the small hydraulic conductivity layer, and thus L becomes smaller in relation to H_0 and S. In addition, when the entire soil–water profile is at steady state under ponded conditions, the value of S at the lower boundary of the surface limiting layer will be lower than commonly encountered under agricultural field conditions. The result is that L and S become smaller in relation to H_0, and that sensitivity of infiltration rate to ponded depth increases. The responsiveness of infiltration to H_0 under such conditions is further enhanced by the fact that increasing

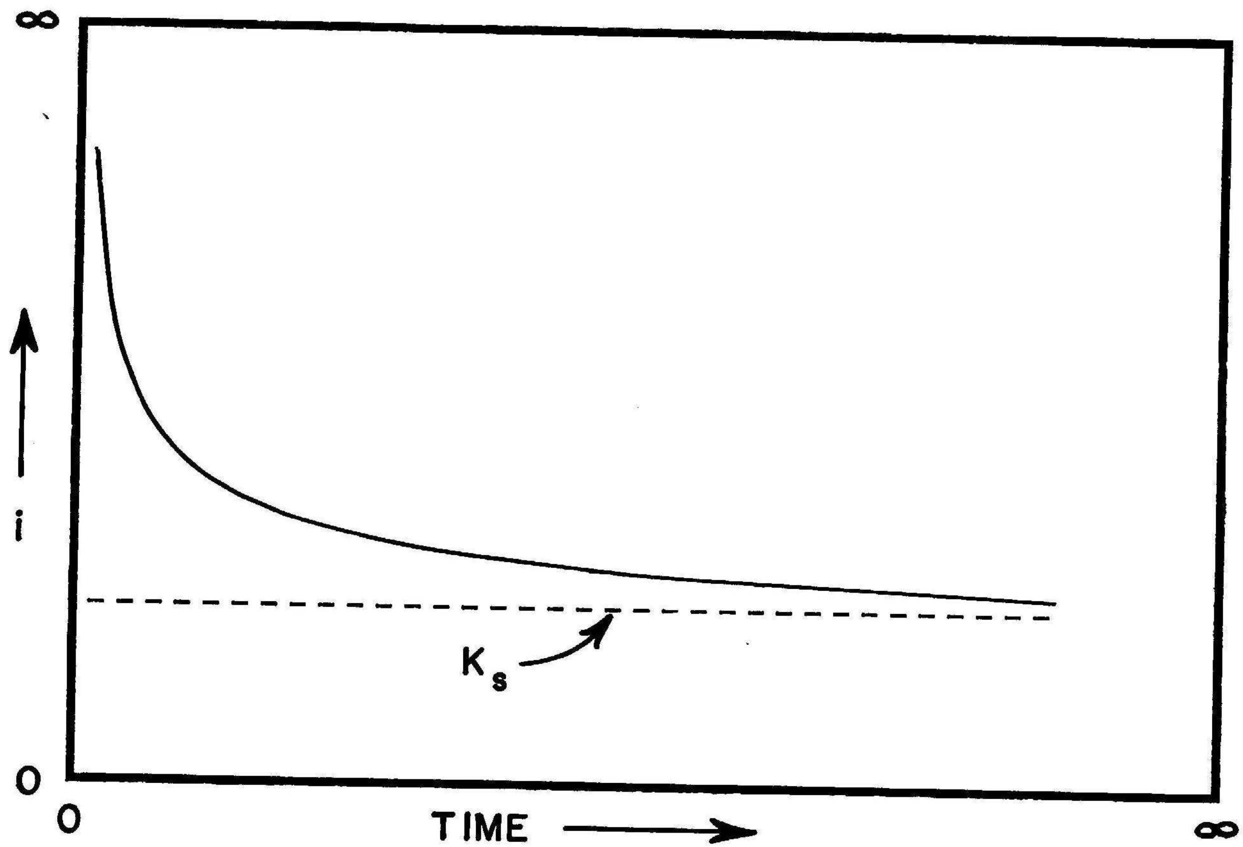


Fig. 6. Unscaled plot of infiltration vs. time.

H_0 results in increased wetting of the bottom boundary of the limiting layer, which in turn results in a decrease in S. The degree of responsiveness of S to H_0 will vary with different soil materials and initial moisture ranges, since the steepness of the $\theta(S)$ (soil moisture characteristic) function differs for different soils and $\theta(S)$ ranges.

Where infiltration is limited by hydraulic properties controlling vertical flow through the vadose zone, the response of recharge rates to different head components can vary widely, depending on the degree of heterogeneity of the vadose profile and the thickness and sequence of soil layers. During the operation of an artificial recharge facility, physical sedimentation, and biological and chemical changes in the subbasin alter hydraulic properties, infiltration rates, and the response of the basin to management techniques involving manipulation of individual head components. Implications of these properties and changes for basin management will be discussed in later sections.

Ground–Water Mounds

Water–Table Mounds

For a homogeneous isotropic medium, the infiltration rate through the bottom of a recharge basin to the top of the water table is partially governed by a hydraulic gradient (I) that approaches unity. In most practical field situations, when the infiltrating water arrives at the water table, the hydraulic gradient is significantly less than unity. Therefore, the downward flux immediately below the water table is less than the arrival rate of water and a water–table mound develops (Fig. 7, case A). If the water–table mound and associated capillary fringe remains below the bottom of the recharge basin, the water–table mound will not affect the infiltration rate (Fig. 7, case A).

The height to which a mound will rise during a surface recharge operation depends on: 1) rate of infiltration, 2) duration of surface recharge, 3) hydraulic conductivity of the infiltration media, 4) porosity of the infiltration media, 5) initial saturated thickness of the aquifer, and 6) slope of the base of the aquifer (Baumann, 1965).

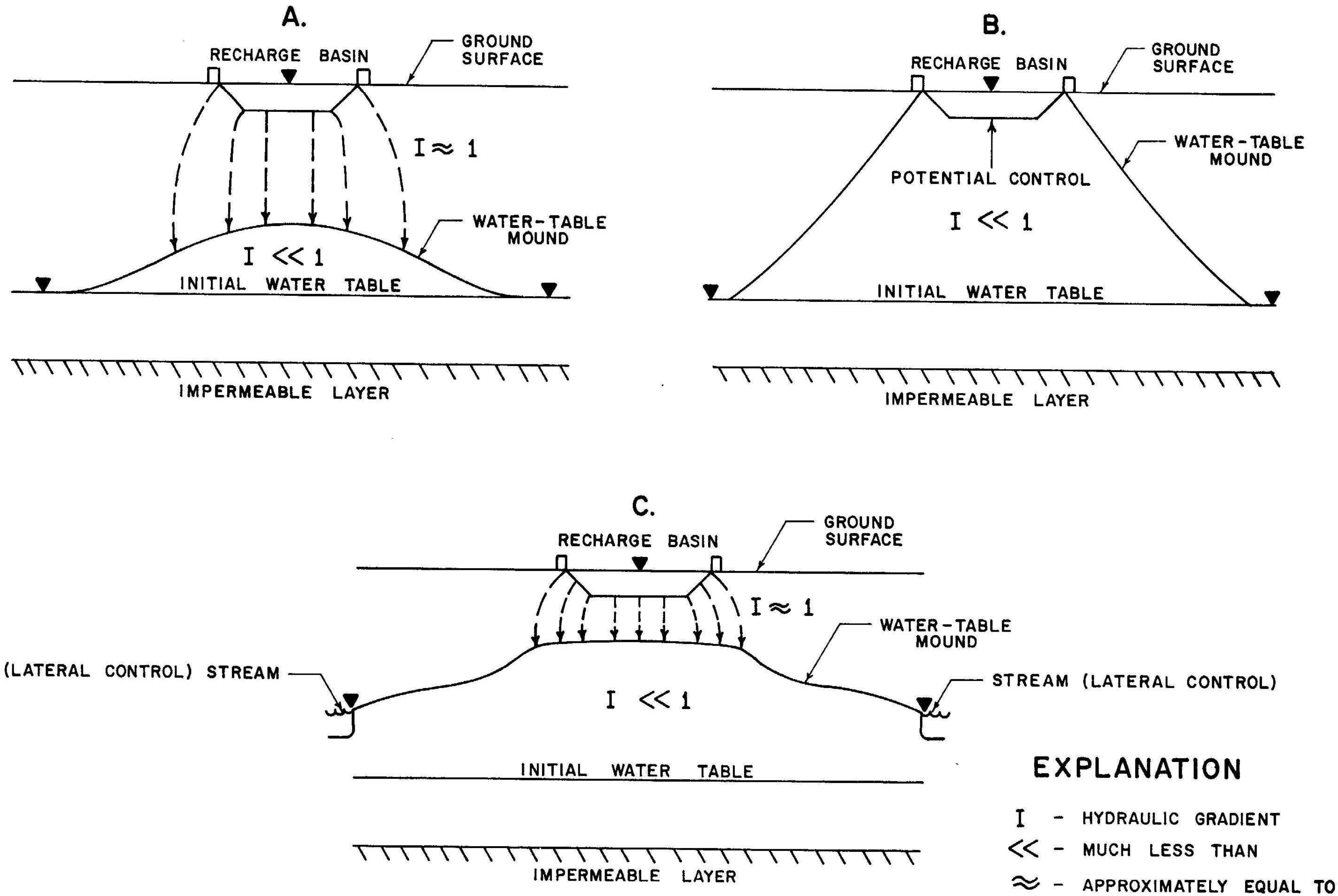


Fig. 7. Water-table mounds and the effect of selected boundary conditions on mound height and shape.

Baumann (1965) also described two types of boundary conditions that control the height of a water–table mound: 1) potential controls, and 2) lateral controls. Potential controls include the bottom of a recharge basin (Fig. 7, case B) or ground surface. After the water–table mound intersects a potential control, the hydraulic gradient decreases and, as a result, infiltration rate decreases.

Lateral controls include streams (Fig. 7, case C) or relatively impermeable barriers. For case C, the parallel streams prevent the water–table mound from intersecting the bottom of the recharge basin. As in case A, the water–table mound does not affect the infiltration rate.

Hantush (1967) developed analytical solutions which describe the growth and decay of the water–table mounds in a homogeneous, isotropic media below surface recharge basins with different geometries. For a rectangular pond the following formula applies:

$$h_{x,y,t} - H = \frac{V_a t}{4f} \{ F[(W/2 + x)N, (L/2 + y)N] + F[(W/2 + x)N, (L/2 - y)N] + F[(W/2 - x)N, (L/2 + y)N] + F[(W/2 - x)N, (L/2 - y)N] \} \quad (2)$$

where,

$h_{x,y,t}$ = height of water table above impermeable layer

H = original height of water table above impermeable layer

V_a = arrival rate at water table of water from infiltration basin

t = time since start of recharge

f = fillable porosity ($1>f>0$)

L = length of recharge basin (in y–direction)

W = width of recharge basin (in x–direction)

N = $(4\,t\,T/f)^{-1/2}$

T = transmissivity ($K \cdot H$)

$K =$ hydraulic conductivity

$F(\ell\beta) = \int_0^1 \mathrm{erf}\,(\ell\tau^{-1/2}) \cdot \mathrm{erf}\,(\beta\tau^{-1/2})\, d\tau$

(which was tabulated by Hantush)

The symbols used by Hantush for the surface basin and water–table mound are illustrated in Figure 8. For the height of the center of the mound, x and y are zero, in which case the sum of the F functions between brackets in Eq. (3) reduces to 4F (W N/2, L N/2). The solution loses validity if the mound height is more than one half the original saturated thickness of the aquifer (i.e. when $h_t > 0.5H$).

When H is large compared to W (thick aquifers or narrow basins), flow in the aquifer is concentrated in the upper portion or "active" zone of the aquifer (Bouwer, 1978). The deeper portions of the aquifer contribute very little to the flow and are essentially stagnant or "passive". Therefore, the effective transmissivity of the aquifer is less than the transmissivity of the entire aquifer. Studies with an analog model have shown that the maximum depth of the active region is about equal to the width of the recharge area for isotropic aquifers (Bouwer, 1962).

The maximum height of a water–table mound is also a function of basin geometry. Bianchi and Muckel (1970) developed a dimensionless plot of the rise at the center of a water–table mound beneath a rectangular recharge area for different ratios of length to width (Fig. 9). Figure 9 shows that given equal recharge areas mound heights will be greater beneath square basins than beneath rectangular basins because lateral flow is a smaller percentage of total flow. In addition, Figure 9 shows that when $L/W > 4$, the mound rises at almost the same rate as below an infinitely long strip–like recharge basin.

Perched Ground–Water Mounds

Stratification is a property of fluvial deposits that is caused by nonuniformity of supply, transportation, and deposition of sediment. A common type of stratification results when layers of different texture comprise a sedimentary sequence. The layers may

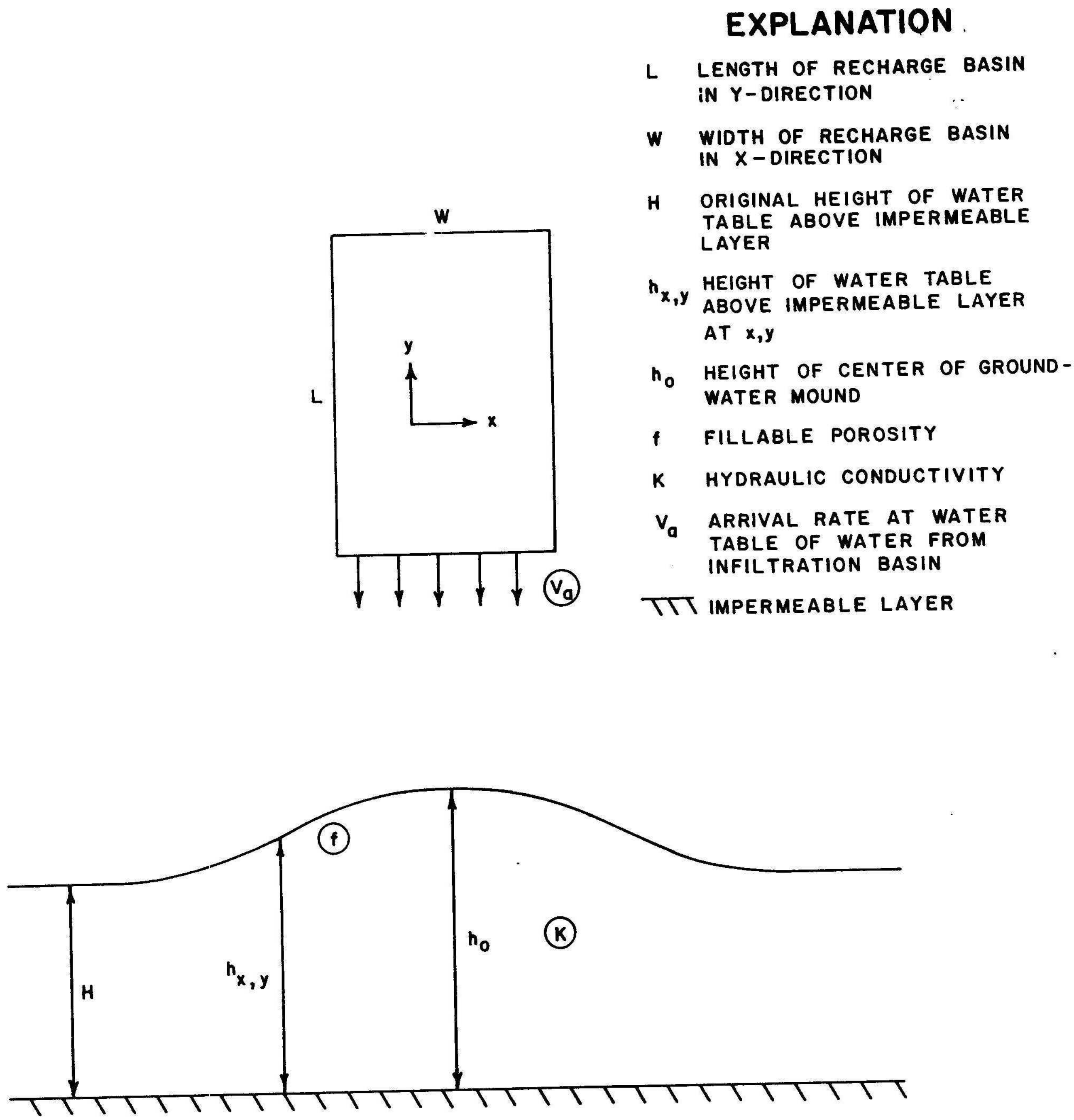


Fig. 8. Geometry and symbols for a rectangular infiltration area and underlying water-table mound in an unconfined aquifer (from Bouwer, 1978).

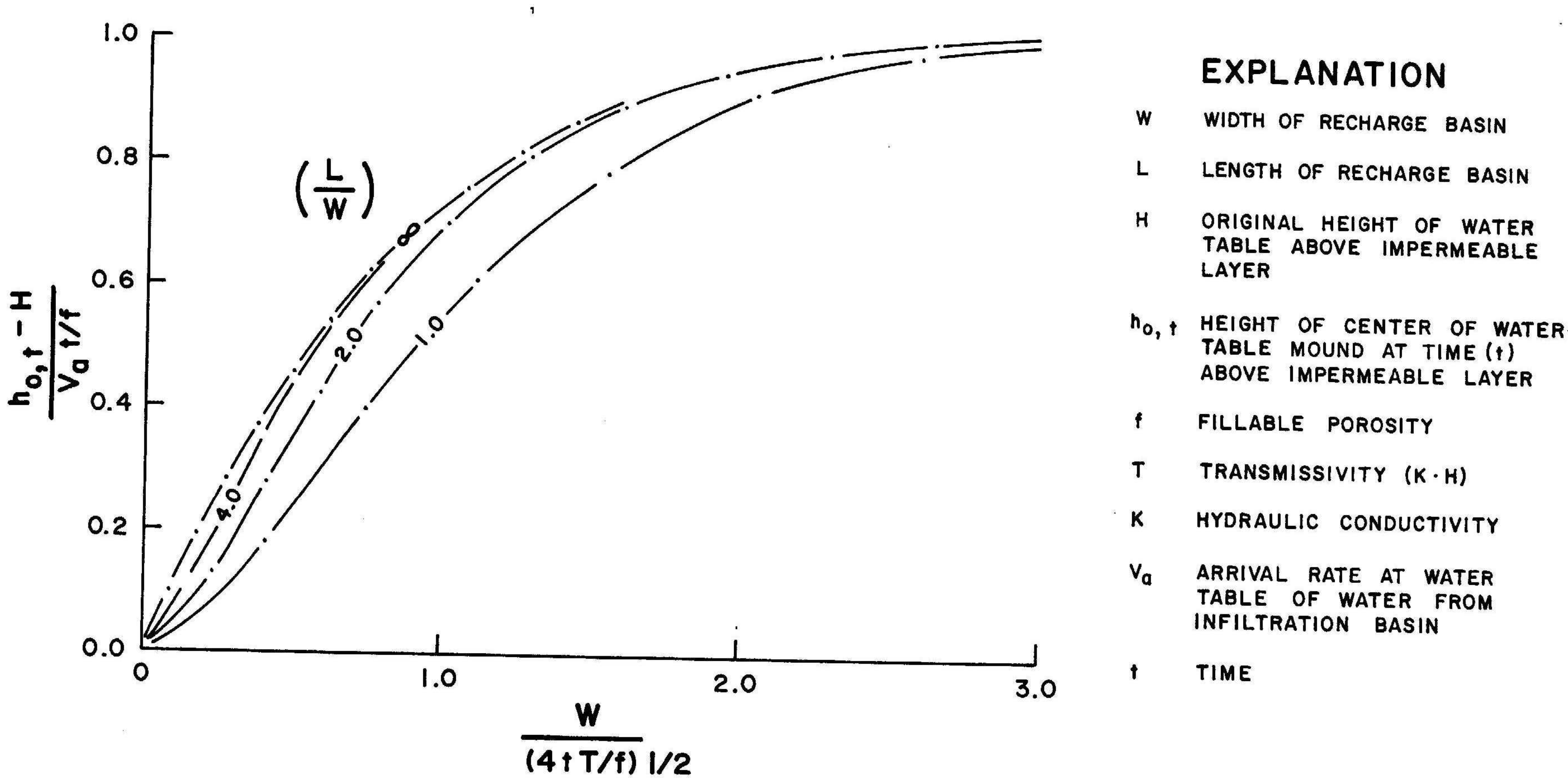


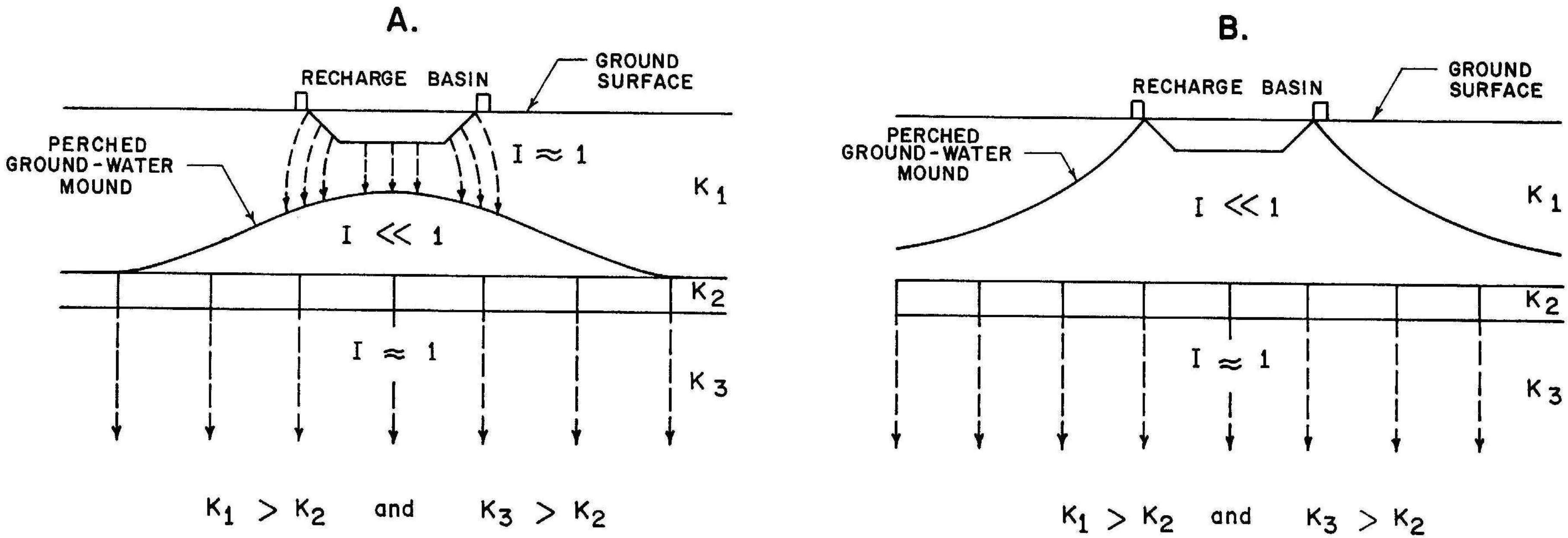
Fig. 9. Dimensionless plot of the rise at the center (ho) of the mound beneath a rectangular recharge area for different ratios of length to width (from Bianchi and Muckel, 1970).

be less than 0.25 cm (0.1 inch) thick (thinly laminated) or greater than 0.3 m (1 ft.) thick (thick–bedded). Textural stratification results in a sediment profile of nonuniform hydraulic conductivity. Providing that the layer of finest grain size (lowest hydraulic conductivity) is not at the surface, infiltration through a sediment profile of nonuniform hydraulic conductivity is conducive to the development of perched ground–water mounds. Perched ground–water mounds can significantly reduce the rate of infiltration through a surface or basin recharge facility.

The development of a perched ground–water mound is illustrated in Figure 10. In Case A, the perched ground–water mound develops above a layer of low hydraulic conductivity. Conditions are such that lateral flow along the flanks of the mound and cross–sectional infiltration area through the restricting layer are sufficient to accommodate the total inflow available through the bottom of the recharge basin. Therefore, the mound does not intersect the bottom of the basin. For this case, the perched ground–water mound does not affect the infiltration rate through the recharge basin. Infiltration rate through the bottom of the recharge basin to the top of the ground–water mound is, in part, governed by a hydraulic gradient that approaches unity.

In Case B, lateral flow and cross–sectional infiltration area through the restricting layer are not sufficient to prevent the ground–water mound from rising until it intersects the bottom of the recharge basin. When the mound intersects the bottom of the basin, the hydraulic gradient beneath the basin decreases and as a result, the infiltration rate through the recharge basin decreases. The maximum height of the ground–water mound is the ponded surface in the basin. However, the ground–water mound may continue to spread laterally. As the lateral hydraulic gradient decreases with time after the maximum height is reached, the recharge rate will also decrease slowly with time (Todd, 1961).

The maximum height of a perched ground–water mound is governed, in part, by the geometry of a surface recharge facility. In areas where the potential exists for perched ground–water mounds to restrict infiltration rates, surface recharge facilities should be



EXPLANATION

K – HYDRAULIC CONDUCTIVITY

I – HYDRAULIC GRADIENT

≪ – MUCH LESS THAN

> – GREATER THAN

≈ – APPROXIMATELY EQUAL TO

Fig. 10. Development of perched ground-water mounds.

relatively small and provide the highest ratio of the wetted perimeter to the wetted area. This maximizes lateral flow and reduces the heights of the ground–water mound. The highest ratio of the wetted perimeter to the wetted area is achieved with long, narrow, strip–like recharge facilities.

EFFECTS OF TURBID WATER ON INFILTRATION

Limitations in the recharge capability of a basin facility are frequently imposed by the interaction of the filtering medium comprising the vadose zone between the basin floor and the water table, and the physical load and chemical properties of the influent water. During the operation of a recharge basin the infiltration rate can be altered by: 1) clogging of subbasin pores by sediment–laden water, 2) in–situ formation of solid and gaseous products of microbial respiration and metabolism at or near the basin floor, 3) dissolution of subbasin salts, or precipitation of salts from influent water, 4) dispersion of the filter matrix materials, 5) flocculation, 6) ion–exchange reactions, and 7) swelling of clays due to hydration (Todd, 1961). In some cases,dissolution of soluble matrix grains can result in increased recharge rates (Aronovici et al., 1972). Usually, the rate of infiltration decreases with time.

Suspended Solids

One problem of concern for the operation of artificial groundwater recharge facilities is the formation of layers of increased hydraulic impedance caused by the application of turbid water. Long–term cost effective design for management of a basin recharge facility requires that a balance be reached between maximum short–term water recharge, and the resulting depth of sediment penetration and clogging. Deposition of suspended solids frequently decreases intake rates to the point where renovation of the facility is required. If significant hydraulic impedance due to deposition occurs too deeply, the cost of renovation may be prohibitive, requiring termination of the facility.

Sediment deposition varies considerably with depth, and deposition profiles are governed by numerous complex properties and processes. In a recent review, McDowell–Boyer et al. (1986) classified sediment filtration phenomena into three categories: 1) filter cake or surface–mat formation, resulting from interception of particles on the surface of the filter medium; 2) straining, which is mechanically similar to filter–cake formation, resulting from the mechanical interception of larger sediment particles in smaller pores; and 3) physical–chemical filtration, in which very small particles are removed through electrochemical attachment to the grain matrix materials.

Predominance of modes of filtration are primarily dependent on the sizes of the sediment particles and those of the filter grain matrix. McDowell–Boyer et al. (1986) cited d_m/d_p ratios (d_m =diameter of matrix grains, d_p = diameter of sediment particles) of 10 to 20 for straining in uniform media filters, while physical–chemical processes were cited for d_m/d_p exceeding 1000. Ives (1970) labeled the physical–chemical filtration "rapid filtration" and observed that dilute sediment–laden solutions (< 500 mg/l) of particles between 0.1 and 50 νm (USDA silt and clay fractions) defined the range of practical application.

The type of sediment removal process greatly influences the degree of hydraulic conductivity changes, and the degree of renovation required for the facility. For water treatment, the rapid filtration (Ives, 1970) allowed by filters designed to operate on physical–chemical properties, maintains large rates of flux through the filter. Particles are moved within the range of electrical interaction with matrix grains by interception, inertia, sedimentation (gravitational forces), diffusion, and hydrodynamic forces induced by shear gradients within the fluid stream, and are removed by London Van–der–Waals forces, or in some cases cation bridges bonding the matrix and sediment particles. Rapid filtration results in the deposition of sediment throughout a large filter volume. Attenuation of infiltration is more gradual (gradient changes in the clogged zones are, in some cases, linearly related to porosity changes) during deposition (Ives, 1970). Eventually, however, the entire filter must be removed and replaced or cleaned. Straining mechanisms have limited capabilities for decreasing porosity and permeability (McDowell–Boyer et al., 1986). However, straining near the surface may prime the filter for the initiation of filter cake formation (Ives, 1985) resulting in severe clogging and attenuation of infiltration. In the design of a rapid filter, the filter cake is avoided because of the low permeability of the materials strained on the surface.

The necessity of avoiding surface sediment concentration in rapid filtration, and the importance of water velocity as a key variable in determining depth of sediment deposition in many rapid filtration models (Ives, 1970; Deb, 1969; Harmeson et al., 1968) illustrate the problem of the tradeoff between maintaining high flow rates and minimizing renovation costs. If conditions for greater velocities exist, then the conditions that drive sediment deeper into the subbasin profile also exist. Harmeson et al. (1968) reported that between 18 and 90 % of the suspended solids in recharge water were retained in the water after passing through a 61 cm (24 in.) thick, 0.48 cm (3/16 in.) particle–diameter filter, depending on the approach velocity of the water. It is clear that gradual sediment clogging can occur to considerable depths under conditions of rapid infiltration. On the other hand, the objective of optimizing flux through the filter is obstructed by the deposition of the sediment as a mat on the surface.

Examples of varying depth of particle penetration during operation of artificial recharge facilities have been documented by Kovenya et al. (1972) who reported less than 50% of particle mass retained in the top 40 cm (15.8 in.) during infiltration through a soil with large pores; and by Goss et al. (1973) who reported 91% of sediment deposited in the top 2.54 cm (1.0 in.), and 97% deposited within the top 15 cm (6 in.) of a tilled clay loam subsoil. Harmeson et al. (1968) reported that depth of penetration for suspended solids in gravel filters was a function of sediment size, sediment load, filter media diameter, and flow velocity. Rice (1974) found that deeper penetration of solids resulted from higher hydraulic gradients and corresponding higher flow velocities. For clay and silt sediment, it is clear that unless a coarse filter is added to the system, a filter cake will form at some point of operation and will strongly inhibit flow.

Clogging resulting from irrigation with turbid water was reported by Shainberg and Singer (1986) to result in a 2 to 3 order of magnitude decrease in the hydraulic conductivity of the soil surface layer. Dilyunas (1976) reported a 100 fold decrease in hydraulic conductivity for the top 5 cm (2 in.) of a recharge surface flooded with water containing 10 to 30 mg/L suspended solids. Hydraulic conductivity decreased by a factor of 5 to 7 at the 5 to 20 cm (2.0 to 7.9 in.) depth. Schuh (1988) observed increases of two to three orders of magnitude in hydraulic impedance for the top 8 cm during recharge with water containing 50 mg/L suspended solids, while changes of 0 to 1 order of magnitude were observed for the 8 to 23 cm layer. Deeper deposition occurred during early infiltration and ceased after filter cake formation began. The deeper deposition was primarily of clay, while the filter cake was proportionally higher in silt. These results are consistent with the observations of Behnke (1969) who reported the following three phases of infiltration during artificial recharge through a Hesperia sand: 1) little change in infiltration during the initial operation phase; 2) rapid decreases in infiltration during the middle phase as particle straining near the surface resulted in removal of successively smaller particles, forming a surface mat; and 3) little change during the final phase, since extremely small (clogged) infiltration rates resulted in less sediment input to the basin.

Biological Clogging

Clogging of biological origin has been documented by Ripley and Saleem (1973), Rice (1974), and others. Primary causes of clogging are: 1) biomass formation, 2) solid microbial biproducts, and 3) gases formed during photosynthesis and respiration. Studies documenting direct attenuation of flux due to clogging by aggregates of bacteria have been cited by McDowell–Boyer et al. (1986) and Oberdorfer and Peterson (1985). Using nonsediment–laden water, Ripley and Saleem (1973) reported that disinfection of influent water did not ultimately improve infiltration because of adaptation and selection of resistant bacterial populations which proliferated after each treatment.

Flux attenuation in laboratory experiments and field facilities treated with water containing organic substrates has been similarly described as a three–phase process by Allison (1947), Okubo and Matsumoto (1979), and Wood and Bassett (1975). The first phase is characterized by a decreasing infiltration rate. Allison (1947) attributed the decrease to air entrapment and destruction of soil structure, while Okubo and Matsumoto (1979) attribute the decline to aerobic microbial activity and proliferation. The second phase is characterized by a period of rising infiltration rate. Allison (1947) credited the increased flux to purgation of entrapped air from the system, while Okubo and Matsumoto referred to this phase as a period of arrested aerobic microbial growth, characterized by a lower level of dissolved oxygen. The lower levels of dissolved oxygen are also consistent with the hypothesis of Allison. During the third phase, a decreasing infiltration rate is accompanied by a decrease in dissolved oxygen beneath the basin floor which each of the authors attribute to anaerobic microbial activity. Wood and Bassett (1975) , in observing the same characteristic relationship for a field facility, suggest that both the physical processes described by Allison (1947) during the early phase, and the predominantly biological phenomena are likely occurring.

Pore Obstruction by Solids

Solid microbial products may consist of organic materials or of mineral precipitates resulting from a changing oxidation–reduction environment and microbial byproducts. Allison (1947) attributed substantial decreases in permeability to polysaccharide formation (microbial gums) in the filtering soil matrix. Citing the aggregation experiments of Martin (1945), he suggested that the period of rising flux was partially due to aggregation of soil particles by microbial gums. Similarly, the final degradation and destruction of those gums was suggested as a cause for the final infiltration rate decline. Although these mechanisms may occur, it is felt that the effect of such gums on a sandy soil during the process of basin operation would be to directly clog the soil matrix rather than restructuring the soil matrix. Nevo and Mitchell (1967) have observed the occurrence of clogging caused by the presence of polysaccharides. They have also noted that the survival range of pH for bacteria producing polysaccharides is broad (6 to 9) and that pH control of influent water is not a practical measure. The bacteria are somewhat temperature sensitive, however, and polysaccharide production should decrease with temperatures below 20^oC.

Because biomass accumulation is dependent upon the counterbalancing rates of formation and degradation, the position and persistence of biological products is dependent upon the degree of oxygenation of the water. Generally, dissolved oxygen is highest near the surface, and decreases with depth beneath the basin floor (Okubo and Matsumoto, 1979; Wood and Bassett, 1975). The final destruction of the microbial products near the source of water input has been documented by Oberdorfer and Peterson (1985), who noted that following injection of waste water, almost no organic material was found near the injection point. They attributed the lack of net deposition to microbial decomposition in the well–oxygenated water near the point of influx.

Beneath the surface oxidized zone, mineral precipitates may result from mobilization of iron and manganese due to anaerobic respiration, and due to the formation of H_2S during the reduction of sulphur. The latter reacts with iron and manganese to form mineral precipitates (gley), which later oxidize on the pore surfaces. Oberdorfer and Peterson (1985) recorded the predominance of metal sulfides near the injection point, and conjectured that the exclusively anaerobic sulfate–reducing bacteria must be surviving in the micro environment provided by some smaller pores, which receive less of the oxygenated injection water. For a basin facility, however, Wood and Bassett (1975) observed a black gelatinous zone 10 to 20 cm (3.9 to 7.9 in.) thick forming beneath a 2 to 5 cm (0.79 to 2.0 in.) thick well–oxidized surface layer. The black layer was attributed to sulfate–reducing bacteria . The black color disappeared within a few hours of oxygen exposure for the samples.

Bouwer and Rice (1984) have documented mineral clogging due to changes in water chemistry induced by algal photosynthesis. Under conditions of slow water cycling, algal blooms and consequent increased photosynthesis resulted in high basin water pH. This, in turn, resulted in calcium carbonate deposition which sealed the basin floor.

Gupta, et al. (1977) described the decreasing hydraulic conductivity of dredged soil materials due to direct clogging from sludge materials. Webb and Watson (1978) similarly described the direct clogging of a basin due to deposition of algae on the basin surface. Direct clogging of this sort is similar to mineral sediment clogging, with the exception that it is degradable and that hydraulic conductivity is more easily recovered. Experiments by Rice (1974) indicated that flux attenuation due to microbial activity was not significant in cases where substantial sediment loads were added to the basin. Sediment clogging was perceived to be dominant. Rice also observed that decreased hydraulic conductivity due to microbially induced clogging was recoverable during intermittent rest periods, which allowed for decomposition of solid microbial products and venting of gases.

Gaseous Pore Obstruction

Gaseous blockage of soil pores has been shown to be a significant factor in decreasing hydraulic conductivity. Direct oxygen entrapment due to fingering (uneven wetting front advance) and entrapment above underlying layers of low air permeability have been described by Norum and Luthin (1968) and by Bianchi and Haskell (1966). Under high pH conditions, ammonium ions can be transformed chemically to ammonia gas. Ammonia blockage might occur in soils containing ammonium ions after flooding with high pH water. Webb and Watson (1978) have demonstrated diurnal decreases in basin hydraulic conductivity due to oxygen production in a surface mat caused by algae photosynthesis. In one case, Rice (1974) found that oxygen produced by algae actually increased recharge through renovating the basin. Oxygen produced and entrapped under the algae lifted the algae mat and floated the mat to the surface, inducing a large increase in surface hydraulic conductivity. Carbon dioxide (CO_2) produced by aerobic respiration can also block pores and inhibit infiltration under some circumstances where the rate of gas production exceeds the rate of hydrolysis and dissolution.

Gases formed from anaerobic respiration beneath the well-oxidized surface zone (Wood and Bassett, 1975 ; Okubo and Matsumoto, 1979) have been shown to impede flux. Primary causes of clogging are most likely denitrification products (N_2, NO, and NO_2) with N_2 predominant given sufficient time (Alexander, 1977 , pp. 273–275). Other gases, such as methane, and sulfate reduction products (dimethyl sulfide and H_2S) can also be produced (Alexander, 1977, p. 365). Of these, H_2S should react quickly with soil metals and would not likely remain volatile. Denitrifying bacteria are frequently faculative (Alexander, 1977, p. 277) and can therefore persist during periods of intermittent aeration. Denitrifying bacteria may be heterotrophic, relying on organic substrate for energy, or autotrophic, deriving energy from such processes as sulfide oxidation (thiobacillus denitrificans). In the presence of ample organic substrate, heterotrophic bacteria will provide the most prolific means of denitrification . It is known (Bouwer et al., 1972 ; Alexander, 1977, p. 279) that the presence of roots can enhance denitrification.

Clogging due to denitrification has been documented by Oberdorfer and Peterson (1985) at a distance of approximately 0.5 m from the point of injection. Rice (1974) reported hydraulic conductivity decreases of 50 to 60 % after three years of intermittent infiltration for the 10 to 30 cm depth on test columns. Hydraulic conductivity was recovered by passing CO_2 through the column, and nitrogen blockage was suggested as the cause. Bouwer et al. (1972) investigated the use of intermittent flooding and aeration as a means of controlling nitrogen influx to the water table. In Bouwer's experiment, most influent nitrogen was in the ammonium species. Bouwer flooded the basin, and allowed the soil to intercept the positively charged ammonium ions. The following aerated rest period resulted in the nitrification of the ammonium. The next flooded period enabled denitrification of almost all of the nitrogen, following a brief initial delivery of nitrate to the water table.

Recovery

One characteristic of clogging due to organic agents is that hydraulic conductivity should be substantially recoverable, given proper management and sufficient time. Gases produced should be vented during rest periods. Nevo and Mitchell (1967) have observed that clogging due to polysaccharide formation is substantially reduced during recovery periods . They have noted, however, that recovery is not complete, due to the presence of some products that are more resistant to decomposition. Even the presence of organic substrate in the form of algae matting, etc. should be decomposable with proper management. Maintaining an optimal microbial environment during rest periods with adequate moisture, aeration, pH, and nitrogen should enhance decomposition. Tillage, for example, would enhance biodegradation by increasing soil aeration. Organic clogging mechanisms differ from mineral sediment clogging in that they are more transitory and can be substantially removed from the system without actual removal of the soil surface layer.

Chemical Reactions Causing Precipitation

Porosity reduction by mineral precipitation generally has not been a serious problem in the recharge of potable water at field sites (Wood, 1976). Several reasons can be cited for the minimal effect of mineral precipitation including: 1) the slow kinetics that cause precipitation to occur over a large area rather than at the water–aquifer interface; 2) precipitation usually occurs in relatively dead pore space with little effect on the hydraulic conductivity; and 3) the total volume of precipitation is usually too small to significantly affect the hydraulic conductivity (Wood, 1976).

Particle Rearrangement – Clay Dispersion and Flocculation

Clay minerals are composed of two basic structural units that include a tetrahedron of four oxygen atoms surrounding a central cation (usually Si^{4+}) and an octahedron of six oxygen atoms or hydroxyls surrounding a larger cation of lesser valency (usually Al^{3+} or Mg^{2+})(Hillel, 1980). Cations are adsorbed on the external surfaces of clays due to unbalanced negative charges within the clay lattice. A more diffuse second layer of anions are attached to the adsorbed layer of cations.

Forces of both repulsion and attraction exist between clay particles. When repulsive forces are dominant, the particles separate and remain apart from each other and the clay is dispersed. When the attractive forces dominate, the clay is flocculated. One of the significant factors causing dispersion or flocculation is the thickness of the double layer of cations and anions surrounding a clay particle. Repulsion is maximized (favoring dispersion) when the double layer is thick and fully extended. A thick double layer occurs when: 1) the solution is very dilute; 2) the pH is high; 3) the dominant cation is monovalent; and 4) the clay is fully hydrated. Repulsion is minimized (favoring flocculation) when the double layer is thin. A thin double layer occurs when: 1) the total solution salt concentration is high; and 2) monovalent cations (Na^{+}) are replaced by divalent cations (Ca^{2+}, Mg^{2+})(Hillel, 1980). Interparticle attraction is caused by London Van der Waal's forces when the double layer is thin.

Most geologic formations contain some clay which, in a dispersed state, can significantly reduce hydraulic conductivity (Wood, 1976). Nightingale and Bianchi (1977) found that infiltration of a low salinity calcium–magnesium–bicarbonate type water (30 to 50 mg/l total dissolved solids) caused dispersion of submicron–size colloids within the surface weathered zone. When the salinity of the water was increased above 80 to 90 mg/l total dissolved solids, dispersion was greatly reduced. Gypsum was added to the recharge water and dispersion was also reduced. Even though an estimated 148 metric tons of clay colloids were removed from the surface sandy loam by dispersion, there was no evidence of aquifer clogging due to clay flocculation and adsorption.

Cation Exchange

The cations in the double layer can be replaced or exchanged by other cations introduced into the solution (Hillel, 1980). Exchange capacity is a function of valence state, atomic radius, and hydration properties. In general, the smaller the ionic radius and the greater the valence, the more closely and strongly is the ion adsorbed. The greater the ion's hydration, the further it is from the adsorbing surface and the weaker its adsorption. Monovalent cations are replaced more easily than divalent or trivalent cations. The order of preference in exchange reactions is as follows:

$$Al^{3+} > Ca^{2+} > Mg^{2+} > NH_4^{+} > K^{+} > H^{+} > Na^{+} > Li^{+}$$

Cation exchange affects clay dispersion and flocculation. For example, soil dispersion is reduced by application of gypsum. Gypsum provides Ca^{2+} that exchanges with Na^{+} adsorbed on the clay particle. The double layer around the clay particle is compressed because of the increased charge. Compression of the double layer permits clay particles to aggregate because interparticle attraction increases due to London Van der Waal's forces.

Clay Hydration

Clay has a strong affinity for water. Water is attached to clay surfaces by electrostatic attraction of the dipolar water molecules to charged sites and by hydrogen bonding to exposed oxygen atoms on the clay crystal (Hillel, 1980). Hydration of adsorbed cations also contributes to the overall hydration of clays.

When a confined body of clay is hydrated, swelling pressures develop. The swelling pressures are related to the osmotic pressure difference between the double layer between clay plates and the external solution. The osmotic attraction for external water is generally twice as high for monovalent compared to divalent cations, since twice as many monovalent cations are required to satisfy the same lattice change. Swelling and repulsion are greater with monovalent cations such as sodium, and with very low salinity water as the external solution. When calcium is the predominant cation on the exchange complex, swelling is greatly reduced. High salinity in the external solution will also reduce swelling (Hillel, 1980).

Goldenberg et al. (1983) conducted laboratory experiments to investigate the influence of clay type and amount on hydraulic conductivity. When seawater was flushed by freshwater in the sediment columns, the hydraulic conductivity of the montmorillonite–sand mixture decreased drastically. However, flushing with freshwater did not measurably affect the hydraulic conductivity of an illite–sand or kaolinite–sand mixture. This response was attributed to preferential clay hydration that was governed by the chemical composition and the ionic strength of the solution.

RECHARGE BASIN MANAGEMENT TECHNIQUES

Numerous basin management techniques have been tested to optimize recharge and minimize the expense of deep replacement of basin soil materials. Management techniques can be classified as: 1) natural methods (rainfall, shrink–swell, freeze–thaw, etc), 2) cleaning or removal of soil materials, 3) tillage of the basin floor, 4) filtration , 5) flocculation of the sediment, and 6) management of the surface head (ponded depth) within the basin. Common sediment deposition profiles were discussed above. For most river sediment loads during recharge through sandy or loamy soils, near–surface straining and surface filter cake formation quickly dominate infiltration. To a large degree, the optimization of short–term recharge requires methods that prevent or limit the formation of the filter cake. Prevention of filter cake formation, however, will usually result in deeper sediment deposition, and greater eventual soil removal requirements.

Clogging of the basin surface by erosion or slumping of the topsoil of the basin sidewall might be expected to contribute to decreasing basin infiltration. Experience on sandy loam soils at the Ainsworth Nebraska facility, however, has indicated that erosion is not a serious problem. At Ainsworth, 2.5:1 sideslopes and a bromegrass cover were used to stabilize banks. Although some bromegrass stand death along lower banks has been observed following periods of lengthy inundation, the grass cover reestablishes quickly during nonoperational periods, and the residual roots and vegetative cover are usually sufficient to prevent undercutting of the banks (H. Welch, personal communication, 1988). The problem of bank erosion should be solvable using conventional engineering methods for design and stabilization of banks on drainageways and canals.

Natural Recovery

Natural phenomena can be used in a well–engineered facility, and in a well–planned operational schedule, to offset the limiting effects of a surface filter cake. Desiccation of the basin surface following recharge causes cracking and curling of the filter cake which allows for substantial recovery of infiltration rate (Suter and Harmeson, 1960; Bouwer et al., 1972). The operation time before resealing of the surface is shorter, however, as the desiccated cake materials eventually wet and are repositioned on the surface. Bouwer et al. (1972) have indicated that a desiccation period greater than one week is required . According to Bouwer, most of the renovating change occurred during the second week of drying. In some cases, a sloped basin floor design has been used to facilitate natural removal of the filter cake materials by rainfall. This has been used in a facility at Ainsworth, Nebraska (H. Welch, personal communication, 1987) and also in Texas (O.R. Jones, personal communication, 1987). Although recovery of hydraulic conductivity due to deeper sediment deposition would likely be limited using desiccation alone, winter freeze and thaw might effect a dilution of sediment concentration within the soil, and might induce increased porosity due to particle reorientation.

Clogging due to organic materials can be partially reduced by decomposition during rest periods. Nevo and Mitchell (1967) demonstrated that polysaccharides formed by bacteria during flooding were quickly decomposed during recovery periods. Some microbial products, however, are more resistant to degradation and persist. Johnson (1957) demonstrated that a period of natural degradation of an organic mat filter can enhance infiltration. A dry recovery period can also allow for the venting of gases formed and trapped during basin operation.

Replacement and Removal: Cleaning

The most thorough form of renovation is removal of the clogged materials from the basin. Because the filter cake is a surface phenomenon, shallow removal techniques often suffice. Various methods have been used. At Peoria (Suter and Harmeson, 1960) a pool suction cleaner was used to remove surface silt during basin flooding. Small, short–term increases in recharge were achieved, but the operation required two men to operate and was time consuming and expensive. In a Texas facility (Jones et al., 1981) sweeping was used to remove the surface filter cake. Most commonly, surface "shaving" is practiced, using a front end loader, or blade equipment to clean the surface (Ainsworth facility, H. Welch, personal communication, 1987; Bouwer et al., 1972). Where management techniques prevent or delay filter cake formation, eventual deeper replacement of the subbasin soils or of the added filter materials is required. A 3– to 4–year replacement schedule was required at Peoria (R.L. Thomas, personal communication, 1987) for a pea gravel filter.

Tillage

Tillage of the basin surface is commonly used to restore hydraulic conductivity. Physical effects of tillage include: 1) mixing of the soil materials, and 2) an increase in total porosity of the soil. The latter function is of questionable value because, despite the increase in total porosity, large porosity is often destroyed, causing lower hydraulic conductivities near saturation (Ehlers, 1977 ; Klute, 1982). In addition, lofted materials would be expected to reconsolidate under the stress of the applied ponded water. The mixing function serves to dilute the concentration of added sediment. In some cases caked sediment and basin material mixtures might be broken to stable peds during tillage, resulting in long term infiltration enhancement. Bouwer et al. (1972) used shallow tillage with a spring–tooth harrow after "shaving" the surface. The Ainsworth facility (H. Welch, personal communication, 1987) also uses the combination of shaving, followed by shallow tillage. Welch has observed that tillage moved the sediment deeper, and eventually required greater depth of removal. A common tillage depth for a spring–tooth harrow would be about 8 cm (3 inches).

An additional problem from renovation operations can be compaction from trafficking of the basin floor. Suter and Harmeson (1960) reported a compaction problem resulting from filter replacement. Compaction could also result from trafficking during tillage. Disc harrows tend to form compacted volumes beneath the tilled zone. Moldboard plows also tend to form underlying "plow–pans". Compaction resulting from repeated surficial tillage could be partially offset using a deep chisel plow. Repeated deep chiseling, however, would result in deep mixing of the sediment, and could eventually require larger scale renovation. One additional management method related to tillage, is the practice of corrugating the basin floor. Jones et al. (1981)reported that higher infiltration rates were sustained by corrugating the basin floor. This may have resulted from greater surface area, and subsequent dilution of sediment deposition.

Flocculation and Pretreatment

River waters contain suspended solids in the form of silt and colloidal clay. When used for recharge purposes, the suspended load of river waters can significantly reduce infiltration and injection rates through surface recharge facilities and wells.

Conventional water treatment methods commonly used in municipal water treatment are cost prohibitive for artificial recharge – irrigation projects. Conventional flocculants (iron and aluminum sulfates) have disadvantages for treating river waters (Rebhun and Hauser, 1967):

1) large doses are often required;
2) the pH of the river water is reduced; and
3) relatively fine, light, breakable floc are produced.

Various investigators (Rebhun and Hauser, 1967; Brown et al., 1978; and Jones et al., 1981) used polyelectrolyte flocculants to reduce suspended solids concentrations in recharge water. Rebhun and Hauser (1967) evaluated flocculation of stable and unstable colloidal suspensions using polyelectrolytes. Stable colloidal suspensions contain colloidal size particles in suspension that remain in suspension indefinitely. Unstable colloidal suspensions contain colloidal size particles that, due to natural flocculation and sedimentation, result in reduced suspended solids content, usually over a long period of time. Cationic polyelectrolytes were found to effectively clarify water containing either stable or unstable suspensions of colloidal size material and appeared well suited to field use. Anionic polyelectrolytes were ineffective on stable suspensions, but were effective on unstable suspensions. In field use, cationic polyelectrolytes removed 90 percent of the suspended solids in playa water containing over 200 mg/l of suspended solids.

Brown et al. (1978) compared the effectiveness of the types and concentrations of flocculants in water collected from playa lakes in drainage basins with various soil types. In addition, field tests were conducted on water samples from a playa lake by injecting a mixture of cationic polyelectrolyte and ferric chloride ($FeCl_3$) through the intake hose of a water pump. Flocculation occurred in a 15.2 m (50 ft.) by 1.5 m (5 ft.) settling basin in which the water depth was maintained at about 0.9 m (3 ft.). Water entered the settling basin vertically through a series of four 51 m (2 in.) holes drilled into the top of a capped 152 mm (6 in.) plastic pipe. Turbulence created by the vertical jets of water through these orifices created floc–building conditions comparable to paddle–stirrer agitation in the laboratory. Flocculation in the settling basin reduced the suspended solids concentration of the playa water from 4,700 mg/l to 10 mg/l.

Jones et al. (1981) evaluated the use of injecting a cationic polymer into a recharge basin without using a pretreatment settling basin. As the treated water was released into the recharge basin, large flocs formed when the suspended solids content of the basin water was high. The flocs settled to the basin surface, forming a blanket that was permeable to water flow. The authors concluded that adding flocculant to recharge water with subsequent hydraulic washing and removal of clay flocs immediately following drainage may be a means of avoiding much of the time lost in artifically renovating basin surfaces.

Clarification of turbid water by flocculation is dependent upon a number of factors that include composition and concentration of both the suspended solids and flocculant. Therefore, the feasibility of flocculation as a method to reduce suspended solids concentrations should be examined during pilot–scale field investigations.

Depth Control

By increasing the ponded depth in a basin, the hydraulic gradient driving infiltration is increased. The ponded surface head, however, is only one of the head components driving flow, and the extent to which recharge will be increased is dependent upon the physical properties and homogeneity of the subbasin soil. This was discussed more thoroughly in the section on "INFILTRATION". The greatest increase in hydraulic gradient is effected for the case of a thin, surface filter cake. If a basin pond is sufficiently deep so that the surface static head is large in relation to the thickness of the filter cake and the underlying soil water suction, then an increase in ponded surface head should result in a nearly 1 to 1 proportional increase in infiltration rate. Because the surface filter cake is a common occurrence, depth control can be an effective management tool. Bouwer et al. (1972) reported a nearly 1 to 1 proportional increase in infiltration due to variation in ponded surface. Jones et al. (1981) reported that a test basin maintained at double the head of a check basin for an entire basin operation time resulted in a greater than 1 to 1 proportional increase in total flux. For a variable head test, where the basin increased to double the head of the check basin at a later time, a 56% increase in average infiltration rate over that of the check basin was observed.

Watson and Whisler (1977) demonstrated that the optimal basin ponded depth for infiltration through a surface limiting layer would be the depth that provided sufficient surface pressure to decrease the bottom boundary suction for the limiting layer below the "air entry," or "bubbling pressure" of the underlying soil. This , in effect, is to saturate the entire vadose profile. The result, in terms of the previous discussion on infiltration, is to increase the gravitational head, L, to the full depth to the water table, and to use the fully saturated porosity of the vadose materials in conducting water to the water table. At this ponded depth, for a semi–infinite L in relation to H_0, little further response to head adjustment could be expected. The practicality of reaching such an optimized ponded depth, however, would likely be limited by other constraints. Some limitations would be the cost of deep excavation and the thickness of the vadose zone in relation to potential water table mounds. Also, Baumann (1965) observed that increasing ponded depth beyond four feet caused deformation and consolidation of vadose materials, inhibiting recharge.

The occurrence of greater than proportional increases in recharge in response to greater basin ponded depth (Jones et al., 1981) would be impossible without increasing the infiltration surface, or without disturbance of the filter–cake layer. Jones et al. (1981) hypothesized that the greater than 1 to 1 proportional increase in total recharge caused by doubling the basin ponded depth was a result of deeper deposition of sediment at early times caused by the higher applied head. This, it was thought, resulted in a more gradual attenuation of infiltration rate because of delayed filter–cake formation. Other potential explanations also exist. Additional clean infiltration surface around the borders of a basin is added when the ponded depth is increased. Currents induced by additional water influx while increasing the ponded depth could also cause scour, inducing subsequent increases in recharge rates. Both of the latter potential mechanisms would be highly dependent upon basin size and geometry. Basin sidewall area increases in proportion to the square root of the increase in basin floor area. On a small basin, sidewall effects could thus be substantial, while on a sufficiently large facility they are negligible. Similarly, bottom scouring would be expected to be highest for a small basin, where a significant portion of the bottom surface area could be subjected to the concentrated increased velocity near the inlet. In a larger facility, a higher proportion of the basin floor would be more distant and less influenced by currents in the vicinity of the inlet. The possibility of greater than proportional recharge increases due to head manipulation must be viewed with caution.

Coarse Media Filtration

Optimal short term recharge would be effected by rapid filtration, where sediment is removed in dilute form throughout the filter. This, however, requires eventual removal or cleaning of the filter, whether the filter is the excavated natural basin floor, or an added filter material. The worst case for optimal short term infiltration is that of early near–surface straining with subsequent surface filter cake formation. For this case, however, the basin floor is most easily renovated. Sand filters have been found to promote early surface filter cake formation (Suter and Harmeson, 1960; Schuh, 1988). Various sand and gravel filters were investigated by Harmeson et.al. (1968). A predictive filtration model for sediment removal was developed based on the filter thickness, recharge rate, filter–media diameter, and suspended load of the influent water. Suter and Harmeson (1960) used a 15 cm (6 inch) thick, 9.5 mm (3/8 inch) pea gravel filter to protect the sand surface of a recharge basin, and reported significant increases in recharge. Suter and Harmeson (1960) observed that most of the visible sediment deposition was in the top 4 inches of the gravel. Using a mass balance comparison with influent loads, however, the filtered materials could not account for all of the load. This is not surprising, as the experiments of Harmeson et al. (1968) later would have predicted a substantial amount of solids passing a 15.2 cm (6 in.) pea gravel filter. According to R.L. Thomas (personal communication, 1987), the pea gravel filters required replacement every 3 or 4 years, and were visibly well clogged by that time. Bouwer et al. (1972) reported that a pea gravel filter was not effective for optimizing waste water renovation, and that a secondary dust layer was formed at the boundary between the gravel and the underlying soil.

An organic mat filter composed of cotton gin trash was investigated by Jones et al. (1981). The investigators hypothesized that, in addition to filtration, the mat would provide an uneven surface that would prevent or delay filter cake development. It was found that total recharge more than doubled. Moreover, the organic mat did not quickly fill and was reusable over an extended period of operation. The investigators suggested that aggregation of the filtered materials during the continuing decomposition of the mat might have sustained the macropores. No attempt to balance filtered sediment and mass influx was made, nor was the extent of sediment deposition in the soil beneath the mat investigated.

The effectiveness of organic filters in enhancing infiltration is dependent upon the state of decomposition of the filter. Johnson (1957) demonstrated that a noncomposted cotton gin trash could decrease infiltration rate compared with a nonfiltered soil during the first year of operation, due to high levels of microbial activity which resulted in solid and gaseous by–products beneath the basin. In successive cycles of operation, however, the infiltration rates increased as the organic mat decomposed.

The specific material used in an organic filter is also important. Martin (1942, 1945) demonstrated that partially decomposed organic materials exhibited the greatest electrical charge and were most effective in promoting soil aggregation. Substances that are resistant to decomposition would not likely be as effective in aggregating basin soil and added sediment. For example, wood chips or sawdust (which contain large amounts of α–cellulose that cannot be decomposed by bacterial β–oxidation) would tend to persist and would provide less of the organic byproducts necessary to promote aggregation and structure.

The use of additional filter materials has been shown to be beneficial in increasing and sustaining infiltration rates. The degree to which the filters successfully remove sediment, however, and the size range of the sediment filtered is not completely clear from current investigations. Moreover, the depth of sediment penetration is velocity dependent. Higher sustained infiltration rates would be expected to drive sufficiently small sediment particles more deeply into the soil profile. More research is needed to determine the nature of the filtrate, and to clarify the manner in which shallow filters function in the tradeoff between deeper penetration of fines and optimal short term recharge.

Grass Filters

The use of grasses tolerant to flooding as a method of enhancing infiltration has been investigated by Johnson (1957) and Bouwer et al. (1972). Both authors discussed the function of grass cover in breaking up the continuity of surface mats. In addition, fibrous roots can increase large porosity, and in some cases biodegradation of clogging organic materials can be enhanced. Chhabra and Abrol (1977) observed that rice production enhanced permeability through sodic soils by forming large root pores. Nevo and Mitchell (1967) reported that rice provided oxygen for the subbasin soil and enhanced the degradation of clogging polysaccharides. Johnson (1957) suggested that a grass cover would provide the organic substrate for the formation of a surface organic mat filter, without the necessity of buying and transporting large amounts of filtering materials. One disadvantage in the use of a grass filter is the need for maintenance. Johnson (1957) pointed out that two years were necessary for establishment of bermudagrass. Also, special care is necessary to prevent stand reduction due to submergance during the growing season. Bouwer et al (1957) reported that infiltration could be enhanced using a bermudagrass cover, but that the requirements of having to maintain a lower ponded depth to ensure grass survival negated the benefits of higher infiltration rates gained through maintaining a greater ponded depth. It would also be likely that deep macropores from fibrous grass roots would allow for deeper penetration of fine sediment into the basin sand filter.

In addition to root–induced large porosity and the role of surface roughness in breaking up filter–cake continuity, grass filters have been studied as a means of prefiltration. Wilson (1967) investigated the effectiveness of common and coastal bermudagrass in decreasing turbidity over varying filtration lengths, and concluded that effectiveness of a grass filter in decreasing turbidity is dependent upon vegetal retardance of water velocity. The height and density of the vegetative cover was determined to be the key variable affecting filtration effectiveness, as represented by the roughness coefficient of the Manning equation for open channel flow. Recently harvested grass filters would not likely be as effective as a full stand in decreasing turbidity.

For northern application, bermudagrass (Cynodon dactylon) would not be sufficiently winter hardy. A possible grass filter for use in North Dakota would be reed canarygrass (Phalaris arundinacea). According to Dr. Dwain Meyer (personal communication, 1987), the root system includes deep 1.8 to 2.6 m (4 to 6 ft.) fibrous root penetration, and a dense rhizome system near the surface (to approximately 15.2 cm [6 in.]). Reed canarygrass can withstand inundation periods of as long as 180 days, and can maintain sufficient oxygen to insure survival with minimal amounts of leaf above the surface of the water. It commonly grows to heights of 1.2 to 2.1 cm (4 to 7 ft.) (Smith, 1962), so maintaining leaf exposure above the water surface should be possible under most circumstances. Survival would likely depend upon the period of operation and basin management procedures. The spring period (April and May) would likely be little effected by high water, due to dormancy of the grass. On the other hand, maintenance of high water in the fall might be detrimental, since the grass would be forced to enter the winter period immediately after a period of stress. The use of reed canarygrass may prove to be beneficial in enhancing basin recharge capabilities in northern latitudes under some operation schedules.

EXPERIMENTAL BASIN FACILITIES

A short–term feasibility study cannot investigate all design criteria necessary for the construction and operation of an artificial recharge facility. Time and resource limitations force a partial reliance on existing literature and operational experience available from previous work at other locations. The dependence of recharge on local soil properties, water chemistry, and the quantity, distribution, and nature of sediment load of the applied water, however, requires that some first hand investigation be undertaken to assess the nature of limiting factors peculiar to the area, and to properly evaluate the applicability of prevailing practices and experience to the proposed project area.

Prior to the construction of the test basins the analytical method of Hantush (1967) was used to predict maximum rise of water–table mounds for selected basin shapes and sizes in the test area. The unconsolidated sediments in the test area are well stratified, resulting in a nonhomogeneous, anisotropic hydraulic conductivity profile. Vadose zone nonhomogeneity is conducive to the development of perched ground–water mounds. Therefore, the analytical method of Hantush (1967) was not practical for predicting water–table mound geometry. It was considered that perched ground–water mounds forming within the stratified vadose zone would likely be a limiting condition for infiltration. Also, the analytical method of Hantush (1967) does not account for the dynamic nature of surface infiltration during turbid water application. Because of the inability to predict temporal changes in infiltration rates in the Oakes aquifer study area, it was decided that field investigations should be undertaken to examine the nature and extent of clogging due to application of turbid water from the James River.

Preliminary Infiltration test

Before importing turbid water from the James river, an initial infiltration test was performed using nonturbid ground water pumped from the Oakes aquifer. A 1.2 m (4 ft.)

deep, rectangular test basin, 3.7 m (12 ft.) by 7 m (23 ft.) was constructed in the SE1/4 of Section 29, Township 131 North, Range 59 West. The test basin was centered at drill site P–1 (Fig. 1).

An infiltration test was conducted in the test basin from June 26 to July 3, 1986. The water supply consisted of three, 5.08 cm diameter wells which were jetted into the Oakes aquifer along the base of the pilot drain approximately 23 m (75 ft.) southeast of the test basin. A relatively constant head of 0.67 m (2.2 ft.) was maintained in the basin from the beginning of the test to 0930 hours on June 30. After 0930 hours on June 30 until the end of the test, a relatively constant head of 0.30 m (1.0 ft.) was maintained in the basin.

Discharge into the basin was measured periodically using a stop watch and three 208 liter (55 gallon) drums. The discharge rate varied from 140 cm/h (157 gpm, 110 ft./d) at initiation to 34 cm/h (38 gpm, 27 ft/d) at the end of the test. Infiltration rate steadily decreased throughout the test.

Due to limitations in the size of the work area, three of the basin sidewalls were kept vertical. After a 0.61 m (2 ft.) constant head was attained in the basin, topsoil began to slough into the pit from the vertical sidewalls. The clay and silt fractions in the topsoil settled along the basin bottom and probably decreased infiltration rates.

Near the beginning of the test, a constant discharge rate of 101 cm/h (113 gpm, 79 ft./d) was maintained for about 16 hours to establish a 0.67 m (2.2 ft.) constant head in the basin. Based on a basin bottom area of 25.6 m^2 (276 square feet), an average infiltration rate about 102 cm/h (80 ft /d) was maintained.

The soil beneath the test basin consisted of two fine–grained sand layers between coarser–grained sand layers (Fig. 11). Piezometers were installed near the top of each of the two fine–grained sand layers. The piezometers were screened from 0.24 to 0.55 m (0.8 to 1.8 ft.) (OW–PP–3) and 1.04 to 1.34 m (3.4 to 4.4 ft.) (OW–PP–2) below the bottom of the basin. In addition, piezometer OW–PP–1 was completed in the top of the saturated zone and was screened from 4.8 to 6.3 m (15.7 to 20.7 ft.) below the bottom of the basin.

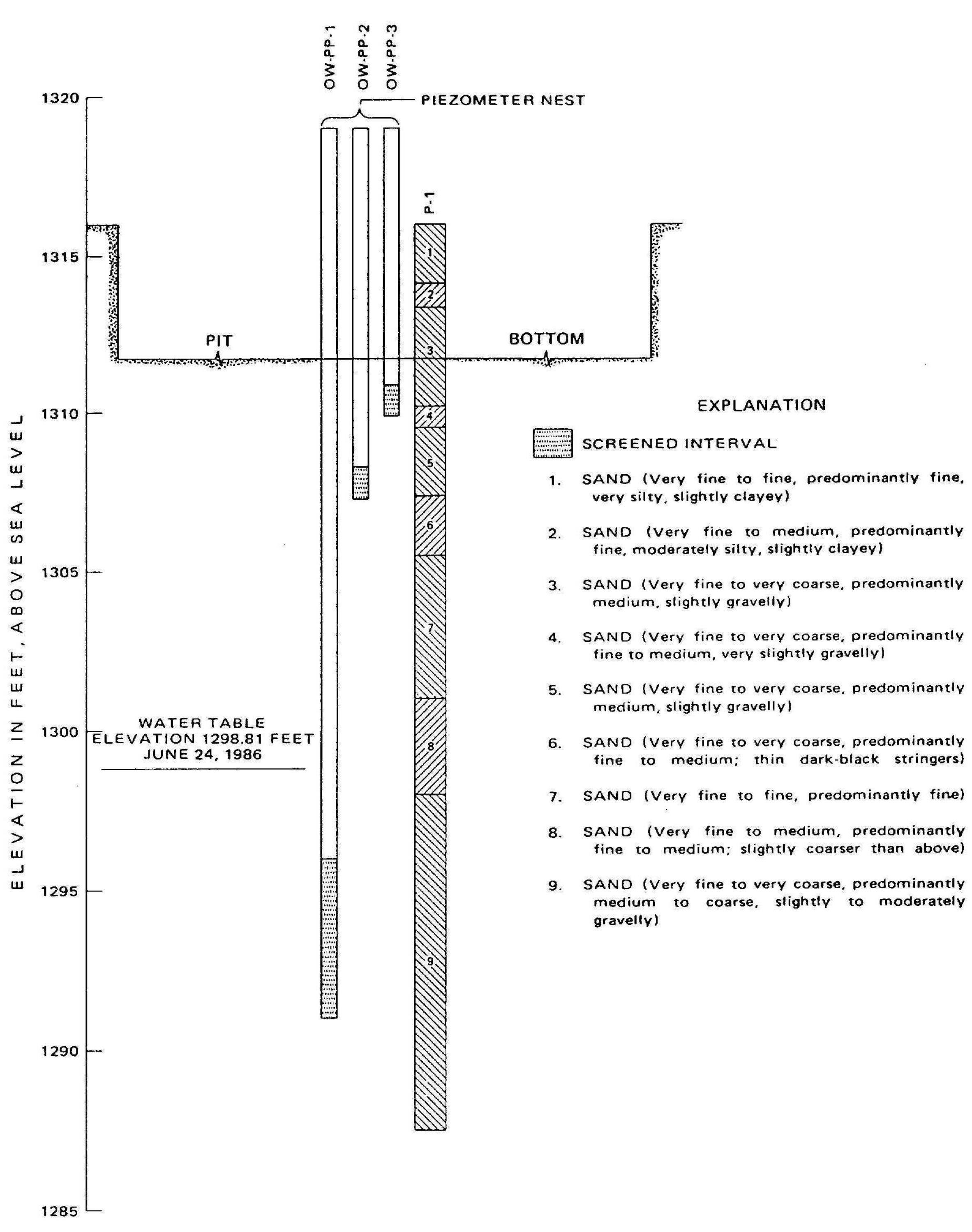


Fig. 11. Vertical profile at center of preliminary test basin showing piezometer depth placement.

Results of the infiltration test indicated development of perched ground–water mounds above the two fine–grained sand layers. Prior to the test, both shallow piezometers were dry. After two hours of infiltration, water levels in both of these piezometers were approximately 0.61 m (2 ft.) above the bottom of the screen. The highest water level measured in OW–PP–3 was about 0.09 m (0.3 ft.) above the bottom of the basin. The highest water level measured in OW–PP–2 was about 0.61 m (2 ft.) below the bottom of the basin. As surface clogging reduced infiltration, the height of both of the perched mounds decreased. After about 24 hours of infiltration, the height of the uppermost perched ground–water mound dropped below the bottom of the basin.

Because of sloughing of the basin walls, reasons for declining infiltration are not certain. Variation of head in the basin near the end of the experiment resulted in nearly 1 to 1 proportional increase in flux. The degree of response of infiltration rate to basin depth variation indicates that the gravitational component of the hydraulic gradient was small and that flux limitations were likely imposed by a thin clay and silt layer that formed near the surface. The clay and silt barrier may have been deposited on the basin floor by sidewall sloughing.

During the preliminary infiltration experiment a shallow perched mound intersected the basin surface. Because of geometric and areal effects on mound formation, it was considered likely that perched mounds or groundwater mounds might provide the major limiting constraint for a significant part of the recharge period on a larger facility. It was expected that different oxidation–reduction environments would prevail during mounded conditions, and unsaturated conditions (controlled by surface infiltration rates). For this reason, two test facilities were constructed. Based on preliminary approximations of mound geometry, simulations using the large facility were selected to evaluate hydraulic effects of turbid water application under conditions where early mound formation limits infiltration. The smaller rectangular facility was constructed near and parallel to the pilot drain, and was expected to evaluate hydraulic effects of turbid water application under conditions where surface clogging limits flow at very early times.

METHODS AND PROCEDURES

It was anticipated that infiltration rate in the test area would be limited by: 1) the intersection of a ground–water mound with the bottom of the recharge basin, and 2) the formation of impeding layers in the vadose zone due to sediment deposition, air entrapment, or biological activity. In order to assess these factors, in–situ and laboratory assessments of hydraulic and physical changes in the basin were undertaken.

Monitoring In–Situ Basin Impedance Development

During infiltration with turbid water soils clog in a layered manner. Commonly a surface–filter cake, or crust, forms with varying amounts of sediment accumulating at different depths. To evaluate and quantify the depth and extent of clogging, an in–situ method for monitoring impedance development within the soil profile was devised. Details of the method were described elsewhere (Schuh, 1988) and will be presented here only in abbreviated form.

Theory

Steady–state infiltration through a crust–covered soil has been described by Hillel and Gardner (1969), and has been applied to the monitoring of impedance development in a surface layer by Bouma (1975). For this experiment, the model of quasi–steady–state infiltration through a crust–covered multi–layered soil is used to describe the process of impedance development in basin floor materials. It is assumed that for any given time interval, quasi–steady–state conditions prevail, and that flux must, therefore, be equal throughout the measured profile. Flow can then be described as

$$i = K(S)_1 \left[\frac{(H_o + S_1) + 1}{Z_1} \right]$$

$$= K(S)_2 \left[\frac{(S_2 - S_1) + 1}{Z_2 - Z_1} \right]$$

$$\vdots$$

$$= K(S)_n \left[\frac{(S_n - S_{n-1}) + 1}{(Z_n - Z_{n-1})} \right] \quad (3)$$

where i is flux, $K(S)_i$ is the unsaturated hydraulic conductivity for the ith layer, S_i is the soil water suction for depth Z_i, and H_o is the height of the ponded surface above the basin floor.

If the nth depth is sufficient so that hydraulic properties of that layer have not been altered by application of turbid water, then for any time, t, flux can be calculated for the entire profile using the known $K(S)_n$ function for the bottom layer, and measured hydraulic potential data for that layer. Calculated flux can be used, in turn, to calculate the hydraulic conductivity of the overlying layer for that time from

$$K(S)_i = i \,/\, [(S_i - S_{i-1}) \,/\, (Z_i - Z_{i-1}) + 1] \quad (4)$$

Impedance is defined as

$$R(S)_i = (Z_i - Z_{i-1}) \,/\, K(S)_i \quad (5)$$

For future reference, the bottom (nth) layer used to monitor flux will be labeled the "control layer". The assumption that hydraulic properties of the control layer are unaltered is critical to the accuracy of this method. If violated, inaccurate flux calculations will result in false impedance estimates for overlying layers. This assumption is verifiable using data gathered in implementing the procedure.

Impedance ratios

Impedance values measured using Eq. 5 may not be due to physical alteration of the hydraulic properties caused by clogging within the layer itself. In many cases desaturation may be induced by altering the properties of overlying layers. In such cases, removal of the affected layers would result in complete recovery of the flow capabilities of the system. In order to discern impedance changes due to clogging alone, calculated impedance, $R(S)_t$, for a given layer at time, t, is divided by expected impedance for the same layer without clogging $[R(S)_0]$, for the suction S measured in the soil layer at time, t. Thus, impedance ratios, hereafter labeled I_R, are determined from

$$I_R = R(S)_t / R(S)_0 = K(S)_0 / K(S)_t \qquad (6)$$

where $K(S)_t$ is the hydraulic conductivity calculated from Eq. 4, and $K(S)_0$ is the hydraulic conductivity measured before flooding the basin. In this manner, impedance is presented for each time as a multiple of nonclogged impedance at the same suction. This results in evaluation of clogging effects only. An unaltered material would maintain an I_R value of 1, while ratio values rise as clogging occurs. Depth and extent of clogging were evaluated using I_R values, and hydraulic gradient information provided by these measurements.

The validity of this model depends on nonalteration of the bottom control layer. The condition of this layer is monitored by observing I_R for the overlying layer, since it is considered unlikely that impedance would increase below an unaltered layer. In addition, a constant (or, in some cases, decreasing) hydraulic gradient in the control layer provides evidence that clogging is not occurring in that layer. If these criteria are not met, then the calculated I_R for overlying layers must be considered unreliable. Steady–state assumptions require that the rate of change in the impedance of overlying layers is slow in relation to the time required for the bottom control layer to equilibrate. Because maximum sediment deposition occurs at early times when flow rates are high and equilibrium times minimal, and because changes in flux are small at later times where slower equilibration times exist, steady–state conditions should be closely approximated during basin operation.

K(S) Measurement

In–situ K(S) was determined for each layer below the basin floor using a modified transient–flow method (Ahuja et al., 1980), which requires only an initial steady–state infiltration measurement and tensiometric readings for a draining soil profile, protected from evaporation and further boundary influx of water. The method was tested by Schuh et al. (1985) on layered, in–situ soil profiles ranging in texture from gravelly sand to silty–clay loam, and to depths as great as 138 cm. In all tests results corresponded well with determinations made using transient flow methods and accompanying neutron moisture data. More recent tests by Ahuja et al. (1988) have further demonstrated the accuracy of this method.

Monitoring procedures

Each measurement installation consisted of a double ring infiltrometer with a 1.2 m outer ring, and a 0.6 m (2 ft.) inner ring. Tensiometers were placed at 8, 23, 38, and 53 cm (3, 9, 15, and 21 in.) depths within the inner ring (Fig. 12). Instruments were installed before initiation of each basin experiment, and in–situ K(S) functions were determined using groundwater from the Oakes aquifer. After determining in–situ K(S) the outer ring was removed. The inner ring was left in place to protect against local scouring, and rubber stoppers in the wall of the infiltrometer were removed to allow for rapid passage of James River water into the infiltrometer without an erosive spill over the top of the infiltrometer. Tensiometers were left in place so that the monitoring disposition was identical to that of preliminary measurement.

Methods of equipment construction and placement, and examples of the application of the Ahuja et al. (1980) K(S) method for interpreting basin impedance development, were described in greater detail by Schuh (1988). Specific placement and management of tensiometer installations varied with experimental objectives and conditions and are discussed in sections describing basin operational histories.

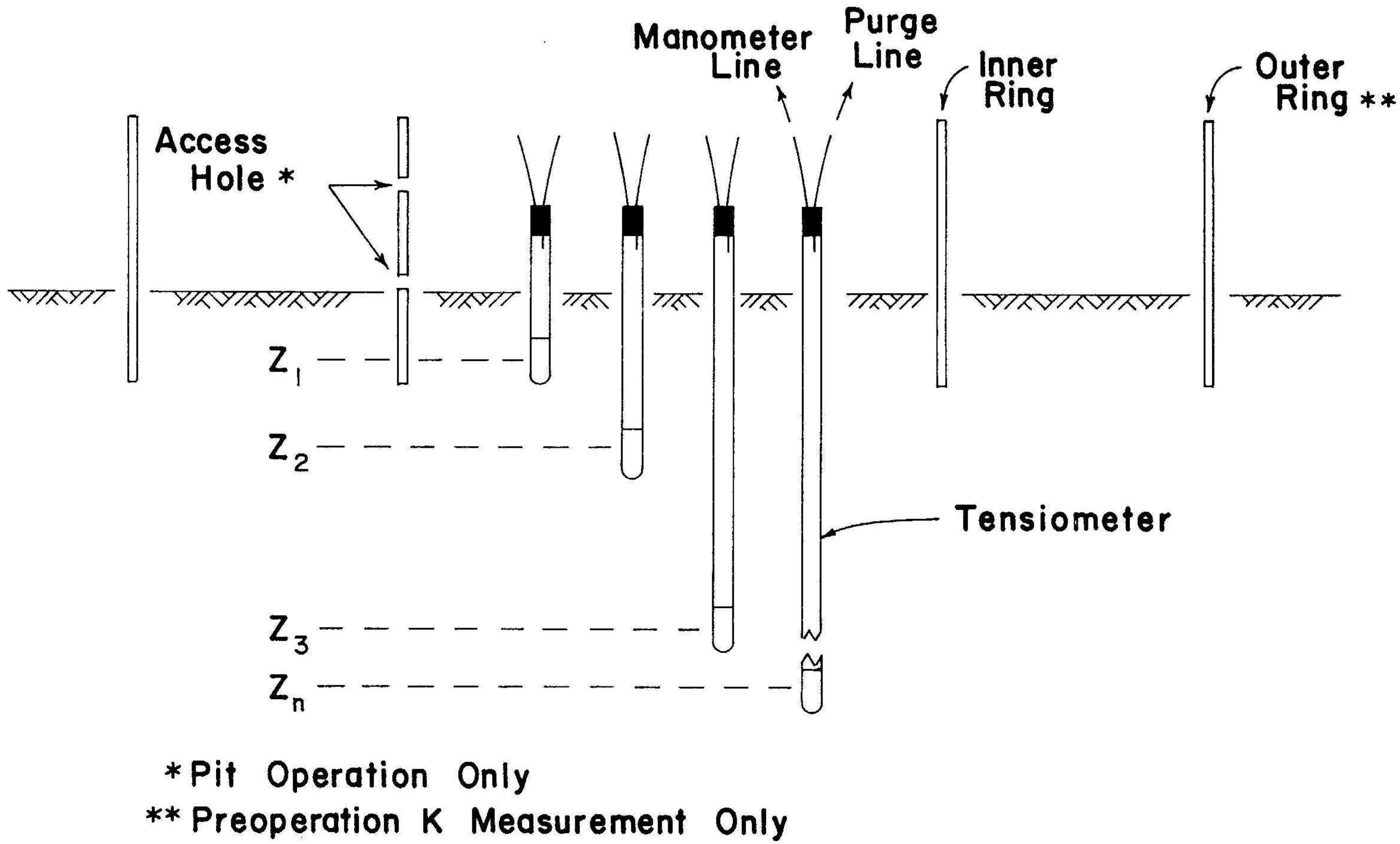


Fig. 12. Apparatus for determining in-situ K(S) and for monitoring local flux and layered impedance development in the basin subsoil during basin operation.

Piezometers

The extent of water table and perched ground–water mounding was investigated using piezometer nests placed at the center of the basins, and at varying distances from the perimeter of the basin. At each site, one piezometer was screened near the top of water table. At the basin center one piezometer was screened immediately above a very fine to fine silty sand layer considered most likely to cause perched ground–water mounds. Water levels in the two piezometers at the basin center were monitored using the wetted–chalked, steel–tape method. Water levels in the piezometers beyond the perimeter of the basin were monitored using a Stevens Type F recorder coupled with a Keck water level sensing device. Well construction and placement are described in the section detailing basin construction design and procedures.

Basin Water Level

The water level in each basin was monitored using a Stevens Type F float recorder. The float recorder and manometer boards used for monitoring in–situ flux and impedance development were placed near the center of the basin on an access dock. Original land surface levels were marked on the observation wells at the center of the basin. Mercury manometer scales were set to zero for a submerged tensiometer cup with water level placed at the original land–surface marker. Basin floors at tensiometer nests and at float–level recorders were then calibrated with land surface using the same submerged tensiometer cup by summing the depth of water in the cup, and the equivalent water depth for the mercury readings recorded on the manometer boards. This calibration allowed for precise calculation of basin ponded depth at each tensiometric position.

Soil Samples and Laboratory Procedures

In addition to in–situ measurement of the depth and extent of hydraulic changes in soil layers beneath the basin floor, changes in selected soil properties were monitored using soil samples taken from each basin. After construction or renovation of the basin floor prior to each experimental operation, sample areas were flagged and protected from trampling and compaction. Samples were taken before and after each experiment using a 7.62 cm (3 inch) Giddings probe tube fitted with an anvil, and driven to a depth of 53 cm (23 inches) using a specially made post driver. Each soil sample was tested for particle–size distribution using the pipette method (USBR, 1982: chap.4, par. 514.4.2), and for organic carbon using the modified Walkley–Black wet combustion method (USBR, 1982: chap. 8, par. 514.8.7). Sampling depth increments varied with experimental objectives and conditions, and are detailed in sections describing basic operational histories.

Desorption–moisture–retention data were measured before and after selected test operations, as detailed in the sections describing individual basin experiment histories. Measurements were made using "undisturbed" samples taken in 3 cm (1.2 in.–length) x 5.5 cm (2.2 in.–diameter) brass rings at depths of 0 to 8 (0 to 3 inch), 8 to 23 (3 to 9 inch),23 to 38 (9 to 15 inch) and 38 to 53 (15 to 21 inch) cm depths using a sampler described by Schuh (1988). For each depth interval, two samples were taken and the results averaged. Laboratory determinations were made using pressure extractors (Klute, 1986), with each sample fitted on an individual 3–cm diameter, 1–bar ceramic plate. Sample–plate assemblies were wetted with distilled water in stepped increments over a 2 day period before final placement on a larger 1–bar ceramic plate. Pore continuity was maintained by two moist Watmann No. 2 paper filters between the two ceramic plates. Pressure head steps of 10, 20, 30, 40, 60, 80, 100, and 120 cm (range 4 to 47 in.) were successively applied, and water loss from each sample was determined gravimetrically for each step. Volumetric water content was calculated by multiplying gravimetric water content by the bulk density of the sample determined from oven–dried (110 ^{o}C) weights after completion of the final pressure step.

Additional bulk density samples were taken for selected test operations (reported separately) using 6 cm (2.4 in.–length) x 5.5 cm (2.2 in.–diameter) ring samples taken at 0 to 8,8 to 23, 23 to 38, and 38 to 53 cm depths using the ring sampler described by Schuh (1988). Bulk density for ring samples was determined as described by Blake and Hartge (1986).

Water Samples and Laboratory Procedures

Water samples were taken periodically through a tap near the outlet of the discharge pipe to determine particle–size distribution of the sediment load delivered to the basin from the James River. Water was strained through a 0.45 micron filter, and the filtrate from 8 clogged filters was washed with distilled water into a collection bottle. The water and filtrate were then diluted directly to the volume required for pipette analysis (USBR,1982: chap. 4, par. 514.4.2). Water samples for determination of suspended solids were taken from the same tap at regular intervals during each experiment. Laboratory measurements were made within 15 days according to the method of Guy (1969).

Total Sediment Deposit

The specific sediment deposit, s_p (mg/cm^2), from initiation of a basin experiment to any given time, t, can be determined from

$$s_p = \int_0^t i \times L \, dt \; / \; A \tag{7}$$

where i is instantaneous flux (l/h) (or discharge for steady state), L is the sediment load (mg/l) of the discharge water, and A is the basin floor area (cm^2). The flux term was available for the overall basin (from discharge measurements) and for specific sites where it was measured in–situ. Flux followed an approximate decreasing log–log relationship with time. However, the random scatter of the data, and complex curvatures apparently caused by gas entrapment made a simple functional solution to Eq. 7 impractical. Dense data acquisition and lack of well–defined curvature within small localized groups of points indicated that the midpoint numerical approximation for integration would be adequate within the accuracy of the data. Linear interpolation was used to match less frequent suspended solids data to instantaneous flux.

Other Work

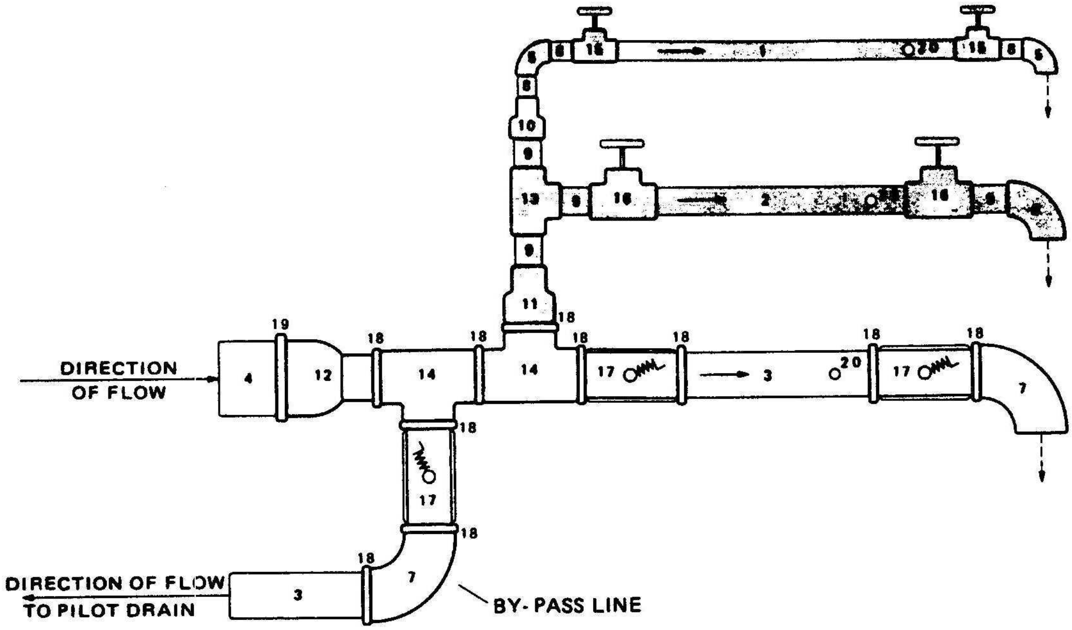
Water chemistry and biochemistry was monitored: 1) in the basin, 2) throughout the vadose zone, and 3) at the water table during each operational period. These determinations were made by other investigators and will be presented in a separate report to be published by the U.S. Geological Survey.

BASIN CONSTRUCTION AND DESIGN

Large Recharge Test Basin

The large recharge test basin was located in the SE 1/4 of Section 29, Township 131 North, Range 59 West, and was centered within the rectangular area defined by test drilling sites V1–2, V2–2, V3–2, and V2–3 (Fig. 1). Basin dimensions were 15 x 15 m (50 x 50 ft.) with a depth of 1.2 m (4 ft.). The sidewalls were constructed with a 2:1 slope and were covered with heavy polyethylene to prevent sloughing and erosion and to limit infiltration to the 232 m^2 (2500 $ft.^2$) basin floor.

Water was pumped to the basin from the James River through aluminum irrigation pipe placed adjacent to the pilot drain south of the basin (Fig. 1). To avoid a large pressure drop across the upstream gate valve before entry into the basin, a bypass valve was used to divert excess water to the pilot drain (Fig. 13). A wood frame stilling basin was installed along the southwest margin of the test basin to reduce scouring during test initiation, and turbulence during the test . Discharge to the basin was controlled manually using a gate valve, and was continuously monitored at early times using a Barton flowmeter coupled to a Cox pitot tube. At flow rates below the effective range of the flowmeter, discharge was measured volumetrically using a stop watch and a calibrated 55 gallon, or 5 gallon container. A detailed description of the basin design and plumbing was



MATERIAL LIST

1. 3-INCH STEEL PIPE
2. 5-INCH STEEL PIPE
3. 8-INCH ALUMINUM PIPE
4. 12-INCH ALUMINUM PIPE
5. 3-INCH 90° STEEL ELBOW
6. 5-INCH 90° STEEL ELBOW
7. 8-INCH 90° ALUMINUM ELBOW
8. 3-INCH STEEL NIPPLE
9. 5-INCH STEEL NIPPLE
10. 5X3-INCH STEEL REDUCER
11. 8x5-INCH STEEL REDUCER
12. 12x8-INCH ALUMINUM REDUCER
13. 5-INCH STEEL TEE
14. 8-INCH ALUMINUM RING LOCK TEE
15. 3-INCH STEEL GATE VALVE
16. 5-INCH STEEL GATE VALVE
17. 8-INCH ALUMINUM BUTTERFLY VALVE
18. 8-INCH RING LOCK
19. 12-INCH RING LOCK
20. PORT FOR PITOT TUBE

——→ DIRECTION OF FLOW

- - -→ TO STILLING BASIN

Fig. 13. Plumbing schematic for discharge measurements into the large test basin.

presented in the project proposal (Shaver et al., 1986).

Basin Lithology

Descriptions of the test holes in the area of construction of the large basin (Fig. 1) were described under the section titled **Geology**. Drill–hole logs are presented as supplemental data (SUPPLEMENTS 1 TO 29). A vertical soil profile for the center of the large basin is illustrated on Fig. 14.

Piezometers and Sampling Wells

Piezometers were installed at five locations, extending linearly from the center of the basin southward in the direction of the pilot drain. Each piezometer was constructed using 5.08 cm (2–inch) diameter polyvinyl–chloride (pvc) casing and 5.08 cm (2–inch) diameter pvc screen. The slot size of the screen was 0.254 cm (0.10 in.) and a check valve was attached to the bottom of each screen. After the casing, screen, and check valve assembly was inserted into the drill hole, silica sand was placed around the screened interval using a tremie pipe. Bentonite pellets were placed on top of the silica sand pack, and a cement slurry was poured into the well annulus to land surface. Detailed specifications for the large basin piezometers are presented on Table 2.

Small Recharge Test Basin

Location and Geometry

The small recharge test basin was located in the SE1/4 of Section 29, Township 131 North, Range 59 West and was centered at test drilling site N–6 (Fig. 1). The floor of the test basin was 6 m (20 ft.) long and 3 m (10 ft.) wide, and the depth was 1.2 m (4 ft.). Side slopes were constructed with a 2 to 1 slope to avoid sloughing, and were covered with heavy polyethylene to prevent erosion, and to limit infiltration to the floor of the basin.

Table 2. Piezometer placement and screened intervals for the large basin

Piezometer No.	Distance from Center of Basin, in Meters	Screened Interval, Below Land Surface, in Meters	Depth to Water Table Below Land Surface, in Meters	Time and Date Water Level Measured
TPL-1	0.6 m (2 ft.)N.	6.3-7.0 m (2.08-23 ft.)	4.73 m (15.60 ft.)	1050 hrs., 9/17/86
TPL-1A	0.6 m (2 ft.)S.	2.0-2.7 m (6.7-8.8 ft.)	Dry	
TPL-2	10.7 m (35 ft.)S.	6.3-7.0 m (20.8-23 ft.)	4.67 m (15.40 ft.)	1025 hrs., 9/17/86
TPL-2A	10.7 m(35 ft.)S.	1.2-1.9 m (4.0-6.2 ft.)	Dry	
TPL-2B	10.7 m(35 ft.)S.	4.8-5.5 m (20.8-23 ft.)	4.61 m (15.21 ft.)	1006 hrs., 9/17/86
TPL-3	15.2 m (50 ft.)S.	1.5-2.2 m (5.0-7.2 ft.)	Dry	
TPL-4	19.8 m (65 ft.)S.	6.3-7.0 m (20.8-23 ft.)	5.00 m(16.5 ft.)	0950 hrs., 9/17/86
TPL-4A	19.8 m (65 ft.)S.	1.4-2.0 m (4.5-6.7 ft.)	Dry	
TPL-5	35 m (115 ft.)S.	6.3-7.0 m (20.8-23 ft.)	4.93 m(16.27 ft.)	0940 hrs., 9/17/86

Table 3. Piezometer placement and screened intervals for the small basin

Piezometer No.	Distance from Center of Basin, in Meters	Screened Interval, Below Land Surface, in Meters	Depth to Water Table Below Land Surface, in Meters	Time and Date Water Level Measured
TPS-1	Center	7.8-8.5 m(25.8-28.0 ft.)	6.39 m (21.10 ft.)	1827 hrs. 9/22/87
TPS-1A	Center	1.9-2.6 m (6.3-8.4 ft.)	Dry	Dry
TPS-2*	5.5 m (18 ft.)	6.3-7.0 m (20.8-23.0 ft.)	NM**	NM**
TPS-2A	5.5 m (18 ft.)	7.8-8.5 m (25.8-28.0 ft.)	6.35 m (20.97 ft.)	1641 hrs. 9/22/87
TPS-12B	5.5 m (18 ft.)	2.2-2.9 m (7.3-9.5 ft.)	Dry	Dry
TPS-3	8.5 m (28 ft.)	7.8-8.5 m (25.8-28.0 ft.)	6.28 m (20.74 ft.)	1633 hrs. 9/22/87

* Sampling well
** Not measured

which was connected to a main 30 cm (12 inch) pipeline used to carry water from the James River to the large basin at a point approximately 122 m (400 ft.) west of the small basin. To avoid a large pressure drop across the valve before entry into the basin, a bypass valve was used to divert excess water to the pilot drain. Water entered the test basin through two 1.5 m (5 ft.) lengths of 5 cm (2 inch) diameter, 25 slot plastic well screen which was wrapped with a roll of wire mesh (window screen) to prevent scouring of the basin bottom. Each well screen was positioned on top of burlap to prevent scouring of the basin floor. Discharge to the basin was controlled manually using a gate valve, and was monitored at early times using an in–line flowmeter. At flow rates below the effective range of the flowmeter, discharge was measured volumetrically using a stopwatch and a calibrated 18.9 l (5 gal. container). A detailed description of the basin design and plumbing was presented in the project proposal (Shaver et al. ,1986).

Basin Lithology

Cross–sectional descriptions of the test holes in the area of construction of the small basin were described under the section titled **Geology**. Drill–hole logs are presented as supplemental data (SUPPLEMENTS 1 TO 29). A vertical profile for the center of the small basin is illustrated on Fig. 15.

Piezometers and Sampling Wells

Piezometers were placed at three locations, extending linearly from the center of the basin westward and parallel to the pilot drain. Methods and materials were identical to those used for the large basin piezometers. Detailed specifications for the large basin piezometers are presented on Table 3.

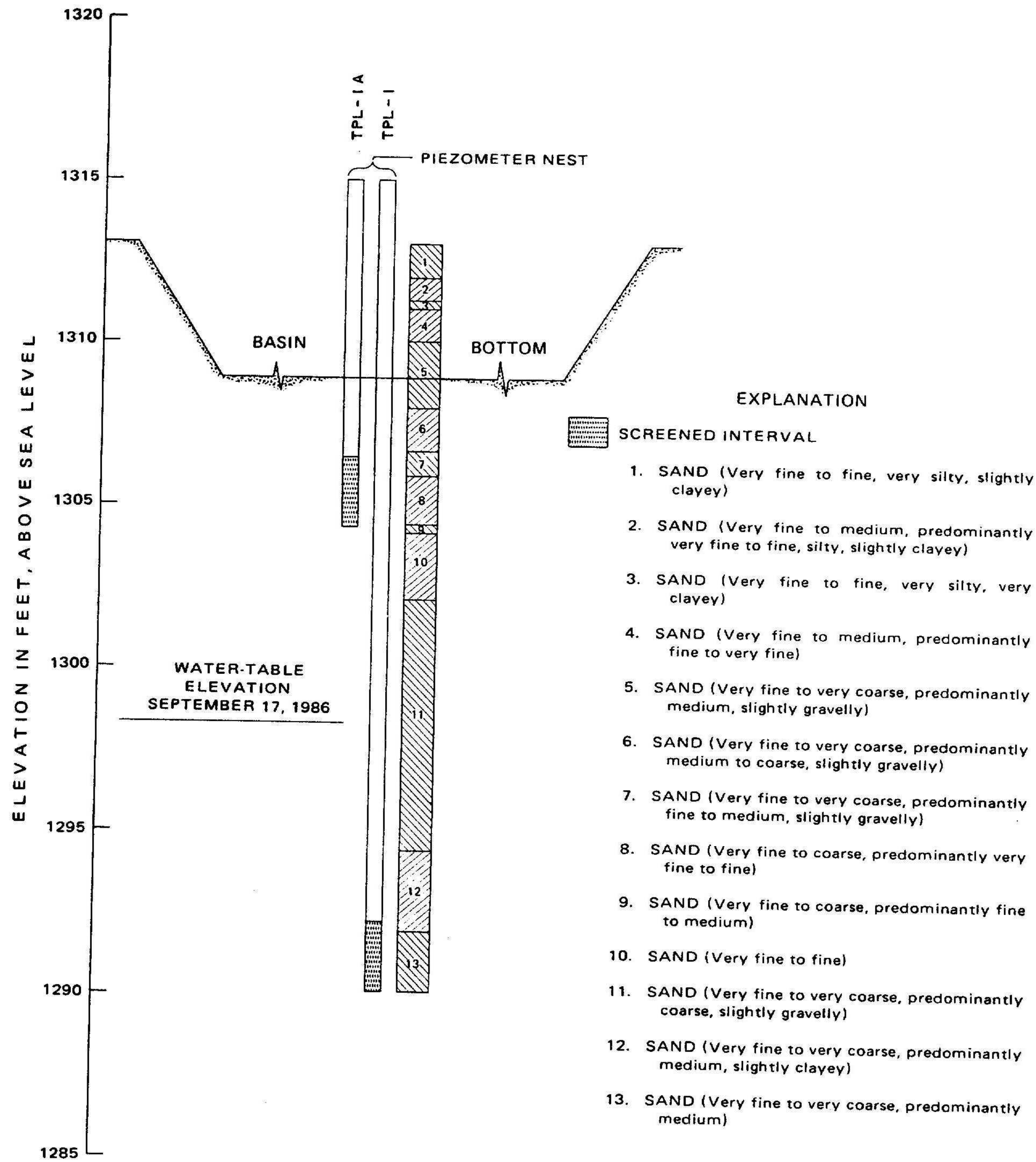


Fig. 14. Vertical profile at the center of the large test basin, showing piezometer depth placement.

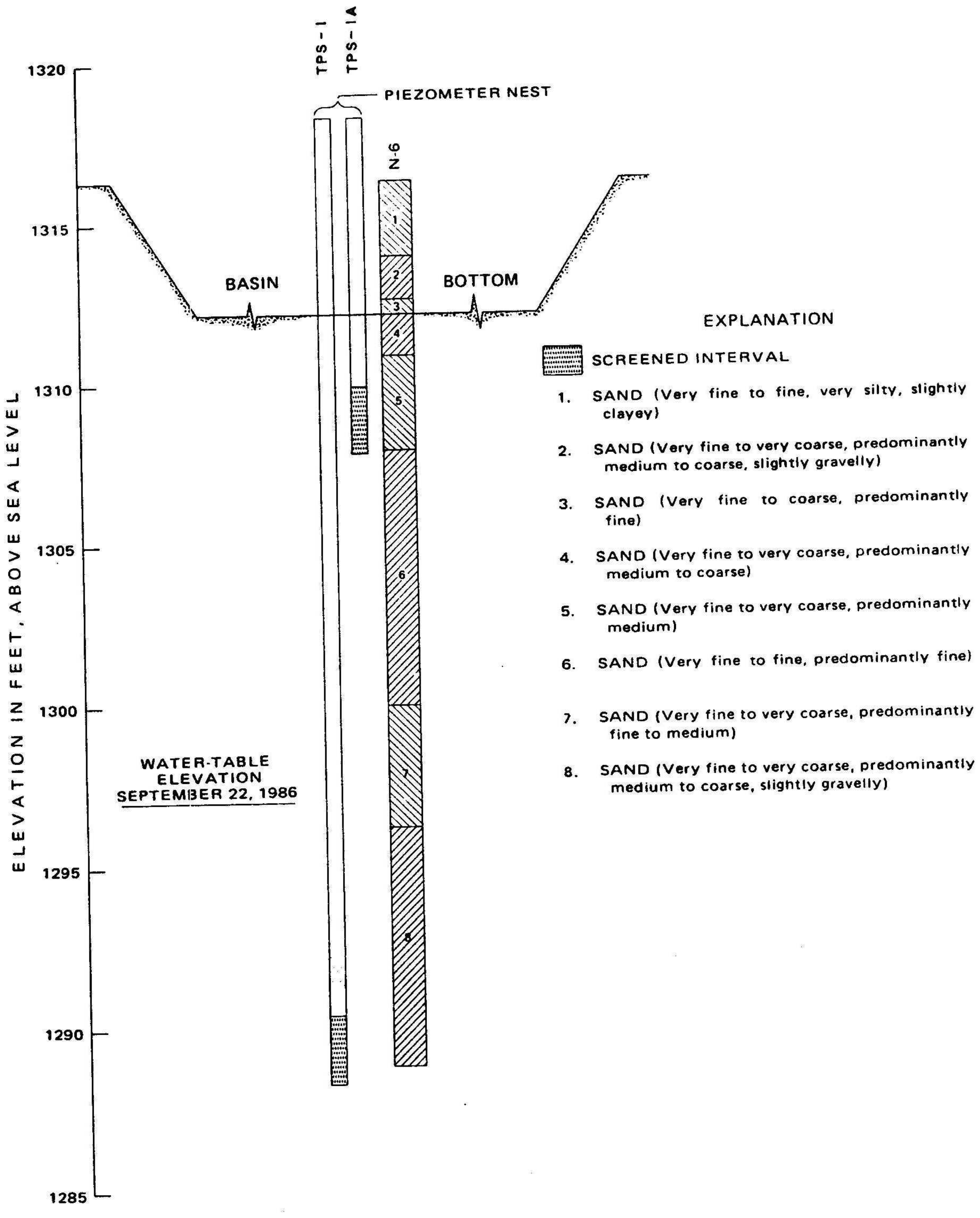


Fig. 15. Vertical profile at the center of the small test basin, showing piezometer depth placement.

BASIN RECHARGE INVESTIGATIONS

The principal objectives in operating the two test facilities were to assess the nature and extent of attenuation of infiltration caused by application of turbid water from the James River. Limiting factors, such as ground–water mound formation and the development of impeding layers were investigated. Selected management practices for optimizing infiltration were tested, including natural desiccation, variable basin depth, and an organic–mat filter. Of particular interest was the depth and extent of hydraulic impedance development from clogging. This was considered to be of importance because of the potential expense of removal and replacement of clogged soil from the basin surface, should renovation be required.

Basin recharge investigations were conducted over three operational periods: 1). in September and October, 1986 , both large and small facilities were operated to determine infiltration capabilities under conditions of a fall sediment load; 2). in May and June, 1987, the large basin was operated in three phases. The first phase was used to investigate infiltration rates under conditions of a spring sediment load. The second phase, following a period of drainage and desiccation, was used to determine the extent of recovery affected by natural dessication of the basin floor. The third phase investigated the effects of basin depth on infiltration rate; and 3). in August, September, and October, 1987, the large basin was again flooded in two phases – before and after desiccation – with an organic–mat filter of composted sunflower–seed hulls.

OPERATION 1: SEPTEMBER 17 TO OCTOBER 21, 1986

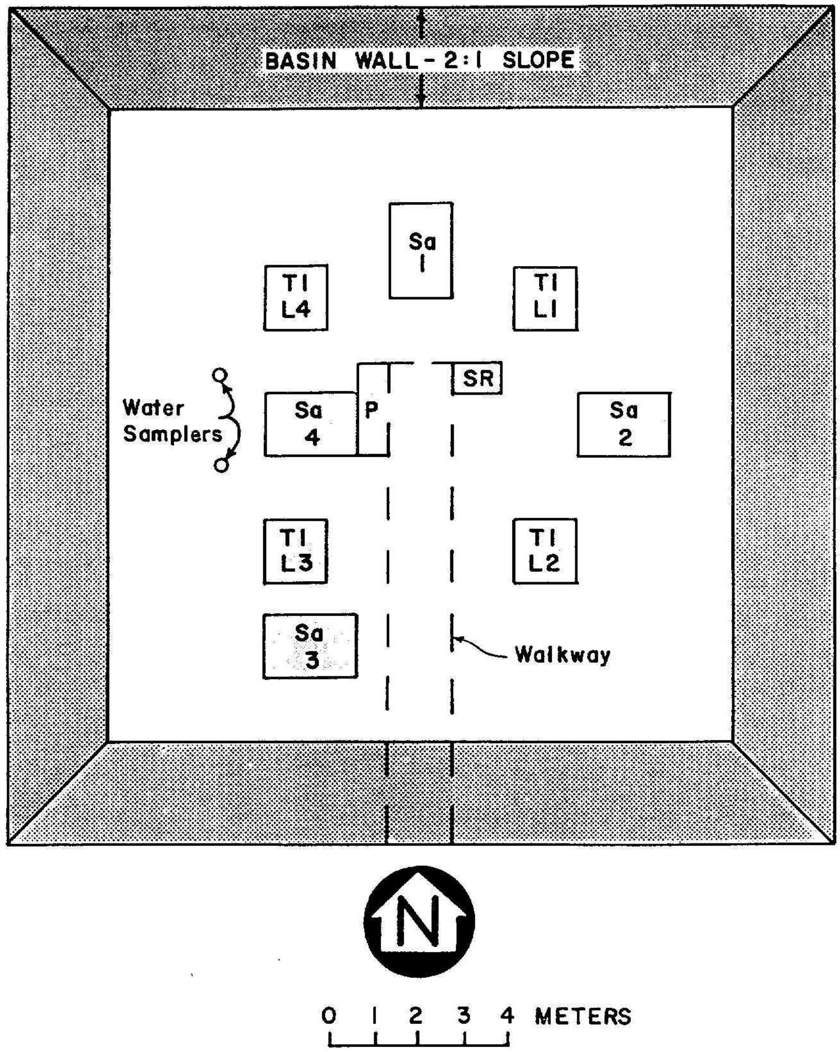
The objectives of the first basin operation were to determine 1) the quantity of recharge , and 2) the depth, extent, and hydraulic effects of clogging of the basin floor caused by the addition of turbid water from the James River under conditions of fall sediment load. The specific layout of instruments for monitoring recharge and sampling areas for the large basin are shown on Fig. 16. The layout for the small basin is shown on Fig. 17.

Soil and Water Samples

Soil samples for determination of particle size distribution and organic carbon were collected from four sample areas within the large basin, and from two sample areas within the small basin. One sample was collected from each sampling area in depth increments described on Table 4. In addition, undisturbed ring samples for determination of moisture retention curves and bulk density were taken from each sample area. Samples were taken before commencement of basin operation, and immediately following its completion. Water samples for determination of suspended solids and sediment particle size distribution were collected as described on Table 5.

Hydraulic Parameters

Infiltrometer and tensiometer installations were constructed at four positions within the large basin (Fig. 16) and at two positions within the small basin (Fig. 17). Prior to commencement of the experiment, unsaturated hydraulic conductivity [K(S)] functions were determined for 0 to 8 cm (0 to 3 inch), 8 to 23 cm (3 to 9 inch), 23 to 38 cm (9 to 15 inch), and 38 to 53 cm (15 to 21 inch) layers using the method of Ahuja et al. (1980). Water for the infiltration tests was pumped from the Oakes aquifer using sand–point wells installed along the bottom of the pilot drain. Water was applied through each infiltrometer until the deepest tensiometer (53 cm) indicated no further response, and until



FALL 1986 LARGE BASIN

EXPLANATION

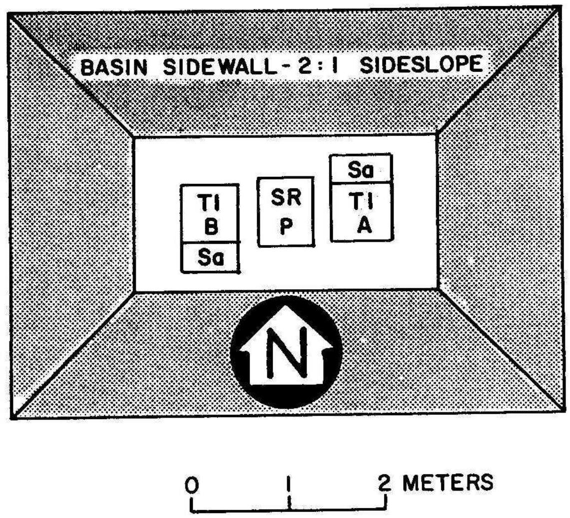
P PIEZOMETER NEST

Sa SAMPLE AREA

SR STAGE RECORDER

TI DOUBLE-RING INFILTROMETER AND TENSIOMETER NEST

Fig. 16. Fall 1986 large basin sampling and instrumentation layout.



FALL 1986 SMALL BASIN

EXPLANATION

P PIEZOMETER NEST

Sa SAMPLE AREA

SR STAGE RECORDER

TI DOUBLE-RING INFILTROMETER AND TENSIOMETER NEST

Fig. 17. Fall 1986 small basin sampling and instrumentation layout.

Table 4. Basin floor laboratory samples taken for the Fall 1986 test.

LABORATORY SAMPLES FALL 1986

Depth (cm)	Particle Size		Organic Carbon		Moisture Retention (10-120 cm)		Bulk Density	
	T	N	T	N	T	N	T	N
0.0 - 0.6	B/A	6	B/A	6	----		----	
0.6 - 1.3	B/A	6	B/A	6	----		----	
1.3 - 2.5	B/A	6	B/A	6	----		----	
2.5 - 5.1	B/A	6	B/A	6	----		----	
5.1 - 7.6	B/A	6	B/A	6	----		----	
7.6 - 22.9	B/A	6	B/A	6	B/A	6	B/A	6
22.9 - 38.1	B/A	6	B/A	6	B/A	6	B/A	6
38.1 - 53.3	B/A	6	B/A	6	B/A	6	B/A	6
0 - 7.6	----		----		B/A	6	B/A	6
Suspended Solids	D	4	----		----		----	
Filter Cake	A	6	----		----		A	3

T = Time N = Number of Samples
B = Before Operation A = After Operation D = During Operation

Table 5. Grain-size distribution for the basin-floor-filter cake and for suspended solids delivered to the large and small basins during the Fall 1986 test.

FALL 1986

FILTER CAKE SAMPLES No.		No.		SUSPENDED LOAD SAMPLES Date	
1	SILT 90% CLAY 10% OC 2.42%	4	SILT 42% CLAY 58% OC 3.43%	09/24/86	SILT 10% CLAY 90%
2	SILT 80% CLAY 20% OC 2.22%	5	SILT 48% CLAY 52% OC 3.44%	09/29/86	SILT 27% CLAY 73%
3	SILT 88% CLAY 12% OC 3.08%	6	SILT 79% CLAY 21% OC 2.37%	10/06/86	SILT 21% CLAY 79%
				10/20/86	SILT 34% CLAY 66%
$\overline{SILT}$= 71% SD=20.8 $\overline{CLAY}$= 28% SD=20.8 $\overline{OC}$ = 2.83% SD=0.56 N=6				$\overline{SILT}$= 23% SD=10.16 $\overline{CLAY}$= 77% SD=10.16 N=4	

CRUST THICKNESS=1.58 mm
CRUST/CLAY SEDIMENT RATIO=0.27

OC = ORGANIC CARBON

no changes in infiltration rate were observed. Steady–state infiltration was then measured, and tensiometer readings were initiated. Each infiltration profile was allowed to drain, and tensiometer readings were taken initially at 30 second intervals. Measurement intervals were gradually increased until after 2 days, when only one reading per day was taken. Tensiometer readings were continued for five days. Each installation was covered with a polyethylene vapor barrier at land surface, a layer of 9 cm (3 1/2 inch) fiberglass insulation (within the inner ring), and two layers of 6 x 6 m (20 x 20 ft.) polyethylene sheet for protection from rainfall. After determination of K(S), the outer rings were removed and inlets to the inner ring were opened to allow free movement of water during early basin operation.

Condition of the Basin Floor

Trafficking of the basin floor during preparation and sampling was limited as much as possible. A large portion of the basin was left in the condition of its construction, which consisted of a slightly corrugated surface from the teeth of the backhoe. The disturbed portions were given a final grooming prior to water delivery. The grooming consisted of a hand spading to lessen compaction, and a hand raking to remove any large fissures left from the hand spading.

Basin Operation

Water was first delivered to the large basin at 13:25 h on September 18, 1986. Initially, a high rate of discharge (3,787 liters per minute or 1000 gpm) was used to bring the water level of the basin quickly to the desired 0.6 m (2 ft.) level. After approximately 1 hour, a 0.61 m (2 ft.) basin stage was reached, and discharge was reduced to maintain that level. As infiltration gradually decreased, the gate valve was manually adjusted to maintain the 0.61 m basin stage [±7.6 cm (0.25 ft.)] and discharge was continuously monitored using the Barton flowmeter.

Tensiometers were read at 15 minute intervals for the first 2 hours, then at half hour intervals for the next 2 hours. Readings were gradually decreased to one per hour, and by the second day four per day were taken. Near the end of the experiment, reading intervals were decreased to two per day. Water levels in the piezometers within the basin were measured at approximately the same intervals as the tensiometers. Water levels in the piezometers outside of the basin were continuously measured.

Water was first delivered to the small basin at 12:50 h on September 23, 1986. An initial discharge rate of about 531 liters per minute (140 gpm) was used to quickly obtain a 0.61 m (2 ft.) basin stage. The desired stage was reached after approximately 2 hours and was maintained [±7.6 cm (0.25 ft.)] throughout the test period. Reading intervals for tensiometers and piezometers were similar to those of the large basin.

Operation of the large basin was terminated on October 20, and operation of the small basin was terminated on October 25, 1986. Residual water was pumped from the basins, and soil samples were taken as soon as the basin floors were dry enough to sample (on the same day). In addition, morphologic profiles were described for basin cross sections at each tensiometric installation.

RESULTS

The initial infiltration rate through the large basin was 39 cm/h (31 ft./d) and declined to 0.75 cm/h (0.59 ft./d) after 33 days of operation. The greatest rate of decline occurred over the first five days, and 75% of the total recharge was accomplished within the first nine days of operation. Total infiltration was 3040 cm (100 ft.). For the small basin, the initial infiltration rate was 142 cm/h (111 ft./d) and decreased to 3.4 cm/h (2.7 ft./d) after 32 days. Total infiltration was 6035 cm (198 ft.). In the small basin, 75% of the total recharge occurred within the first 10 days of operation.

Beneath the large basin, the water–table mound rose to a maximum height during the first 15 hours of operation. After this time the water–table mound dissipated until the end of the test. Excess discharge was conveyed through a bypass pipe to the pilot drain located 55 m (180 ft.) south of the basin perimeter. As the test progressed and clogging reduced the infiltration rate, more water was discharged through the bypass pipe into the pilot drain. Water levels measured in all piezometers indicated that the growth and dissipation of the water–table mound beneath the basin was affected by discharge into the pilot drain.

A perched ground–water mound formed above an interval of very–fine to fine sand (Fig. 14, Piezometer TPL 1–A, layer 10) after about 50 minutes and peaked at a height of 0.15 m (0.48 ft.) after 96 minutes. The perched ground–water mound dissipated after about 6 hours from initiation of water delivery. Piezometers TPL–2A, TPL–3A, and TPL–4A remained dry during the test. This indicates that the perched ground–water mound was confined to the area beneath the test basin. Since the perched ground–water mound did not intersect the basin floor, it did not significantly limit infiltration at any time during the test. Tensiometer data indicated that the vadose zone was quickly unsaturated at 38 cm beneath the basin floor (less than 3 hours in three of four locations), and that saturated conditions were never reached at 53 cm. These data indicate that surface clogging of the basin floor is the primary infiltration rate control.

For the small basin, results were similar. A perched ground–water mound formed above an interval of very fine to fine sand (Fig. 15, Piezometer TPS 1–A, layer 6) after about 35 minutes, and peaked at a height of 0.19 m (0.63 ft.) after 79 minutes. The perched ground–water mound was totally dissipated after 3 hours from initiation of water delivery. Tensiometers indicated that the subbasin soil at 38 and 53 cm depths never reached saturated pressure potentials during the test. In addition, Piezometer TPS 2–B remained dry during the test. These data indicate that the perched ground–water mound was confined to the area beneath the test basin. Since the perched ground–water mound did not intersect the basin floor it did not appreciably limit infiltration at any time during the test.

Spatial Variability Within The Basin

Of eight soil samples taken at the surface of the basin floor before operation, little variability in particle size distribution was detectable. Sand ranged from 86 to 90 % ($\bar{X}$ = 88%, S.D. = 1.5%). Silt ranged from 4.4 to 6.8 % ($\bar{X}$ = 5 % , S.D. = 1.16 %) . Clay ranged from 4.9 to 7.4 % ($\bar{X}$ = 7%, S.D. = 1.25%). Additional hand texturing indicated that the northeast quarter of the basin had a greater clay content than the rest of the basin. The layer containing the clay was discontinuous, however, and was generally only a few cm thick.

Despite the apparent homogeneity of surface materials, there was considerable variation in the hydraulic properties and recharge rates at various positions within the basin. Soil hydraulic conductivity values for the large basin are shown on Fig. 18 . Values vary by more than one order of magnitude between different areas of the basin. They also vary by more than one order of magnitude between layers for any given measurement position. Flux values determined from tensiometer installations are shown on Fig. 19, along with the flux determined at the intake to the basin. Initial rates vary from 8.0 cm/h (6.3 ft./d) at basin position L1 to 45.0 cm/h (35.2 ft/d) at basin positions L2 and L4. Similar variability was found for the small basin (Schuh, 1988). It is evident that the packing and positioning of grains from weathering and construction can cause large differences in conductive properties within a relatively small recharge basin.

The disparity between the spatial variability of the hydraulic properties and physical properties measured within the basin is not unusual. Studies of soil spatial variability have reported coefficients of variation between 280 and 420 (Warrick and Nielsen, 1985), and of 325 (Jury, 1985) for unsaturated hydraulic conductivity, compared with between 22 and 68 (Warrick and Nielsen, 1980) and 40 (Jury, 1985) for particle–size

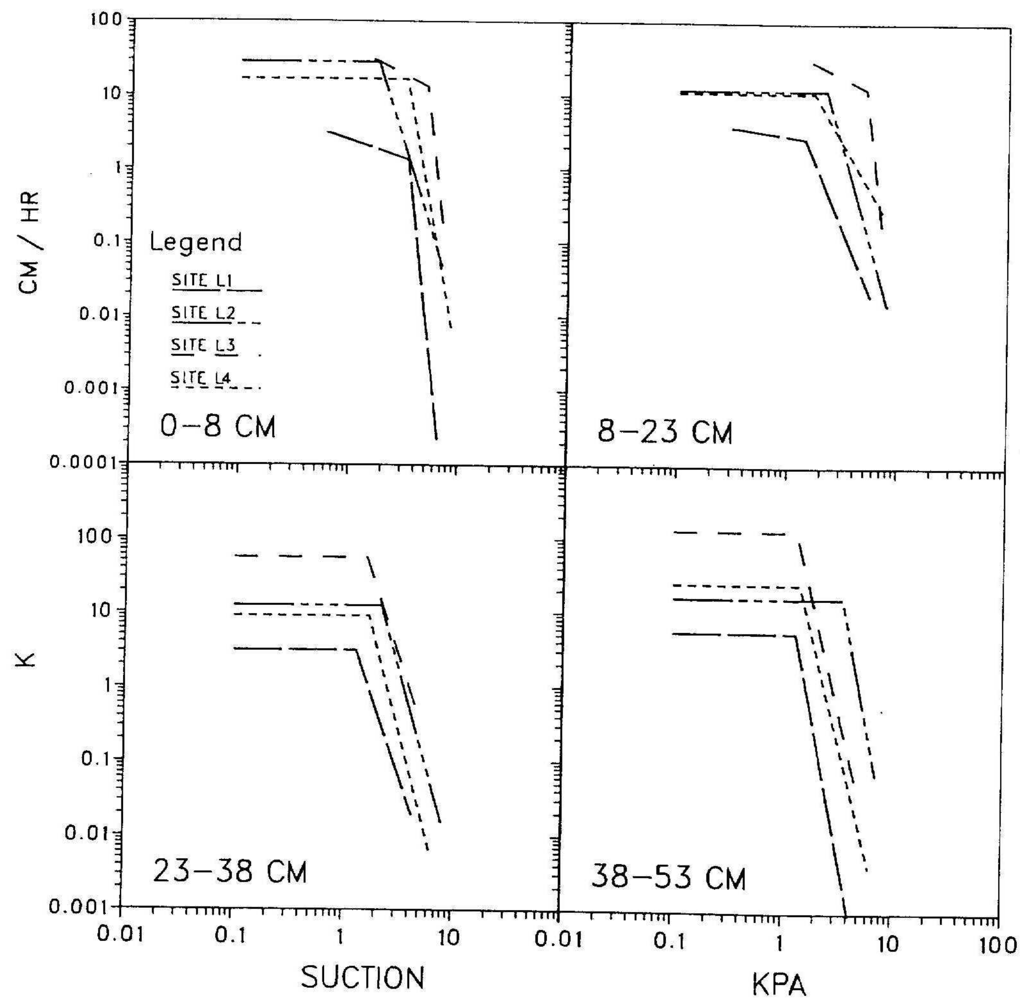


Fig. 18. Unsaturated hydraulic conductivity function [K(S)] profiles for sites L1, L2, L3, and L4 (large basin) during the Fall, 1986, basin test.

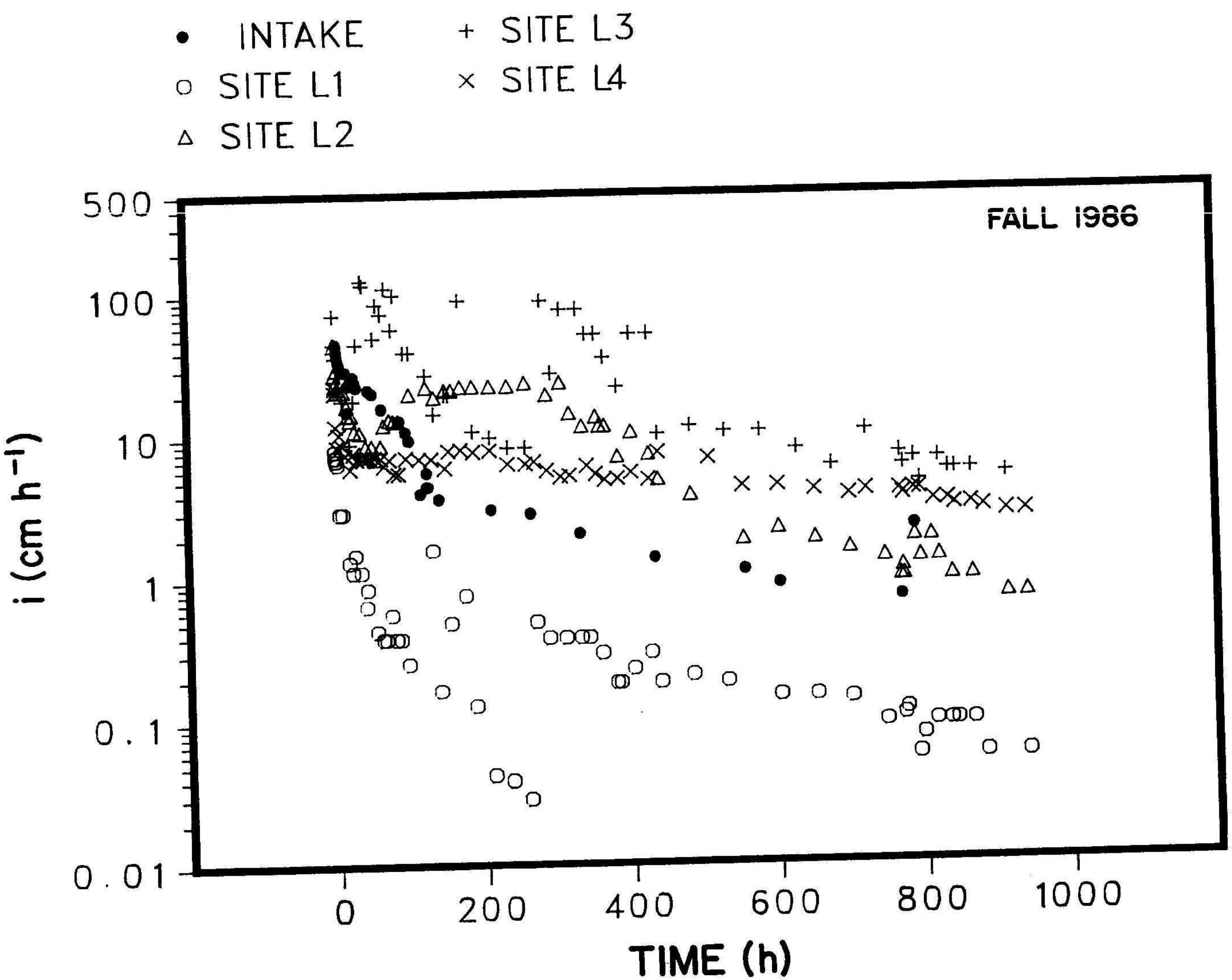


Fig. 19. Large basin infiltration for Fall 1986 determined at the intake to the basin, and at local monitoring sites L1, L2, L3, and L4.

fractions. Bulk density C.V. values were even lower, at 6 (Warrick and Nielsen, 1980) and 9 (Jury, 1985). Moreover, a geometrically greater variability for dynamic hydraulic properties compared with static hydraulic properties was predicted by Miller and Miller (1955) using similar media analysis. Variability levels recorded within the large test basin are thus consistent with realistic expectations.

Clogging of the Basin Profile

Changes in the impedance of soils with depth were monitored at four sites within the large basin (Fig. 16). Interpretations of clogging are made on the basis of changes in hydraulic gradient within each layer, and are quantified by the impedance ratios (I_R) calculated for each layer during basin operation. It is assumed that any rising gradient must result from clogging within the layer indicated. An exception would be the case where the hydraulic conductivity of an adjacent material (above or below) is increasing. However, this requires disturbance and is not considered likely under conditions of turbid water application. A falling gradient may be induced by clogging in an adjacent layer, and indicates that the impedance of the falling gradient layer is increasing at a rate less than that of the adjacent layer. In many cases clogging will have ceased entirely. A constant gradient usually indicates that no clogging is occurring within the layer, although in a few rare cases it may indicate that clogging is occurring at a rate just sufficient to offset a fall in gradient caused by an increase in clogging (and gradient) of an overlying or underlying layer. For a homogeneous soil where no clogging is occurring, hydraulic gradients under quasi–steady–state conditions should be constant and close to unity (Takagi, 1960).

As discussed previously, I_R values indicate changes in impedance due to clogging alone, and do not reflect changes in K(S) due to desaturation induced by impedance in overlying layers. Because water flows at faster velocities in larger pores, and because of increased straining of aqueous sediment as pores decrease in size, it is possible for clogging to occur over entire pore ranges, or limited pore ranges. A soil may be clogged, for example, in pores dominating flow at 100 hours, while little or no clogging might occur for pores of radii flowing at 600 hours.

Because flux and impedance are determined using a bottom control layer within the profile, it is important that the control layer remain unclogged. This condition is monitored by observing the hydraulic gradient of the control layer, and by observing the I_R value for the overlying layer, since it is considered unlikely that sediment will reach a deep layer without first altering the properties of the overlying layers.

Site L1

Hydraulic gradient data (Fig. 20) indicate that clogging of the 8 to 23 cm (3 to 9 inch) layer is greatest during the first 80 hours of basin operation. At early hours some clogging appears to take place in the 23 to 38 cm (9 to 15 inch) layer, and a period of increased translocation to this layer occurs between 80 and 150 hours, and then ceases. The surface layer (0 to 8 cm) indicates little clogging up to 50 hours when the hydraulic gradient begins a slow rise. After 100 hours the top two layers (0 to 8 cm and 8 to 23 cm) are composited because of a malfunction in the 8 cm tensiometer. Composite data indicate that after an initial 80 hour rise, the gradient of the surface layer drops briefly in response to clogging in the 23 to 38 cm layer. At 120 hours the 0 to 23 cm gradient begins to rise, and by 150 hours surface clogging is dominant. Although data is for a composite layer to 23 cm, it is considered most likely, based on other sites studied (Schuh, 1988), that most of the clogging is occurring in the surface filter cake at late times. The increased hydraulic gradient for the surface layer after 760 h was caused by an increase in the basin water level near the end of the test to 0.91 cm (3 ft.). The basin water level was then allowed to fall during the final hours of the test, causing the decreasing hydraulic gradient during the final hours of the test.

I_R data (Fig. 21) indicate a one order of magnitude increase in impedance for the 23 to 38 cm layer for the first 300 hours of operation. This is followed by a drop to negligible

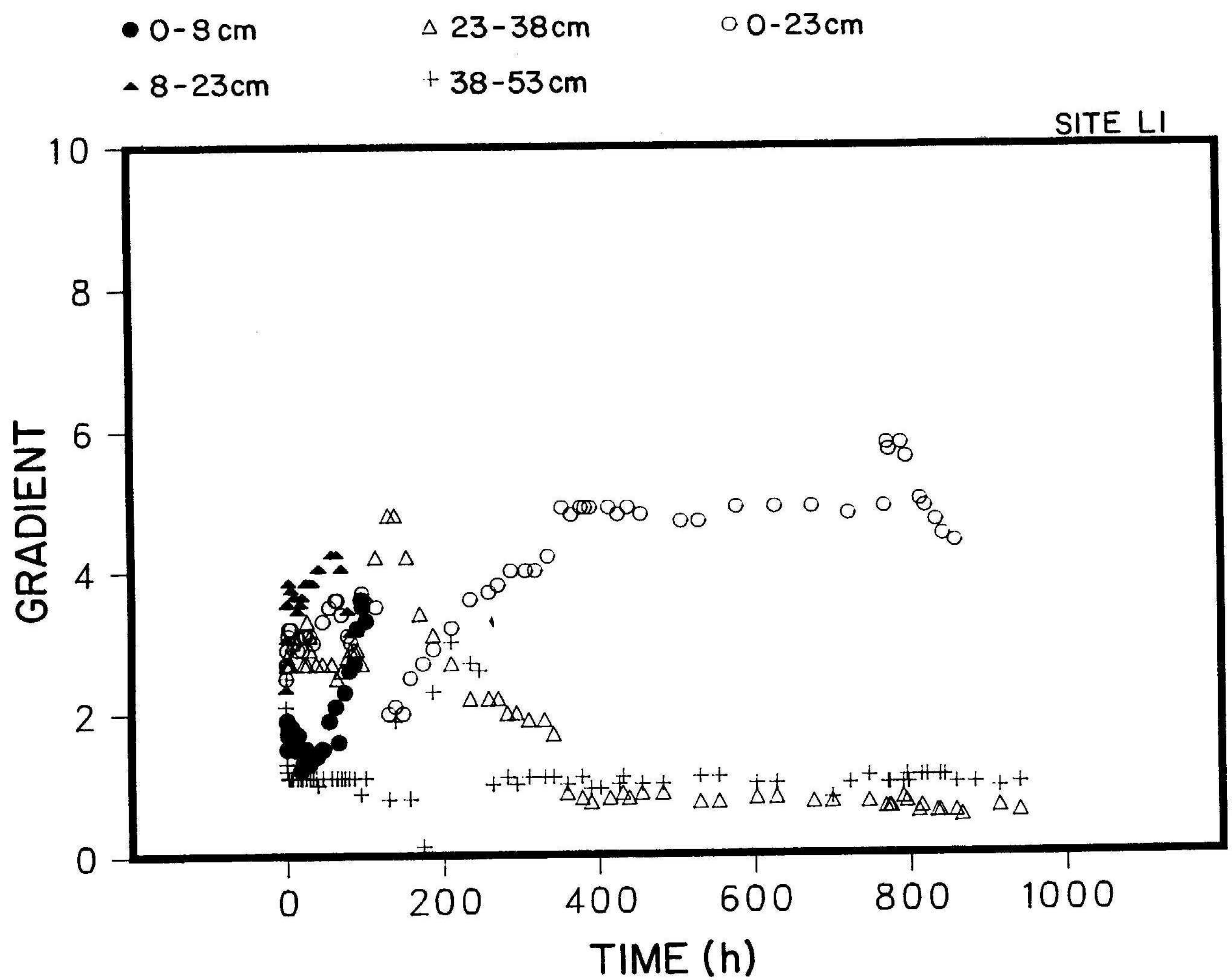


Fig. 20. Hydraulic gradient measurements for site L1 during the Fall 1986 large basin test.

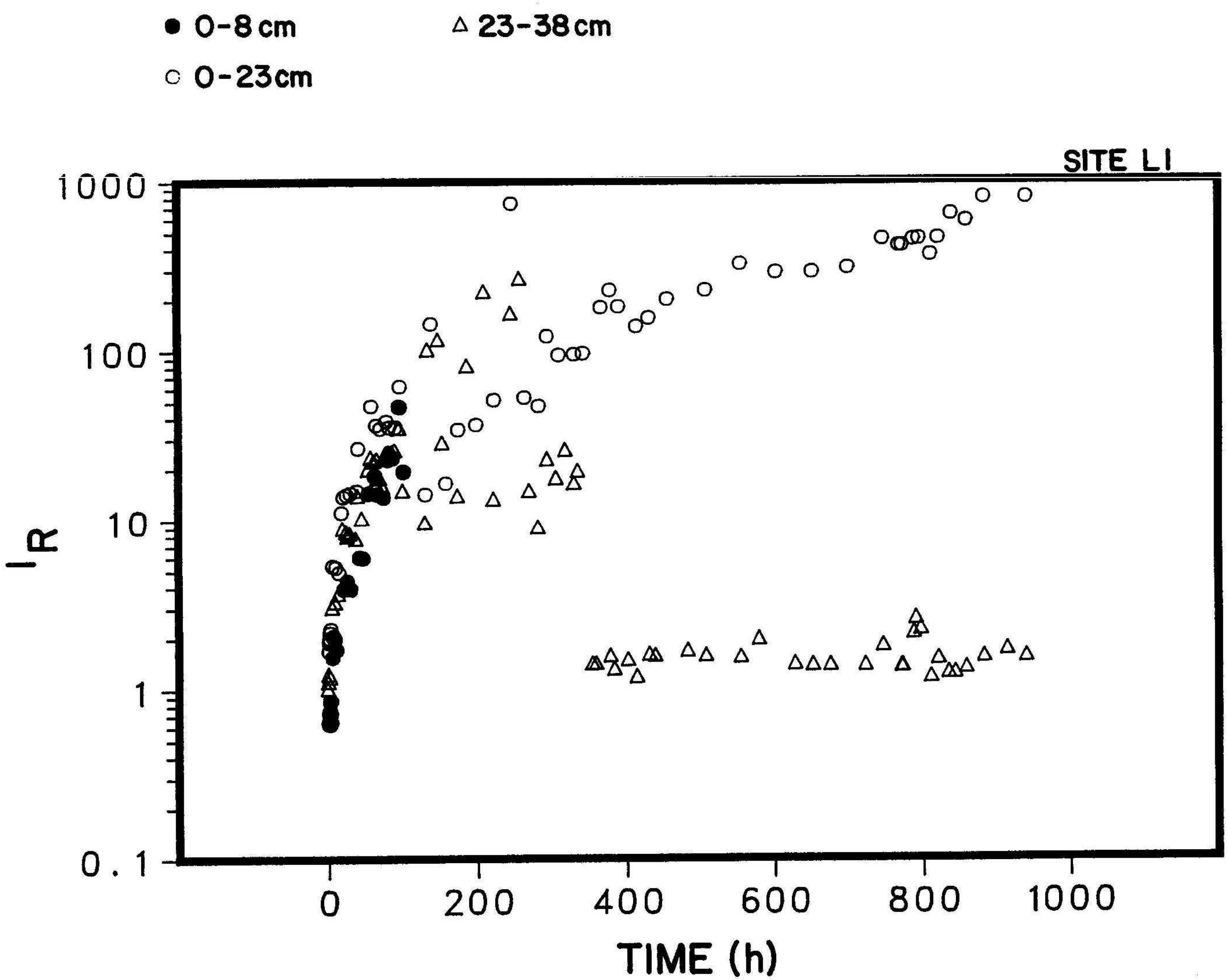


Fig. 21. Impedance ratio measurements for site L1 during the Fall 1986 large basin test.

impedance change from initial properties at later times, and indicates that clogging occurred only in larger pores. The surface composite layer is seen to have an increased impedance over preoperational values by a factor of nearly 300. This is averaged over 23 cm, and likely characterized by a surface filter cake layer of extremely high resistance, overlying less clogged materials.

Site L2

As in site L1, one of the tensiometers malfunctioned early during the operation of site L2. For this reason, the 8 to 23 and 23 to 38 cm layers were combined for analysis. Hydraulic gradient data indicate no clogging of the 38 to 53 cm control layer (Fig. 22). The gradient of the surface (0 to 8 cm) layer increased initially, and then fell in response to predominant clogging of the underlying (8 to 38 cm) layer. Clogging of the second layer predominated until about 80 hours, when the hydraulic gradient began to fall in response to a sharp rise in the gradient of the surface layer. According to gradient data, the surface layer alone seems to have clogged following 80 hours of basin operation. The increased hydraulic gradient for the surface layer after 760 h was caused by an increase in the basin water level near the end of the test to 0.91 m (3 ft.). The basin water level was then allowed to fall during the final hours of the test, causing the decreasing hydraulic gradient during the final hours of the test.

I_R values (Fig. 23) indicate close to one order of magnitude increase in impedance due to clogging in both 0 to 8 and 23 to 38 cm layers at early times. Little clogging for pores flowing after 250 hours is indicated for the 23 to 38 cm layer. The impedance of the surface layer continued to increase throughout the period of operation, and reached a value nearly 300 times that measured prior to importation of turbid water.

Site L3

As with site L1 , the 8 cm tensiometer malfunctioned after 100 hours of operation,

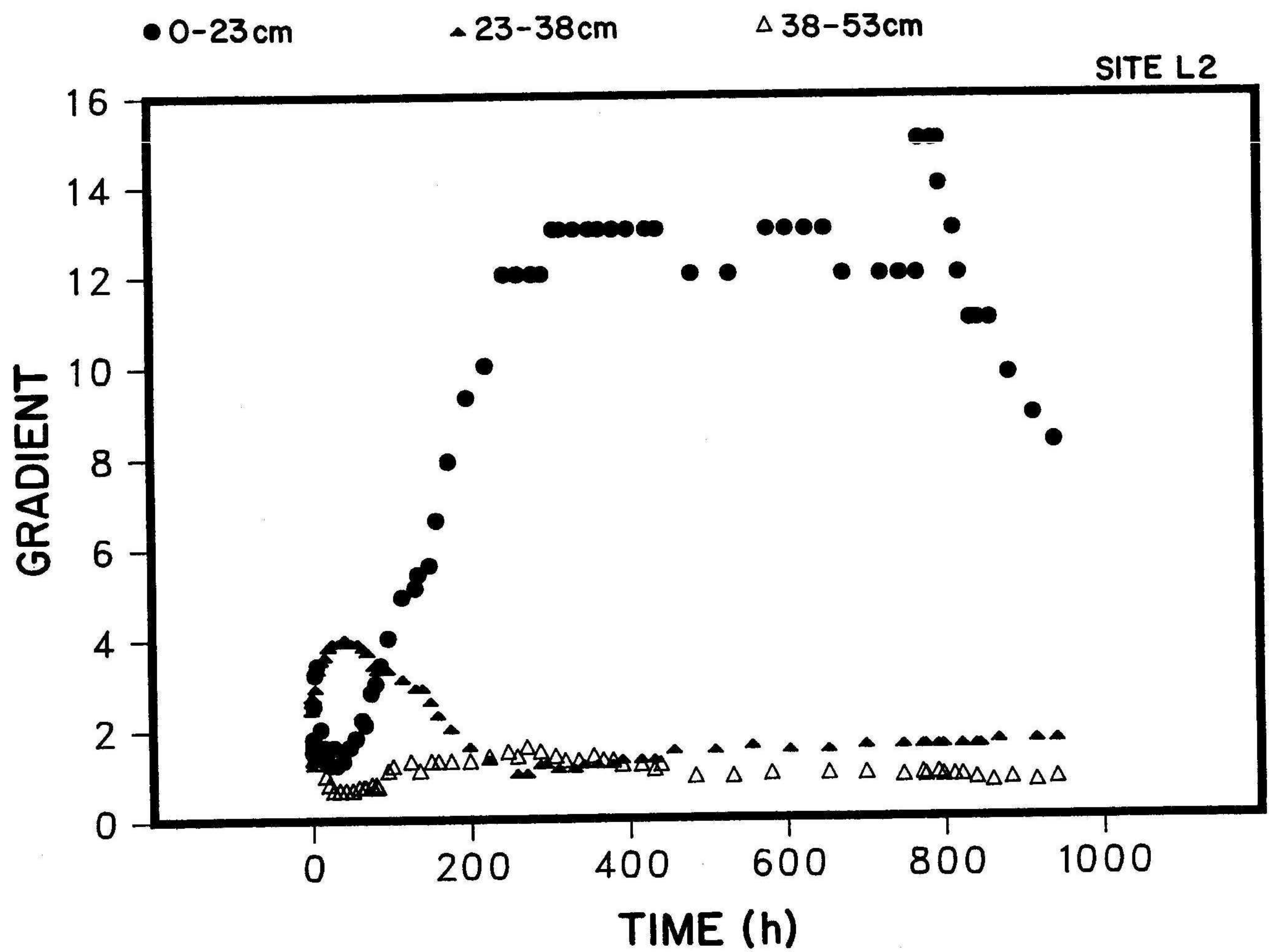


Fig. 22. Hydraulic gradient measurements for site L2 during the Fall 1986 large basin test.

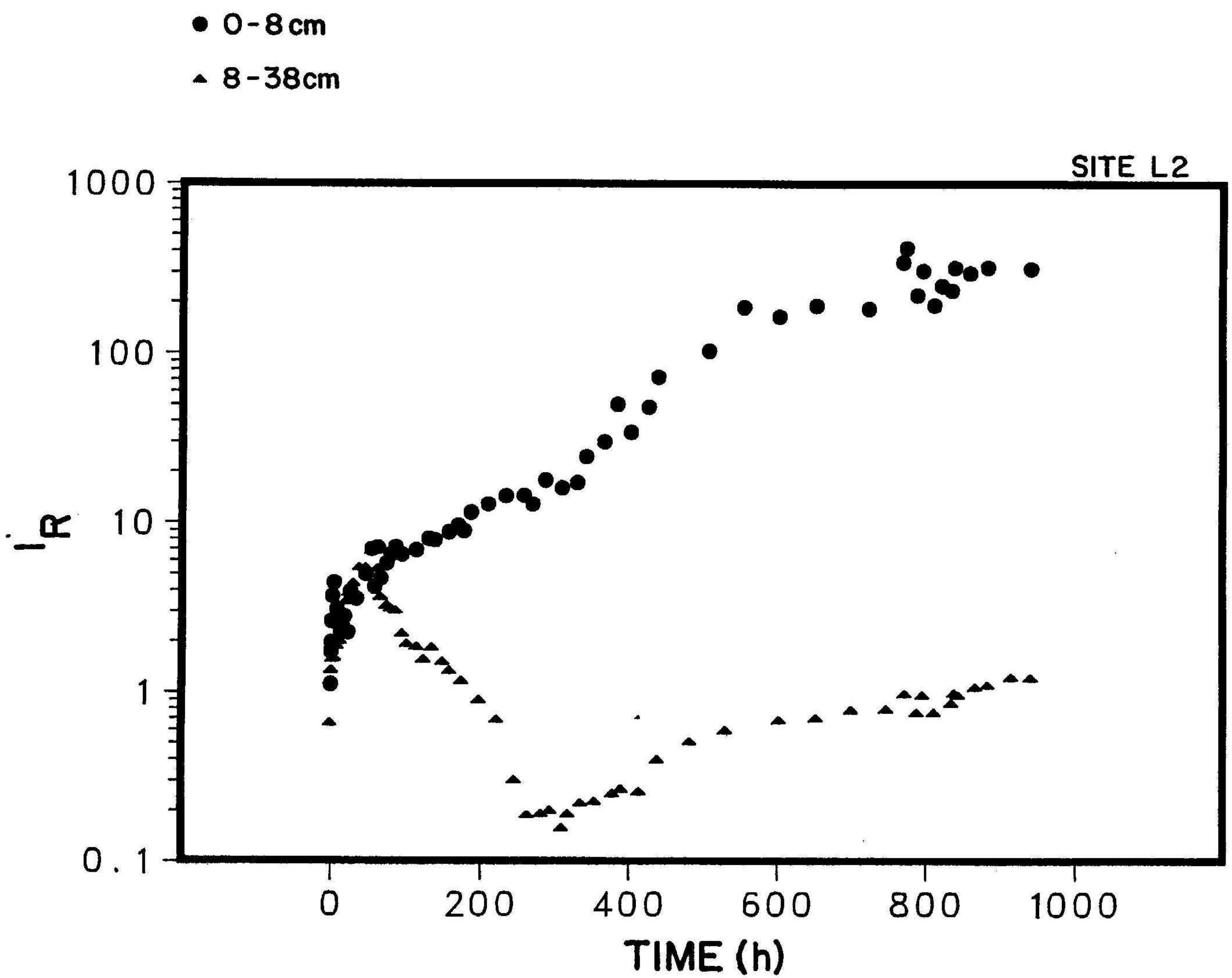


Fig. 23. Impedance ratio measurements for site L2 during the Fall 1986 large basin test.

and 0 to 8 and 8 to 23 cm layers were combined for analysis. It can be seen (Fig. 24) that initially (0 to 10 hours) clogging of the surface layer was dominant. However, clogging of the 8 to 23 cm layer began immediately, and from 10 to 20 hours was sufficiently dominant to force a falling gradient in the surface (0 to 8 cm) layer. The gradient of the 23 to 38 cm layer began to rise early, peaking at 50 hours, indicating clogging of that layer. After 50 hours, only the surface (0 to 8 cm) layer gradient was still rising, indicating that most clogging was occurring near the surface. Some brief early variation of the control layer gradient occurred. Little clogging was indicated, however. The increased hydraulic gradient for the surface layer after 760 hours was caused by an increase in the basin water level near the end of the test to .91 m (3 ft.). The basin water level was then allowed to fall during the final hours of the test, causing the decreasing hydraulic gradient during the final hours of the test.

I_R data (Fig. 25) indicated increased impedance for the 23 to 38 cm layer during the the first 300 hours. I_R initially increased by a factor of nearly 10, but for pores flowing at later times (and higher suctions) little or no clogging was indicated. The combined 0 to 23 cm layer reached an I_R of nearly 30. However, it is evident from the extremely sharp rise in the 0 to 8 cm layer gradient at early times, (Fig. 24) that most of the clogging was occurring near the surface.

Site L4

During the first 10 hours similar hydraulic gradient increases occurred in the 0 to 8, 8 to 23, and 23 to 38 cm layers indicating clogging those layers (Fig. 26). From 10 to 20 hours, the surface layer gradient decreased as clogging in the deeper layers dominated. Beginning at 20 hours the surface layer gradient rose, and the 8 to 23 cm layer began to decrease. Until approximately 130 hours clogging occurred primarily at the surface, and in the 23 to 38 cm layer. After 130 hours, the gradient of the 23 to 38 cm layer decreased quickly as surface layer clogging increased and dominated flow. No clogging was indicated

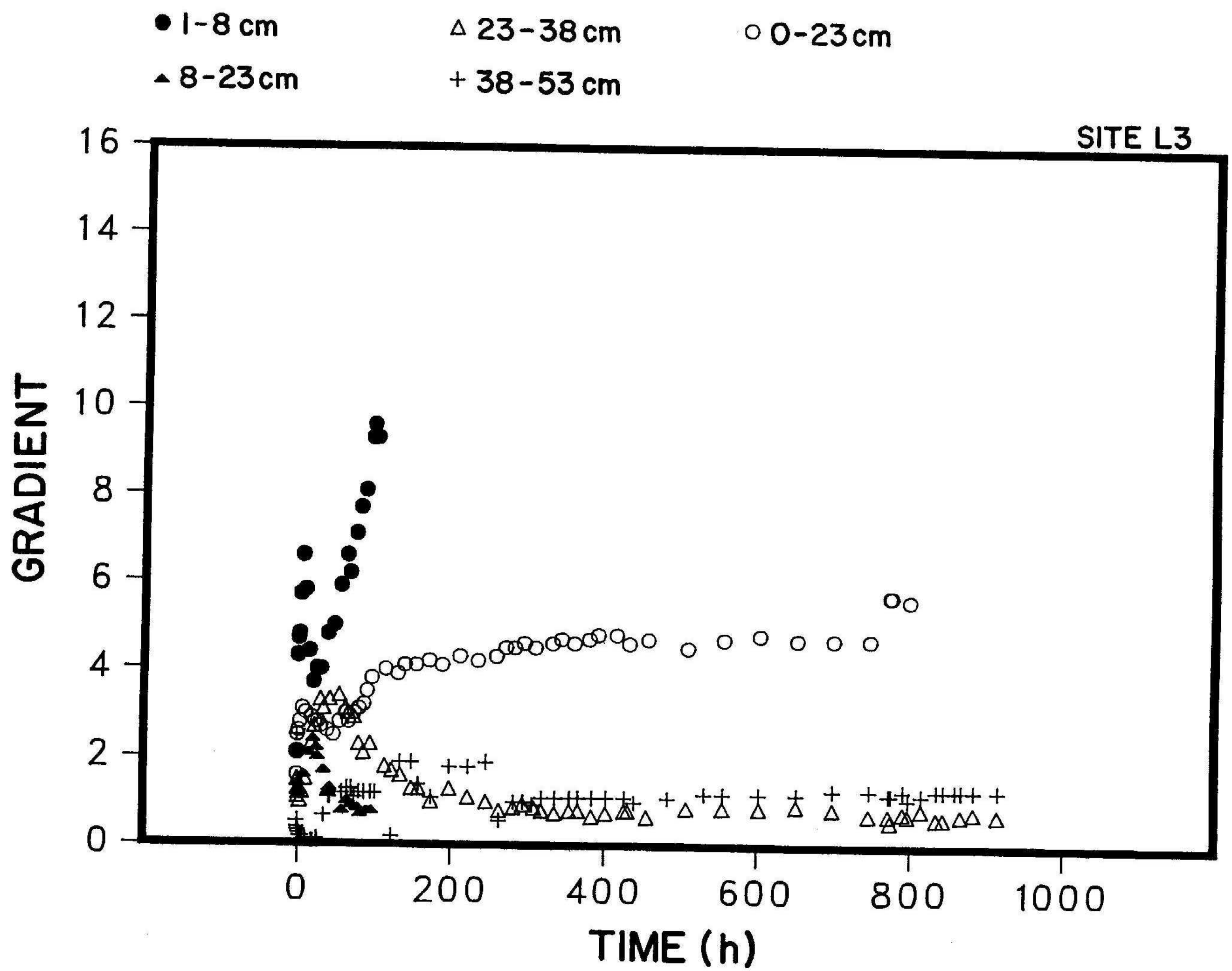


Fig. 24. Hydraulic gradient measurements for site L3 during the Fall 1986 large basin test.

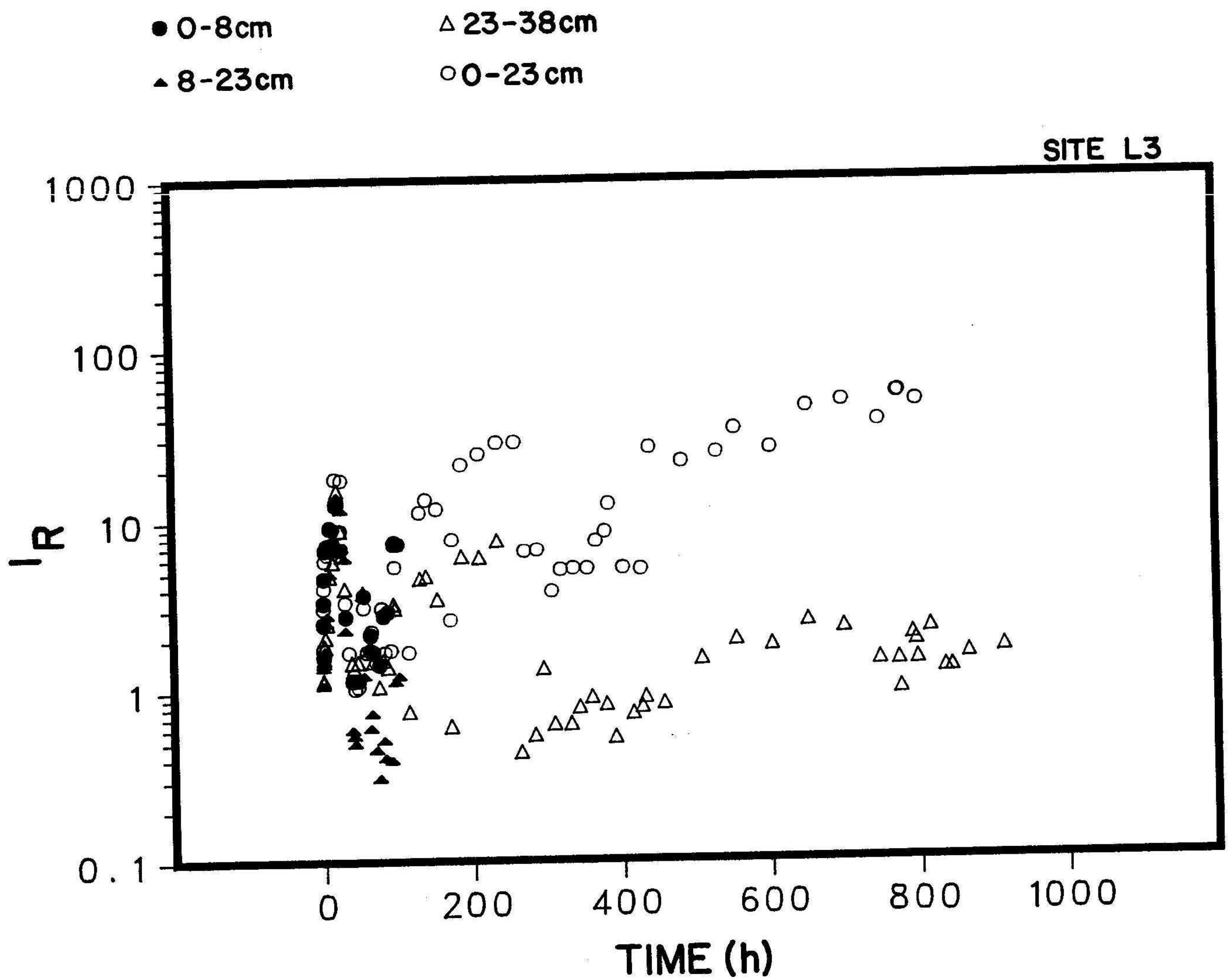


Fig. 25. Impedance ratio measurements for site L3 during the Fall 1986 large basin test.

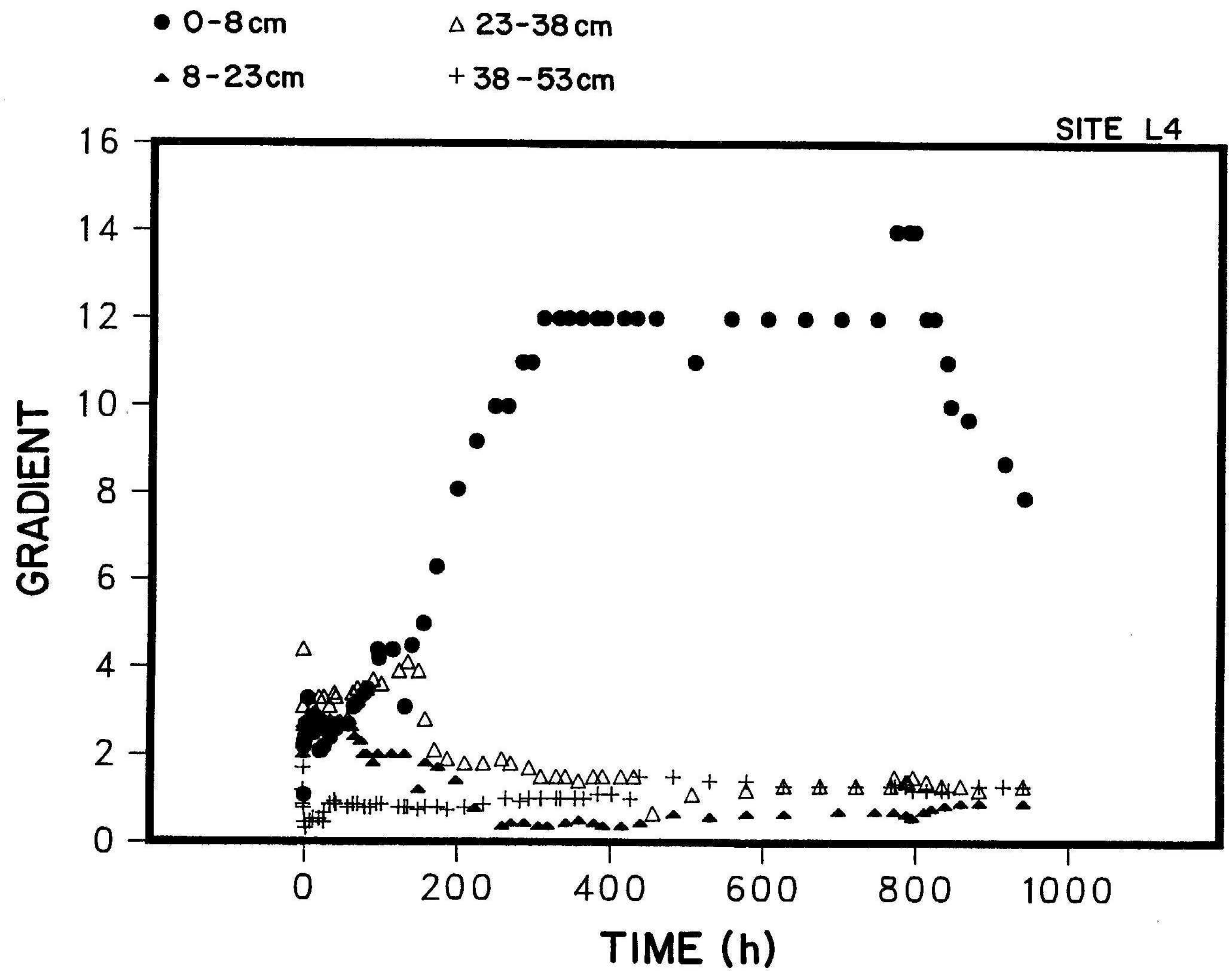


Fig. 26. Hydraulic gradient measurements for site L4 during the Fall 1986 large basin test.

for the 38 to 53 cm control layer. The increased hydraulic gradient for the surface layer after 760 h was caused by an increase in the basin water level near the end of the test to .91 m (3 ft.). The basin water level was then allowed to fall during the final hours of the test, causing the decreasing hydraulic gradient during the final hours of the test.

I_R data (Fig. 27) indicate that impedance for all layers between 0 and 38 cm increased by a factor of 10 during early application of James River water. After 100 hours clogging of the 0 to 8 cm layer continued, and reached an I_R in excess of 1000 times preoperational impedance before termination of water delivery. Although the 8 to 23 and the 23 to 38 cm I_R decreased at later times, indicating nonuniform clogging over the full range of flowing pores during the early initial clogging, some residual increases in impedance were maintained throughout the operational range. At later times an I_R of 2 to 3 was maintained for the 23 to 38 cm layer. For the 8 to 23 cm layer a late rise in I_R may have been due to late translocation of sediment through the surface layer, or the smaller pores may have been clogged in some manner initially. Although no late rise in gradient was seen, the high surface layer gradient would likely overpower and mask any tendency for a minor gradient rise in a lower layer.

Small Basin Sites (S1 and S2)

Detailed evaluations of impedance development for small basin sites S1 and S2 were discussed by Schuh (1988). To summarize briefly, results were similar to those of the large basin. No clogging was found for site S1 below the depth of 23 cm. For the first 75 hours the 0 to 8 and 8 to 23 cm layer impedance values increased to one order of magnitude over preoperational values. Thereafter, the 8 to 23 cm layer remained at 10 to 20 times preoperational impedance, while the surface layer continued to clog until I_R values reached 200 to 300 times preoperational values. For site S2, both 0 to 8 and 8 to 23 cm layers exhibited immediate increases in I_R. However, the 8 to 23 cm layer ceased to clog after 5 hours, and only slight clogging of that layer in the large pore range was indicated. After 5

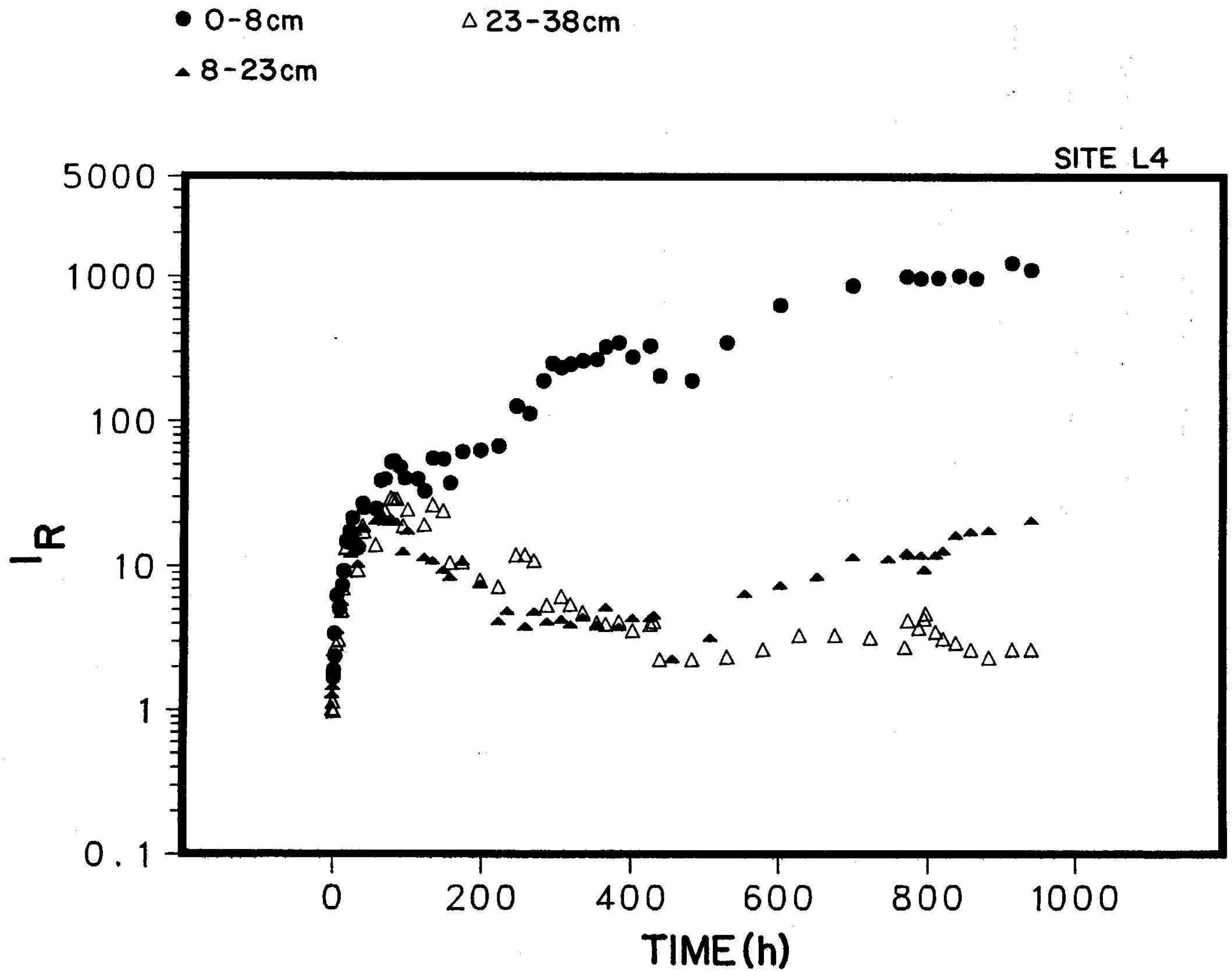


Fig. 27. Impedance ratio measurements for site L4 during the Fall 1986 large basin test.

hours, the surface layer continued to clog until an I_R value of 600 to 700 times initial values were reached. Greater surface impedance development for site S2 may have been duc to a greater proportion of total sediment being deposited on the surface, and less moving to lower depths. Neither site S1 nor S2 indicated deposition of sediment at depths greater than 23 cm.

Physical Data

Particle–size and organic–matter changes for soil samples taken before and after basin operation are summarized on Tables 6 and 7. Because both large and small basins exhibited similar infiltration rate controls (ie. surface clogging rather than perched ground–water mounds) and because of their close proximity, it was decided to combine the particle–size data for statistical analysis. Results indicated that clay content increased significantly to the 5 cm depth. Silt increased only at the 1.3 to 2.5 cm depth interval. A slight gradational increase in silt above and below that layer seems to have occurred, but it is not statistically significant. No silt was deposited immediately below the surface filter cake. A significant increase ($P < 0.05$) in organic carbon was identified only at the 0 to 0.63 cm depth, and at the 1.3 to 2.5 cm depth, although some deposition bridging those two layers is likely from the data ($P < 0.1$).

Bulk density samples taken before and after the experiment are compared on Table 7. As with particle size, small and large basin samples were combined for statistical analysis. Bulk densities for 0 to 8 cm averaged 0.113 g/cm3 greater density ($P < 0.05$) reflecting differences due to sediment deposition and consolidation. Below 8 cm no difference in bulk density was observed. Because analysis was based on differences between spatially paired samples, error due to spatial variability would be assumed principally within the random error term. Thus, the measured significant change in bulk density was almost certainly be due to operational changes.

Changes in bulk density indicate directly the changes in total porosity occurring in

Table 6. Basin subsoil grain-size-distribution changes (% clay and % silt) before and after the Fall 1986 test. Data from the large and small basins are combined for analysis (N=6).

FALL 1986

Percent Clay Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - .63	+ 1.32	0.185	7.14	0.0001
.63 - 1.3	+ 1.14	0.339	3.33	0.025
1.3 - 2.5	+ 1.15	0.307	3.74	0.01
2.5 - 5.1	+ 1.47	0.486	3.02	0.025
5.1 - 7.6	- 0.12	0.928	0.13	NS
7.6 - 22.9	- 0.00	0.442	----	NS
22.9 - 38.1	- 0.02	0.625	0.03	NS
38.1 - 53.3	- 0.22	0.764	0.29	NS

Percent Silt Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - .63	- 0.53	0.395	1.34	NS
.63 - 1.3	+ 0.98	0.597	1.63	NS
1.3 - 2.5	+ 1.38	0.349	3.94	0.01
2.5 - 5.1	+ 0.68	0.649	1.05	NS
5.1 - 7.6	- 0.72	0.813	0.88	NS
7.6 - 22.9	- 1.19	0.795	1.49	NS
22.9 - 38.1	- 0.29	1.302	0.22	NS
38.1 - 53.3	- 0.78	1.171	0.66	NS

SE = Standard Error t = Student's t
P = Probability Level

Table 7. Basin subsoil organic carbon and bulk density changes indicated by samples taken before and after the Fall 1986 test. Data from the large and small basins are combined for analysis (N=6).

FALL 1986

Percent Organic Carbon Difference Before And After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - .63	+ 0.048	0.012	3.93	0.01
.63 - 1.3	+ 0.053	0.023	2.26	NS(0.1)
1.3 - 2.5	+ 0.062	0.020	3.07	0.025
2.5 - 5.1	+ 0.012	0.019	0.63	NS
5.1 - 7.6	+ 0.001	0.017	0.10	NS
7.6 - 22.9	- 0.011	0.009	1.34	NS
22.9 - 38.1	- 0.005	0.00	0.75	NS
38.1 - 53.3	- 0.001	0.008	0.22	NS

Bulk Density Difference Before And After Basin Operation

Depth (cm)	Change g/cm3	SE g/cm3	t	P
0 - 7.6	+ 0.113	0.046	2.45	0.05
7.6 - 22.9	- 0.017	0.034	0.49	NS
22.9 - 38.1	+ 0.000	-----	-----	NS
38.1 - 53.3	+ 0.007	0.065	0.10	NS

SE = Standard Error　　t = Student's t
P = Probability Level

the basin floor materials. In addition, soil moisture retention curves were measured to determine the change in porosity distribution. Large porosity (0 to 120 cm suction) and fine porosity (greater than 120 cm suction) for each of the sample areas before and after basin operation were compared. Although a slight decrease in large porosity, and a slight increase in smaller porosity was indicated, the differences were nonsignificant ($P < 0.05$). The coefficient of variation for the paired comparison was approximately 100 percent.

Morphologic Profiles

After completion of the basin operation, the infiltrometers and tensiometers were removed, and shallow trenches (30 cm) were excavated across each measurement site. Each site was described and hand textured. Descriptions for sites L1, L2, L3, and L4 are shown on Fig. 28. With some variation, each profile consisted of three zones of detectable change. 1) At the surface a 1.59 mm (1/16 inch) filter cake layer had formed on top of the original basin floor. 2) A second layer formed beneath the filter cake to a depth varying from 1.25 cm (1/2 inch) to 7.62 cm (3 inches). The second layer was characterized by a dark color, and a significant difference in clay content from deeper materials was indicated. The third layer was between 6.3 cm (2 1/2 inch) and 20 cm (8 inch) and was characterized by a very slightly loamy texture. Below the third layer, soil profiles appeared to be unaltered.

Sediment Distribution and Filter–Cake Formation

Filter–cake samples were air dried, and particle size distribution was determined using the pipette method (USBR, 1982). In addition, bulk densities were determined for three samples using the clod method with paraffin coatings (Blake and Hartge 1986). Bulk density sample sizes were small because it was necessary to use peds with no cracks after air drying, but the results were reasonably consistent at 1.16, 1.23, and 1.28 g/cm3 (average=1.22 g/cm3). This range is close to the value of 1.22 g/cm3 indicated for bulk

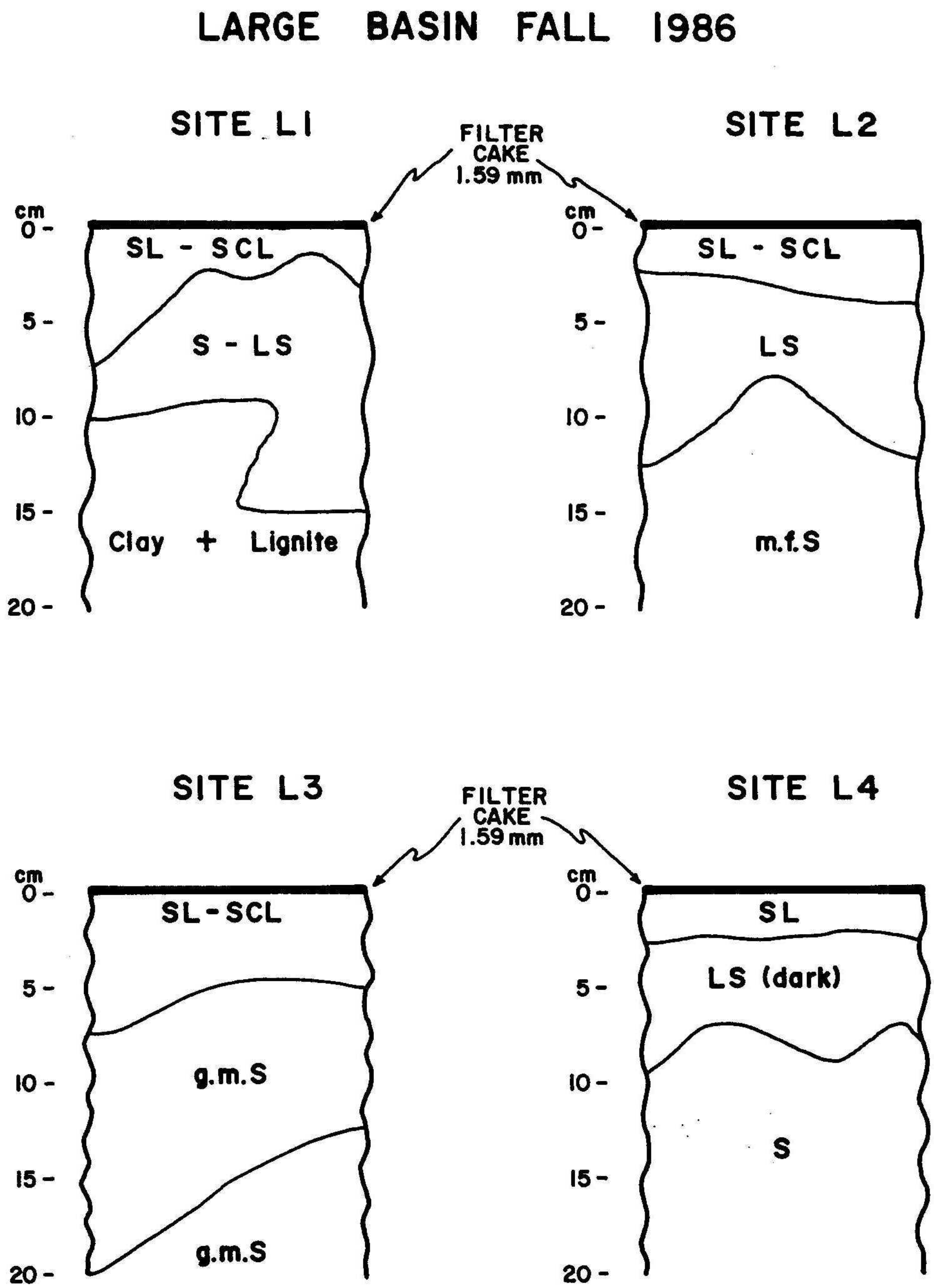


Fig. 28. Large basin morphology at tensiometer installations after completion of the Fall 1986 test. S = sand, SL = sandy loam, LS = loamy sand, SCL = sandy-clay loam, f. = fine, m. = medium, co. = coarse, g. = gravelly.

densities of disturbed and structureless clay soil materials by Gupta and Larson (1979).

Particle–size distribution for filter–cake materials is shown on Table 5. It is seen that the filter cake layer is composed primarily of silt size particles (71%). The particle–size distribution for sediment in water samples taken during basin operation are also given on Table 5. The silt to clay ratio was approximately reversed from the crust composition, with a silt content of only 23 %. This indicates that clay moved deeper into the basin floor profile while silt preferentially deposited on the surface. The silt cake might have later provided a filter capable of removing clay particles.

Mineralogical analyses were not performed on the James River sediment. However, the mineral constituents of numerous soils of Wisconsin grey glacial till origin, and of post–glacial lacustrine origin were measured by Pluth et al. (1970). Although the soils were sampled in western Minnesota, many were of the identical series to those of the James River drainage basin, and thus would be expected to provide the source of the James River sediment load. For the coarse clay fraction, montmorillonite was consistently between 30 and 60%, with the kaolinite content between 15 and 30%. Some vermiculite was also detected. For the fine clay fraction (<0.2 microns) montmorillonite consistently accounted for more than 60% of the clay fraction. Because of the expanding properties of montmorillonite, enhanced clogging of the basin floor due to sediment clay content would be expected. Enhanced sensitivity of basin clogging to changes in influent SAR values would also be expected.

Gravimetric deposition of silt and clay in the filter cake layer was calculated using the measured bulk density and thickness of the layer, and the laboratory silt and clay percentages. In a similar manner, gravimetric deposition within the subbasin profile was calculated using particle percentages and bulk densities for the layers where significant changes in particle distribution occurred. The summation of the silt and clay masses were then used to estimate the average particle size distribution of the material deposited in the soil profile. Results indicated an approximate 50/50 percent distribution of silt and clay, leaving a portion of the clay load of the added water unaccounted for. The additional clay may have moved deeper into the profile in diluted and nondetectable quantities. The disparity may also be due to spatial and temporal variability unaccounted for by our measurement frequencies and methods. The calculated deposition profiles still agree substantially with the assertion that a greater portion of clay moved past the filter cake and into the subbasin profile.

Total sediment load was estimated for the duration of basin operation by integrating the product of flux times suspended solids load. An average "specific deposit" of 0.188 g/cm^2 (of basin floor) was estimated using infiltration measured at the basin intake. Divided by the average bulk density (1.22 g/cm3), an estimated filter–cake thickness of 1.54 mm was calculated. This is very close to the average measured (1.59 mm) thickness for the basin. This close agreement does not account for deeper deposition within the basin profile. Individual flow cells measured at tensiometer installations indicated calculated deposits of 0.15, 4.0, 1.2, and 2.05 mm (average 1.85 mm) allowing for penetration of as much as 31% of the sediment beneath the filter cake layer. Calculations made from the gravimetric silt and clay deposition budget described previously indicated a 40 % deeper deposition, with 60 % of the total sediment remaining in the surface filter cake layer.

Additional Observations

Crack Formation

As the water receded upon termination of the Fall 1986 test, cracks were observed in the basin floor. All cracks were observed in areas with corrugated surface left by the teeth of the shovel used to excavate the basin. Cracks were nearly always located in the troughs of the corrugations, and extended in the direction of the trough. Depth of cracks extended to 7.6 cm (3 inches) and resulted in deeper deposition of sediment (Fig. 29).

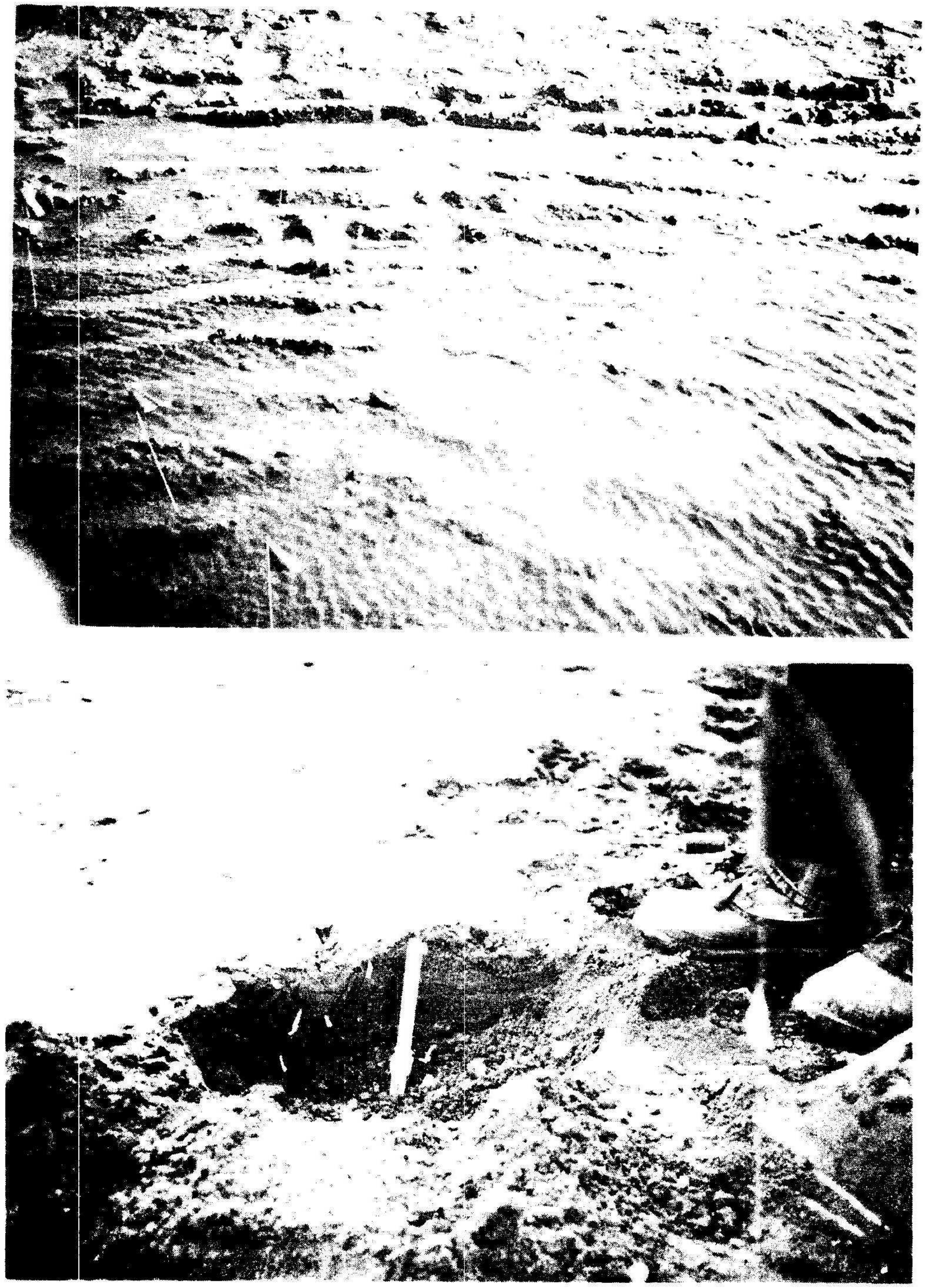


Fig. 29. Photo-illustration of basin floor cracks formed during the Fall 1986 test.

Reasons for the cracks are uncertain. Desiccation is ruled out because the cracks were observed before the water was removed from the basin. Jones et al. (1974) reported bottom cracking on a test facility in west Texas, and attributed increased infiltration rates to the presence of the cracks. Their basin, however, was built on caliche, and the cracks were thought to be due to the voids left by the dissolution of carbonates. In the Oakes test basin, there was no residual carbonate or gypsum in the vadose materials.

During later tests similar corrugated surfaces were left to examine the recurrence of the cracks. We were unable to repeat the cracking observed in the fall of 1986. In later cases, the surface layer of the basin was reconstructed by removal of the surface 38 cm (15 inch) and replacement with sand taken either from the original basin excavation, or from the similar materials taken from a supply pit excavated about 61 m (200 ft.) from the basin. It appears that the greater disturbance from relocation of the floor filter material , and possibly greater compaction resulting from heavy equipment used in moving the materials resulted in a degree of consolidation that would not allow for crack formation, even in corrugated areas. The observed cracking was most likely a product of a metastable structure in the surface materials caused by lofting during excavation of the basin. It is unlikely that the cracking would occur repeatedly over an extended cycle of basin operations. Overall influence of cracking on infiltration rates and depth of renovation would likely be small.

Variable Head

To examine the effects of head variation on infiltration rate, the 0.2 m (8 inch) gate valve was opened at 1730 h on October 20, 1986, and the basin water level was allowed to increase to 0.91 m (3 ft.). The result indicated an infiltration rate increase exceeding 1:1 proportionality with the new hydraulic gradient. Because the walls of the basin were covered with polyethylene, additional infiltration area was not added to the basin. It is considered most probable that scouring of the basin floor was induced by the turbulence of the increased discharge into the basin in the process of raising the water level. A visual increase in turbidity near the stilling basin had been noted during the period of increased discharge. Moreover, an area of scour was observed near the outlet from the stilling basin at the end of the test.

Summary – Fall 1986 Basin Operation

During 772 hours of operation 3040 cm (100 ft.) of water was recharged through the large basin. During 764 hours of operation 6035 cm (198 ft.) of water was recharged through the small basin. At individual flow cells within each basin considerable variability in hydraulic properties and infiltration rates was noted. Although perched ground–water mounds formed for short periods of time, they quickly dissipated, and the formation of a limiting surface layer quickly resulted in an unsaturated basin subsoil zone. Surface clogging comprised the major limitation to infiltration during this test.

Most (60 to 70%) of the total sediment was deposited in the filter cake layer above the basin floor. The remaining portion was deposited predominantly in the 5 cm layer immediately below the filter cake, resulting in an excess of 1% clay increase in that layer during a single operational period. Composition of the sediment added to the basin was approximately 70 % clay and 30% silt, while composition of the surface filter cake layer was predominantly silt. Deeper deposited sediment was proportionally higher in clay.

The greatest increase in hydraulic impedance was in the 0 to 8 cm layer, consisting of a 2 to 3 order of magnitude increase in impedance. Less marked increases in impedance (0 to 2) orders of magnitude were observed in the 8 to 23 cm layer, and in some cases a slight increase in impedance (0 to 1 order of magnitude) occurred in the deeper (23 to 38 cm) layer. Little effect was observed below 38 cm. Impedance changes below 8 cm were often transitory, occurring only at early times. This could indicate either differential clogging of large pores which dominate flow at early times, or temporary clogging due to air, carbon dioxide, or denitrification gas bubble entrapment. Because deeper clogging occurs very early and ceases as the surface filter–cake layer begins to dominate, it is thought likely that minor particulate clogging of large pores is occurring. The level of particulate clogging, however, is nondetectable within the sensitivity of our soil samples, and there is insufficient evidence to be certain that more transient nonsediment clogging mechanisms are not involved.

Although cracking of the basin floor occurred and may have influenced recharge rates and depths of sediment deposition, it is considered unlikely that cracking would play a significant role in enhancing or decreasing recharge over long and extended cycles of basin operation.

OPERATION 2 : MAY 4 TO JULY 11, 1987

(Spring Sediment Load + Desiccation + Variable Head)

The principal objectives for the operation of the test basin in the spring of 1987 were: 1) to assess the nature and extent of attenuation of infiltration caused by application of turbid water from the James River under spring sediment load conditions; 2) to evaluate the degree of renovation affected by a period of drying and desiccation between successive operational periods; 3) to evaluate the effectiveness of varying the ponded depth of the basin in increasing recharge rates; and 4) to evaluate the depth and extent of sediment clogging under spring conditions.

Only the large basin was operated during this test, because the Fall 1986 experiment had indicated that a fully saturated vadose zone caused by water table or perched ground–water mounds was not attainable on the 232 m^2 (2500 $ft.^2$) facility. Operation of two basins was considered to be repetitious.

Renovation and Preparation

Following winter freeze and thaw and spring rainfall, the filter cake was not discernible as a distinct layer in the spring. It was assumed to have dispersed and mixed with the basin floor materials. In order to compare spring and fall recharge a complete renovation of the basin floor was undertaken. The top 38 cm (15 inches) were removed and replaced with the deepest soil excavated during basin construction. Some of the new surface layer was of finer texture than the fall surface materials. In addition, greater equipment trafficking during removal and replacement resulted in areas of localized compaction beneath the basin surface. On the other hand, the slightly natural clay content in the NE quadrant of the basin prior to the fall operation was removed during the process of renovation.

After instrument placement and calibration, final preparation of the basin floor was similar to that of the fall experiment. Areas compacted under foot were loosened with a spade, and the basin floor was raked and smoothed, except for two small areas left in corrugated condition to test for crack formation.

Hydraulic Parameters

Infiltrometer and tensiometer installations were placed at four positions within the basin (Fig. 30). Locations were chosen close to the fall measurement sites, but were slightly offset to prevent disturbance from the scars of the deeper tensiometers used the previous fall. In–situ unsaturated hydraulic conductivity was determined for each site in the same manner described for the Fall 1986 experiment. Tensiometers and the inner ring of the infiltrometer were left in place for in–situ monitoring during spring basin operation.

Soil and Water Samples

The soil sample plan was revised for the spring experiment in order to minimize potential effects of soil spatial variability. Instead of four widely separated sampling areas, with one sample taken from each before and after basin operation, two larger sample areas were designated (Fig. 30). From each sample area four pairs of samples were taken for each depth designated in Table 8. Each sample pair consisted of two 7.6 cm (3 inch) Gidding probe tube samples. Sample pairs were combined and mixed according to depth. Each of the four sample pairs was separated by a space reserved for similar samples

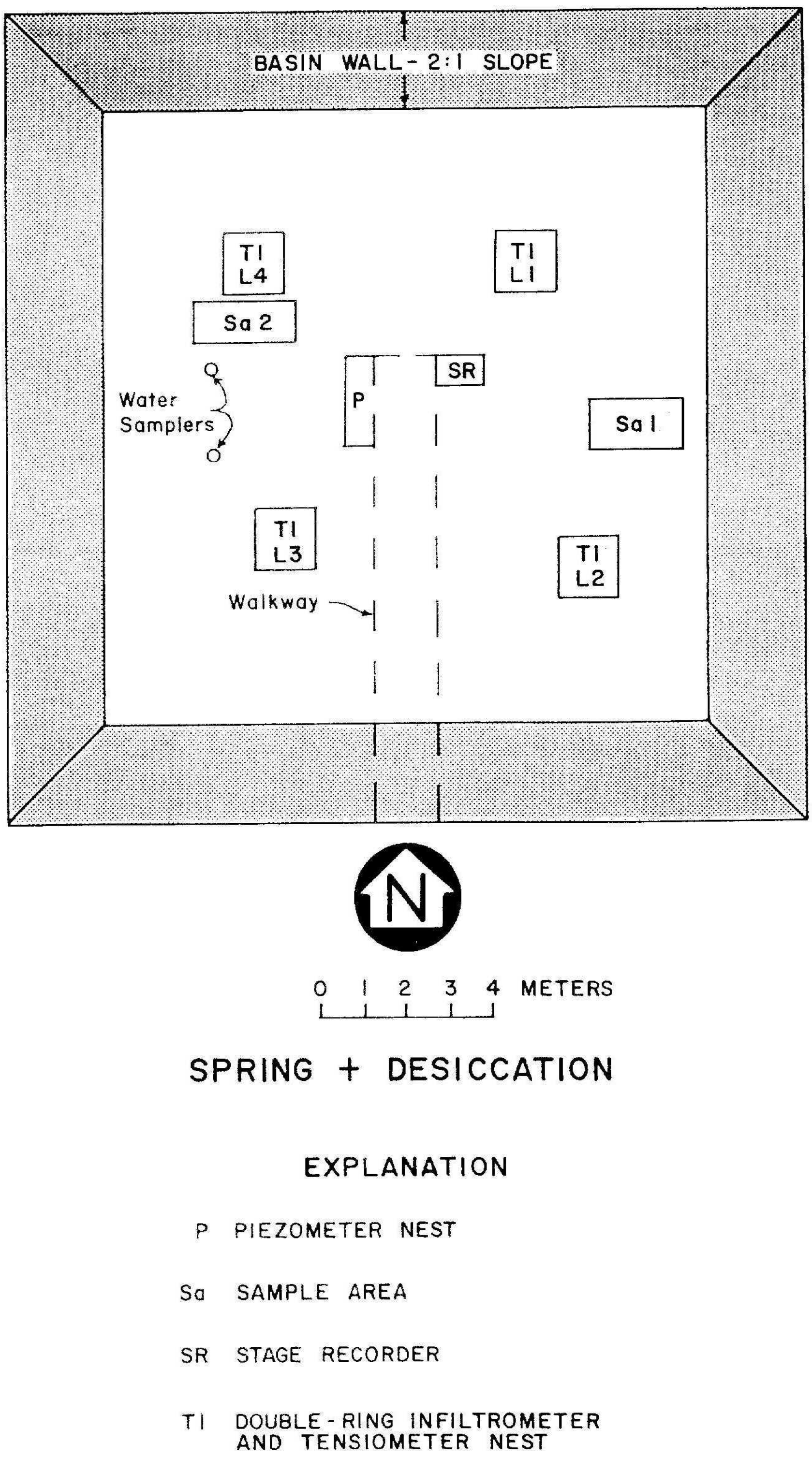


Fig. 30. Spring 1987 large basin sampling and instrumentation layout.

Table 8. Basin floor laboratory samples taken for the Spring 1987 experiment.

LABORATORY SAMPLES (SPRING + DESICCATION)

Depth (cm)	Particle Size		Organic Carbon		Moisture Retention (10-120 cm)		Bulk Density	
	T	N	T	N	T	N	T	N
0.0 - 1.3	B/A	8	B/A	8	----		----	
1.3 - 2.5	B/A	8	B/A	8	----		----	
2.5 - 5.1	B/A	8	B/A	8	----		----	
5.1 - 7.6	B/A	8	B/A	8	----		----	
7.6 - 22.9	B/A	8	B/A	8	----		B	4
22.9 - 38.1	B/A	8	B/A	8	----		B	4
38.1 - 53.3	B/A	8	B/A	8	----		B	4
0.0 - 7.6	----		----		----		B	4
Suspended Solids	D	4	----		----		----	
Filter Cake	A	1	----		----		A	1

T = Time N = Number of Samples
B = Before Operation A = After Operation D = During Operation

to be taken after the basin experiment, so that paired comparisons between initial and final values could be made using Student's t statistic (Snedecor and Cochran, 1967). Particle size and organic carbon were determined on eight samples each for preliminary and final basin floor conditions. Sample comparisons were for the combined spring operation and the period following desiccation. During the period of desiccation no trafficking of the basin floor was allowed, in order to test the renovating effects of natural desiccation alone – without tillage, surface removal, or any other disturbance.

A paired comparison of bulk density before and after basin operation was not made for the spring experiment. Four sets of bulk density samples were taken – two from each of the two major sampling areas – to assess the initial state of compaction of the basin floor following renovation. A comparison of laboratory soil moisture characteristics was not undertaken for the spring experiment.

The schedule of water samples for suspended solids was intensified. For the first five days one sample was taken. Thereafter, a sample was taken every 2nd day for the duration of the spring experiment. The sample frequency was then increased to one per day for the entire period of operation following desiccation. Water samples for determination of sediment particle size distribution were taken as indicated on Table 9.

Condition of the Basin Floor

Because of the additional equipment traffic from removal and replacement of the basin floor soil, the basin was harrowed to an approximate 23 cm (9 in.) depth. As for the Fall 1986 test, additional trafficking during preparation and sampling was avoided. Final grooming consisted of hand spading to loosen the soil in compacted areas and hand raking to remove any large cracks. For the Spring 1987 test, corrugations formed during the final harrowing were removed from most of the basin floor. A few corrugated areas were left to further investigate the cracking phenomenon observed during the Fall 1986 test. Following completion of the Spring test, the basin was allowed to dry and crack for 10 days, before

Table 9. Grain-size distribution for the basin-floor filter cake and for suspended solids delivered to the large basin during the Spring 1987 + Desiccation test.

SPRING + DESSICATION EXPERIMENT 1987

FILTER CAKE SAMPLES No.	SUSPENDED LOAD SAMPLES Date
1 SILT 53% CLAY 47% OC 3.96%	05/04/87 31% SILT 69% CLAY 05/11/87 35% SILT 65% CLAY 05/19/87 30% SILT 70% CLAY 05/26/87 31% SILT 69% CLAY
	$\overline{\text{SILT}}$ = 32% SD = 2.2 $\overline{\text{CLAY}}$ = 68% SD = 2.2 N = 4

CRUST/CLAY SEDIMENT RATIO 0.69
OC = ORGANIC CARBON

initiation of a second test operation. The condition of the basin floor following desiccation is illustrated on Figures 31 and 32.

Basin Operation

Water was first delivered to the basin at 15:10 hours, May 4, 1987. Water level control, and tensiometer and piezometer measurement frequencies were the same as used during the Fall test. By 16:08 hours, the 0.61 m (2 ft.) control level for the basin was reached. Between 13:50 h on June 1 and 12:00 h on June 5, variable head tests were conducted to assess the basic depth effect on infiltration rate. The spring operation was completed June 5, 1987. Residual water was then pumped from the facility, and the basin floor was allowed to desiccate naturally until June 15. During the desiccation period no rainfall occurred to disperse the crust. Also, no trafficking of the basin floor was allowed. Only a few small crust samples taken near the edge of the basin were removed from the basin floor.

Following desiccation, water was again pumped to the basin beginning at 14:45 h on June 15, 1987. At 15:30 hours, however, electric power to the pump was shut off by the power company. Power was restored at 17:45 h (before the basin fully drained) and by 18:45 h the 0.61m (2.0 ft.) control level for the basin was reached. From 12:45 h on June 22 to 08:35 h on July 11, the ponded depth of the basin was varied. It was first allowed to decrease to 0.46 m (1.5 ft.), and steady–state discharge was measured. The water level was then increased to 0.76 m (2.5 ft.) and steady–state discharge was again measured. Water delivery was stopped on July 11, following 26 days of basin operation.

RESULTS

For the spring test, recharge through the large basin, as measured at the intake, began at 44 cm/hr (34 ft./d) and declined to a minimum of 0.28 cm/h (0.22 ft./d) after 596

Fig. 31. Photo-illustration of spatial differences in crust deposition following the Spring 1987 test.

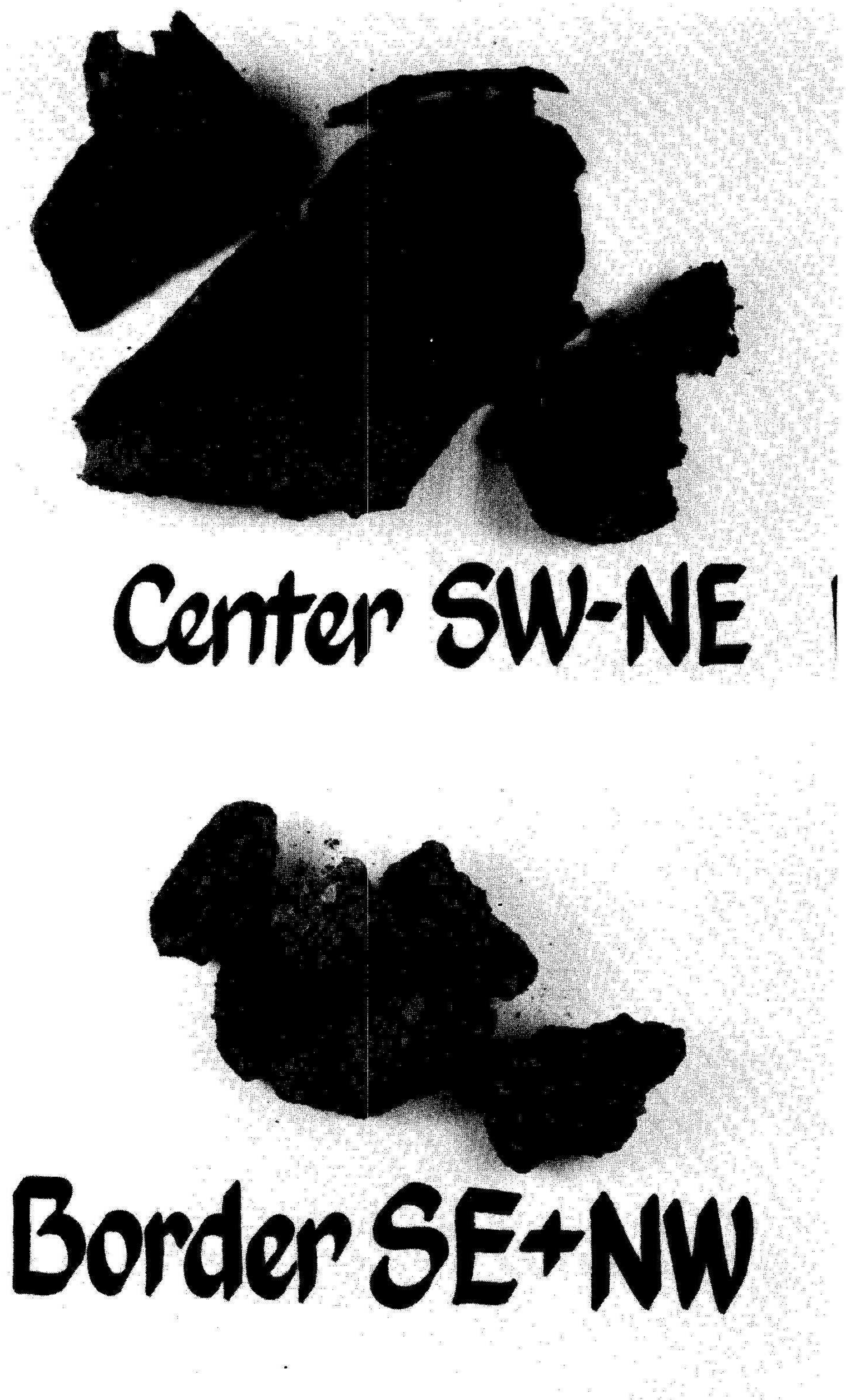


Fig. 32. Detailed photo-illustration of spatial differences in crust deposition following the Spring 1987 test.

hours. The increased recharge during the late phase of operation shown on Figure 33 is due to a combination of increased depth of water in the basin, and disturbance of the basin floor caused by turbulence from sudden increase in discharge into the basin during the raising of the water level. The total amount of recharge at 596 hours was 2490 cm (81.7 ft.), while at the time of termination (765 hours) it was 2660 cm (87 ft.).

Recharge for the second Spring basin operation, following the 10 day desiccation period, is also shown on Figure 33. The initial rate of recharge, measured at the intake, was 28 cm/hr (22 ft./d). To investigate the effects of variable basin depth, the basin inlet was temporarily closed after 163.5 hours of operation, and the water level was allowed to decrease to 0.46 m (1.5 ft.). The minimum infiltration rate, reached at 253 h, was 0.233 cm/h (0.182 ft/d.). After 253 h the basin water level was increased to 0.88 m (2.94 ft.). Discharge to the basin was then set to allow for a gradual decrease in water level throughout the remainder of the test. The total recharge at 253 hours was 1040 cm (35.43 ft.). Final total recharge at 529 hours was 1200 cm (39.4 ft.).

From Fig. 33 it is clear that only a partial recovery of the basin capacity was effected by the period of desiccation. Except for the brief increase in infiltration rate caused by the rising head, experiment recharge rates were lower following desiccation than they were for comparable times during the Spring operation. A summary comparison of total recharge for Spring and post–desiccation operational periods is found in Table 10. At any given time, after about 24 hours, post–desiccation total recharge was half that effected by the initial Spring test through a fully renovated basin.

Water levels measured at piezometer TPL1–A indicated that a perched ground–water mound formed after about 50 minutes during Spring basin test, and peaked at a height of 0.61 m (1.99 ft.) after 172 minutes of operation. The perched ground–water mound was totally dissipated after about 20 hours. Since the mound did not reach the basin floor, it did not comprise a significant limit for infiltration rates. As during the Fall 1986 test, the perched ground–water mound was confined to the soil volume beneath the

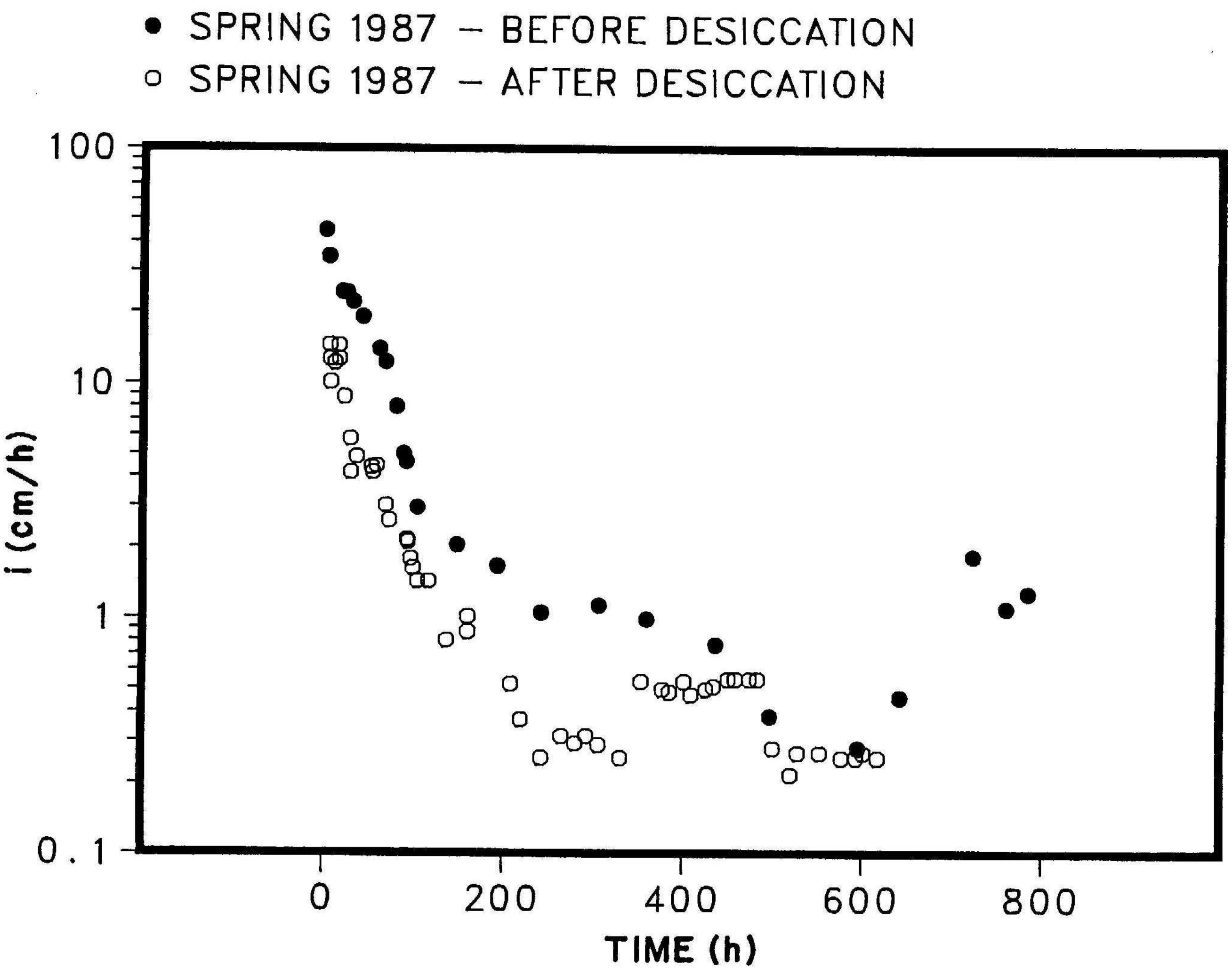


Fig. 33. Infiltration rate as measured at the basin intake for the Spring, 1987, test before and after natural renovation by desiccation.

Table 10. Comparison of Spring 1987 cumulative infiltration before and after natural desiccation

SPRING 1987 (Fully Renovated vs. Desiccation)

Time (h)	* Des. Recharge (cm)	** FR Recharge (cm)	Des./FR
24	579	795	.73
48	742	1390	.53
71	881	1700	.52
96	947	1880	.50
120	987	1980	.50
144	1020	2070	.50
168	1040	2120	.49
192	1060	2170	.49
216	1070	2210	.49
240	1080	2240	.48

* 10 day Desiccation
** Fully Renovated Basin Floor

basin. Tensiometers indicated that the 8 cm depth was unsaturated within 30 hours; the 38 cm depth was unsaturated within 8 hours; and the 53 cm depth was unsaturated within 6 hours of the initiation of water delivery to the basin. Clogging of the surface layer quickly became the limiting factor for infiltration.

For the post–desiccation basin experiment, the pump was temporarily shut off after 45 minutes of operation. As a result, the growth of the perched ground–water mound was much more subdued, compared with previous tests. The maximum height of the perched ground–water mound was 7.0 cm (0.23 ft.) after 4.2 hours of operation. Tensiometer data indicated that saturated conditions were never reached between the basin floor and the 53 cm depth.

Spatial Variability

Following the first spring operational period, it was clear that crust deposition varied considerably over the area of the basin (Fig. 31). Two areas of the basin floor were discernible: 1) an area of well defined and relatively thick (2 mm) crust extended diagonally from the stilling basin to the northeast corner of the basin. This area exhibited extensive curling and breaking in the filter cake during desiccation; and 2) an area of poorly defined, thin crust occupied the northwest and southeast portions of the basin. In the thin crust area, the filter cake did not separate easily from the soil beneath it. Rather, the surface crust broke off as a cemented briquette of sand, bonded by surface sediment. The two crust characteristics are compared in Figure 32. The four tensiometer nests all exhibited the second type of crust.

A comparison of recharge measured at the intake, and at each of the four tensiometer nests is illustrated on Figures 33 and 34. With the exception of site L2, which is close to the intake determined recharge curve, all of the tensiometer sites indicate greater declines in infiltration rates. Due to the thinness of the crust, it is unlikely that lower infiltration rates compared with values measured at the basin intake, were caused by greater sediment deposition. Rather, the evidence suggests that the thinner crust deposition was due to lower initial infiltration rates in those areas, resulting in lower rates of filtration. The formation of the briquettes (Fig. 32) was likely the result of deeper cementation promoted by a lack of surface sealing in areas of slow infiltration.

A comparison of infiltration before and after desiccation for each of the tensiometer sites is shown on Fig. 34. At each of the sites, post–desiccation infiltration rates were lower than spring rates. However, little difference was noted at early times. For the first 200 hours recharge rates were similar. After 200 hours, post–desiccation infiltration decreased at a greater rate than in the Spring test. This is dissimilar from the overall basin behavior as determined at the basin intake (Fig. 33) where differences were observed at early operation times.

The differences in basin floor hydraulic properties in this instance were most likely due to renovation methods. Soils replaced on the basin floor during renovation were taken from the excavation spoil removed during construction. During restoration it was noted that some of the materials taken to the basin were of finer texture than those previously comprising the basin floor. In addition, more of the spoil had been deposited on the outer areas of the basin.

Physical Data

Particle–size and organic–matter data for soil samples taken before and after Spring + Desiccation experiments are summarized on Tables 11 and 12. A significant increase in clay content occurred at 0.0 to 1.3 cm and at 5.1 to 7.6 cm. A likely gradational increase between the two layers is indicated by an increase in clay ($P < 0.07$) at the 1.3 to 2.5 cm layer. A significant decrease in silt content ($P < 0.05$) is indicated for the 1.3 to 2.5 and 5.1 to 7.6 cm layers. The decreasing silt percentage is likely the result of the relative increase in clay content.

Organic carbon data (Table 12) indicated no significant ($P < 0.05$) increase for any

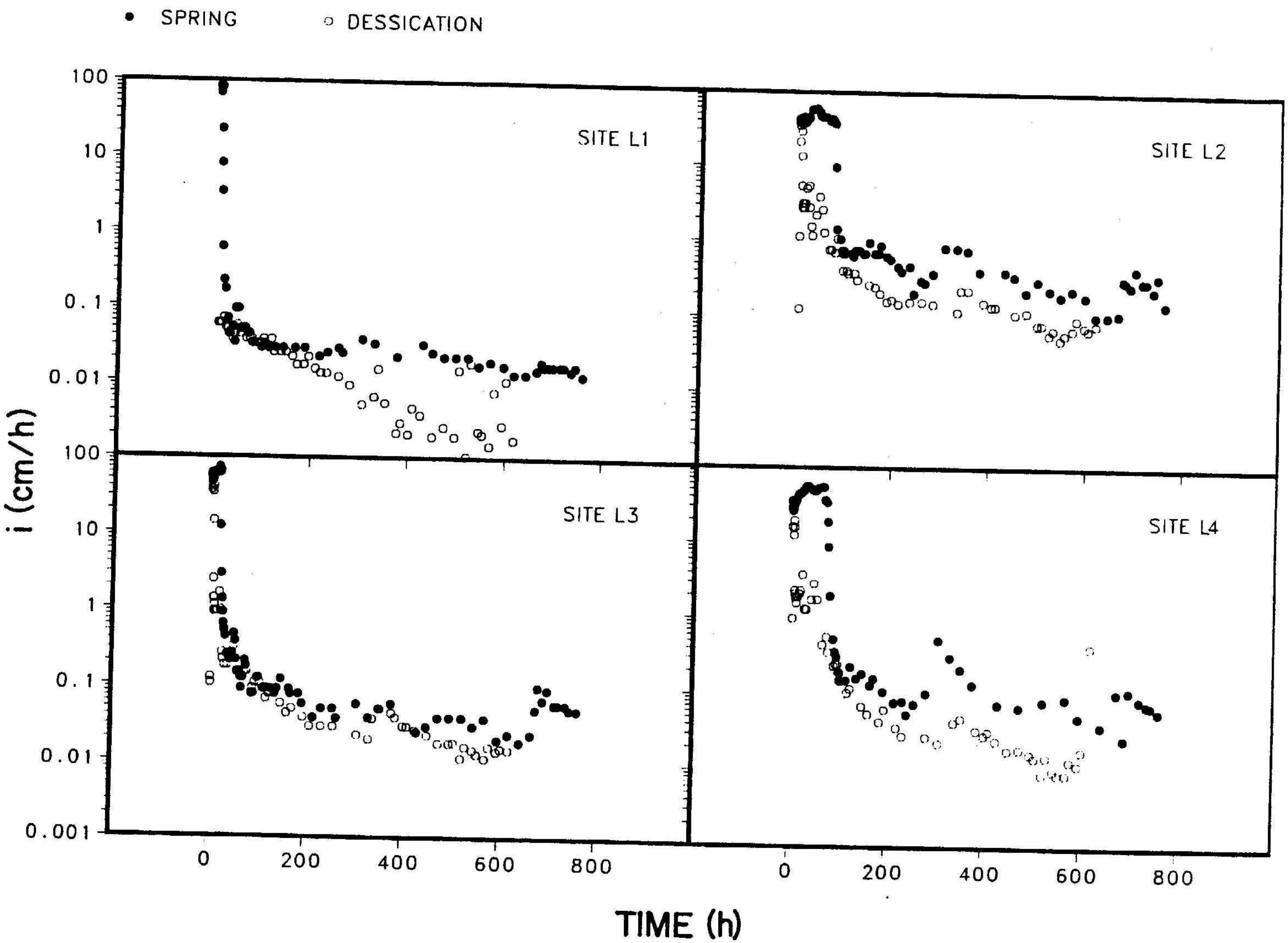


Fig. 34. Infiltration rate measured at in–situ basin positions L1, L2, L3, and L4 during the Spring 1987 test before and after natural renovation by desiccation.

Table 11. Basin subsoil grain-size distribution changes (% clay and % silt) before and after the Spring + Desiccation 1987 test (N=8).

SPRING + DESICCATION 1977

Percent Clay Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	+ 1.38	0.421	3.29	0.01
1.3 - 2.5	+ 0.85	0.379	2.23	0.07
2.5 - 5.1	+ 0.56	0.386	1.45	NS
5.1 - 7.6	+ 0.80	0.224	3.57	0.01
7.6 -15.2	- 0.08	0.531	0.14	NS
15.2 -22.9	+ 0.51	0.425	1.20	NS
22.9 -38.1	- 0.50	0.335	1.49	NS
38.1 -53.3	- 1.25	0.755	1.66	NS

Percent Silt Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	- 0.20	0.313	0.64	NS
1.3 - 2.5	- 0.75	0.662	2.46	0.05
2.5 - 5.1	- 1.49	0.429	1.45	NS
5.1 - 7.6	- 0.61	0.412	2.45	0.01
7.6 -15.2	- 1.99	0.810	0.14	NS
15.2 -22.9	- 0.83	1.08	0.76	NS
22.9 -38.1	- 2.01	1.13	1.77	NS
38.1 -53.3	- 3.14	0.63	5.02	NS

SE = Standard Error
P = Probability Level
t = Student's t

Table 12. Basin subsoil organic carbon changes before and after the Spring + Desiccation 1987 test (N=8).

SPRING + DESICCATION 1977

Percent Organic Carbon Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	+ 0.056	0.028	1.99	NS
1.3 - 2.5	+ 0.041	0.024	1.79	NS
2.5 - 5.1	- 0.003	0.031	0.10	NS
5.1 - 7.6	- 0.031	0.024	1.29	NS
7.6 -15.2	- 0.080	0.038	2.10	NS
15.2 -22.9	+ 0.065	0.094	0.69	NS
22.9 -38.1	- 0.003	0.044	0.00	NS
38.1 -53.3	- 0.048	0.066	0.73	NS

SE = Standard Error
P = Probability Level
t = Student's t

layer of the basin subfloor. This is noted despite the overall warmer temperature regime afforded by May, June, and July operations, compared with the cool, and sometimes freezing temperatures of the previous fall. Algae growth had been observed during both spring and post–desiccation operations.

Bulk density measurements indicated that compaction was not greater than for the Fall 1986 operation. The spring 0 to 7.6 cm layer averaged 1.46 g/cm3 compared with 1.56 for fall. At 8 to 23 cm (3 to 9 inch) bulk density averaged 1.39 compared with a fall density of 1.59. At 23 to 38 cm (9 to 15 inch) spring density averaged 1.5 compared with 1.61 for fall. The 38 to 53 cm (15 to 21 inch) bulk density was 1.34 compared with a fall value of 1.54. The 38 to 53 cm low bulk density was caused by the presence of a thin layer of detrital lignite. Two samples containing the lignite had densities as low as 1.10 and 1.13 g/cm3. The standard error (SE = 0.259) was much higher for the bottom layer than the overlying three layers (SE = 0.11, 0.037, and 0.061 respectively, from the surface).

Suspended Load and Filter Cake Formation

The weighted–mean suspended solids delivered to the basin for the spring experiment was 50.4 mg/l (maximum = 71 mg/l, minimum = 31 mg/l) while during the post–desiccation experiment it was 47.25 (maximum = 129 mg/l, minimum = 7 mg/l). This compares with 61.8 mg/l (maximum = 74 mg/l, minimum = 12 mg/l) for the fall of 1986. The weighted means were calculated by dividing the total sediment load delivered to the basin (Eq. 7) by the total cumulative flux through the basin floor. These indicate that suspended solids did not vary much during the Fall 1986 and Spring 1987 tests for 1986 and 1987.

The particle composition of the suspended solids is shown on Table 9. Clay was 68 % and silt was 32%. This compares with 77% clay and 23 % silt for the fall of 1986. The spring load was slightly higher in silt percentage, but variation was less than 10 %. The higher clay content for the Fall 1986 measurements may have been due to repairs on a highway bridge 1 1/2 miles upstream at Oakes, which caused considerable movement of bank materials and agitation of the water.

The single filter–cake sample taken indicated 53% silt content and 47% clay. As in the fall, the filter–cake layer contained a higher percentage of silt than the turbid recharge water, indicating deeper movement of clay into the subbasin soil profile. This is supported by basin subsoil physical data which indicated significant movement of clay, but no increase in silt beneath the filter cake.

Clogging of the Basin Profile

Site L1 May 4 to June 5

The hydraulic gradient data indicate that clogging occurred in the 8 to 23 and 23 to 38 cm layers from initial times to as late as 35 hours (Fig. 35). Thereafter, gradients began to decrease in response to clogging in the surface layer. The surface layer hydraulic gradient increased steeply to 65 hours and then leveled off. The increased gradient near the end of the experiment was due to the increased ponded depth in the basin which was varied to study the effects of basin stage on infiltration rates.

The impedance ratio data indicate that considerable clogging of the 8 to 23 and 23 to 38 cm layers occurred at early times, resulting in impedance values as much as 5000 times those measured prior to basin operations (Fig. 36). Clogging was transitory, however, and after 100 hours of operation impedance below 8 cm was identical to that measured before basin operation. This data indicates that clogging was either transitory, resulting from early gas bubble entrapment, or that sediment clogging was occurring only in the larger faster flowing pores, and was prevented from entering the smaller pores either through filtration near the surface, or from slower velocities within those pores. The surface layer (0 to 8 cm) impedance increased by 3 orders of magnitude between initiation and 65 hours of operation. Clogging of the surface layer was permanent.

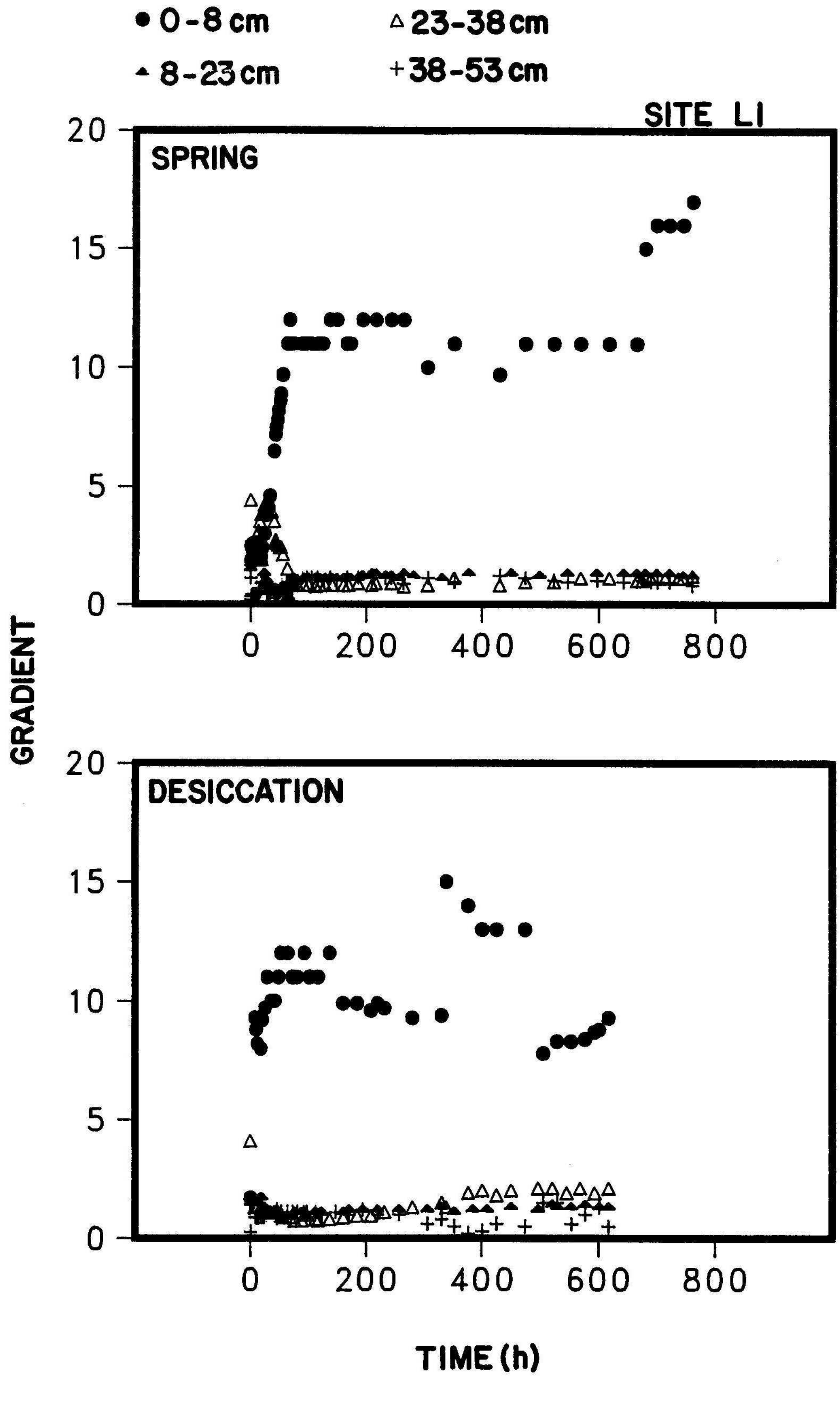


Fig. 35. Hydraulic gradient measurements for site L1 during the Spring 1987 test and following desiccation.

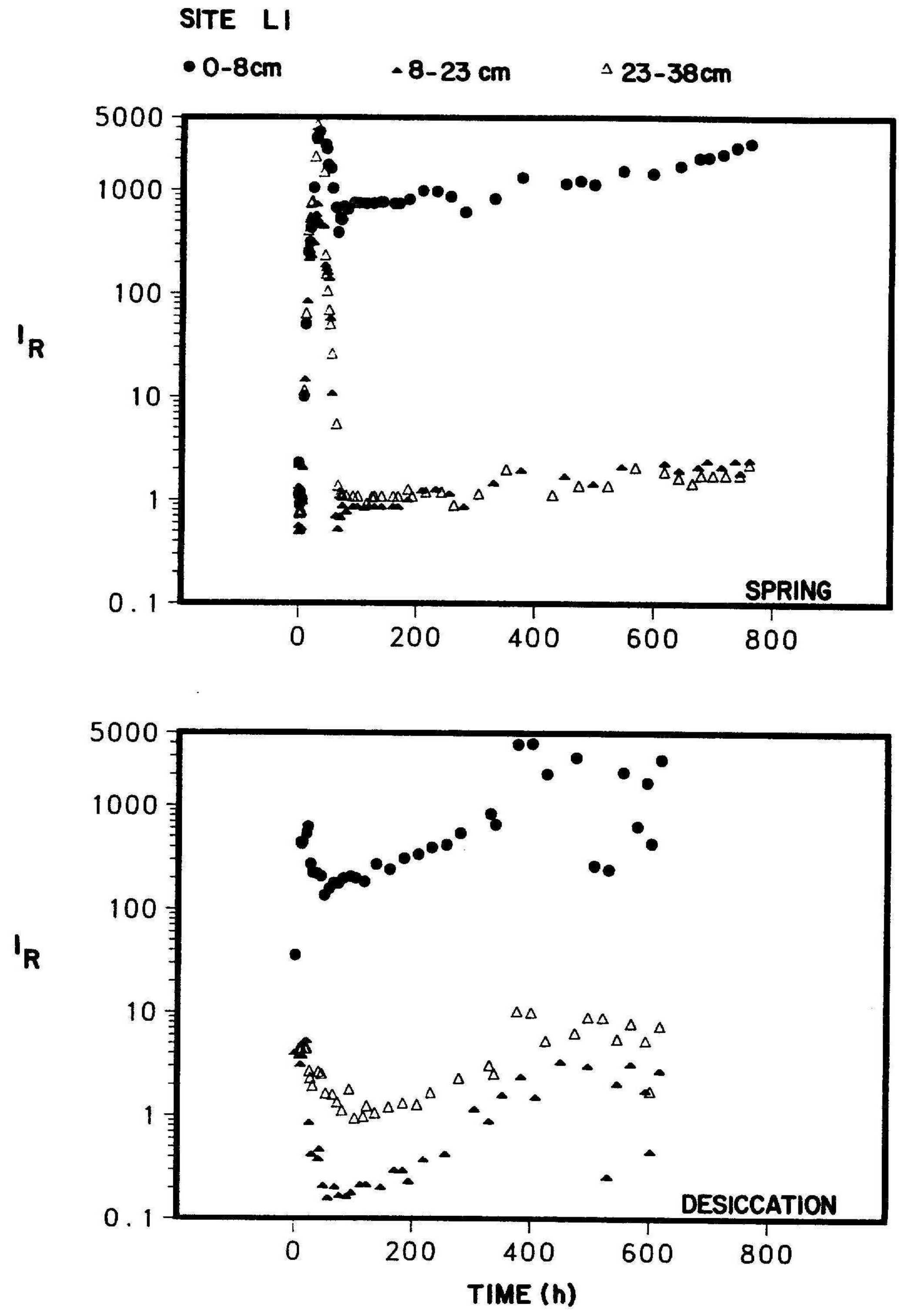


Fig. 36. Impedance ratio measurements for site L1 during the Spring 1987 test and following desiccation.

Site L1 After Desiccation June 15 to July 11

The hydraulic gradient data (Fig. 35) indicate that after desiccation the surface layer reclogged quickly, and that the recovery due to desiccation was short lived. For subbasin layers deeper than 8 cm, however, no clogging is indicated. This indicates substantial recovery during the desiccation period. The variable (decreasing, then increasing) hydraulic gradient for the surface layer following 163.5 hours of basin operation was caused by deliberate changes in ponded depth, used to evaluate the effects of basin stage on infiltration rate.

The I_R data (Fig. 36) indicate that some slight residual clogging (less than one order of magnitude) remained for the 23 to 38 cm layer, but that recovery was substantial.

Site L2 May 4 to June 5

The hydraulic gradient data (Fig. 37) indicate that no clogging occurred below 23 cm and that very slight clogging occurred in the 8 to 23 cm layer as late as 50 hours following the beginning of the experiment. The hydraulic gradient of the surface layer (0 to 8 cm) responded little during the first 40 hours, but increased steeply between 40 and 75 hours (Fig. 37). The increased hydraulic gradient near the end of the test was due to increased ponded depth in the basin, which was varied to study the effects of basin stage on infiltration rate.

The surface layer impedance (Fig. 38) approached 4000 times initial nonclogged impedance. Early clogging in the 8 to 23 cm layer resulted in increased impedance throughout the range of suctions reached during the period of basin operation. Impedance values for the 8 to 23 cm layer approached 100 times initial nonclogged values. Little clogging was indicated in the 23 to 38 cm layer.

Site L2 After Desiccation June 15 to July 11

An immediate increase in the 0 to 8 cm hydraulic gradient (Fig. 37) indicates that recovery during desiccation was only partial. The hydraulic gradient increased more

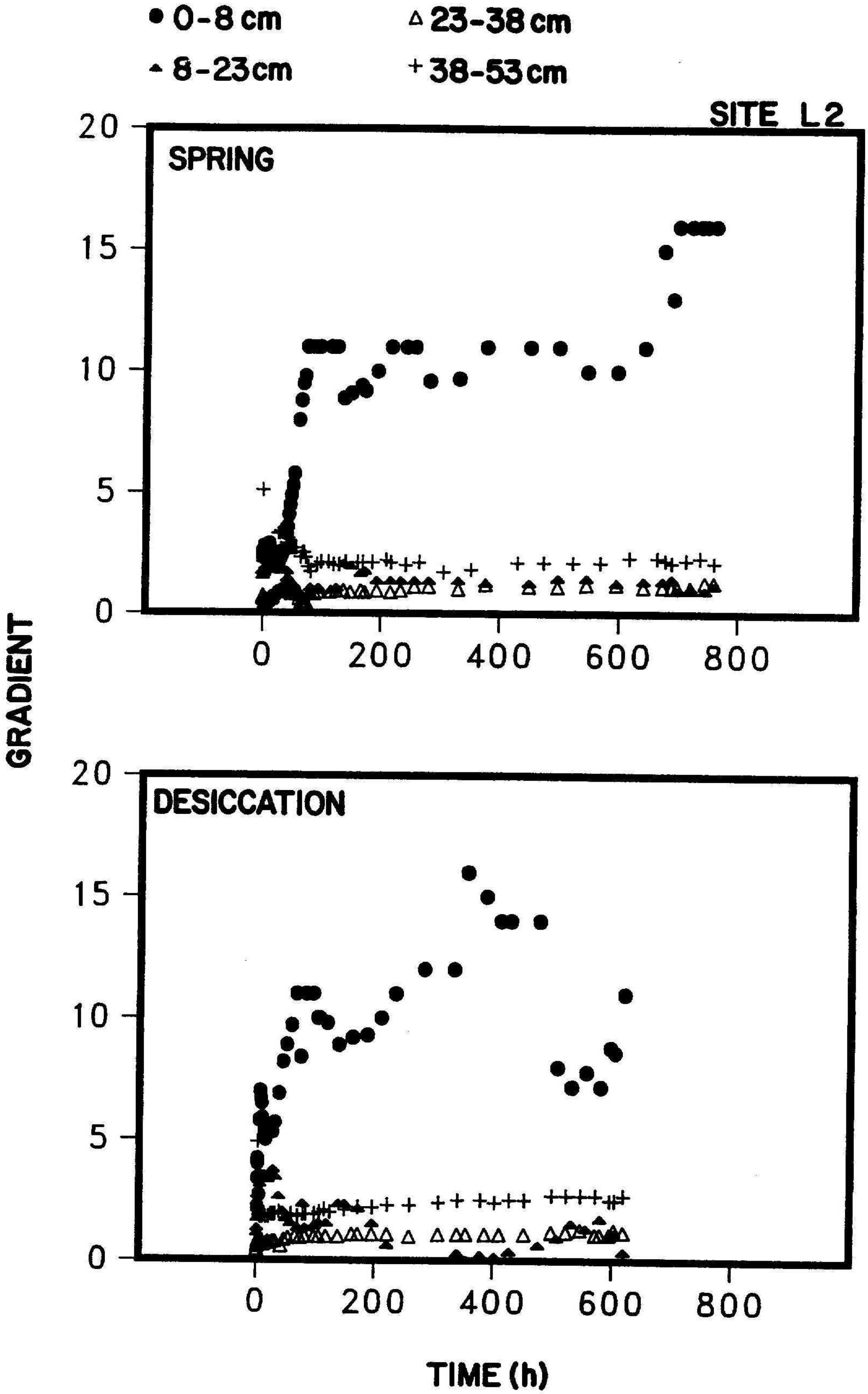


Fig. 37. Hydraulic gradient measurements for site L2 during the Spring 1987 test and following desiccation.

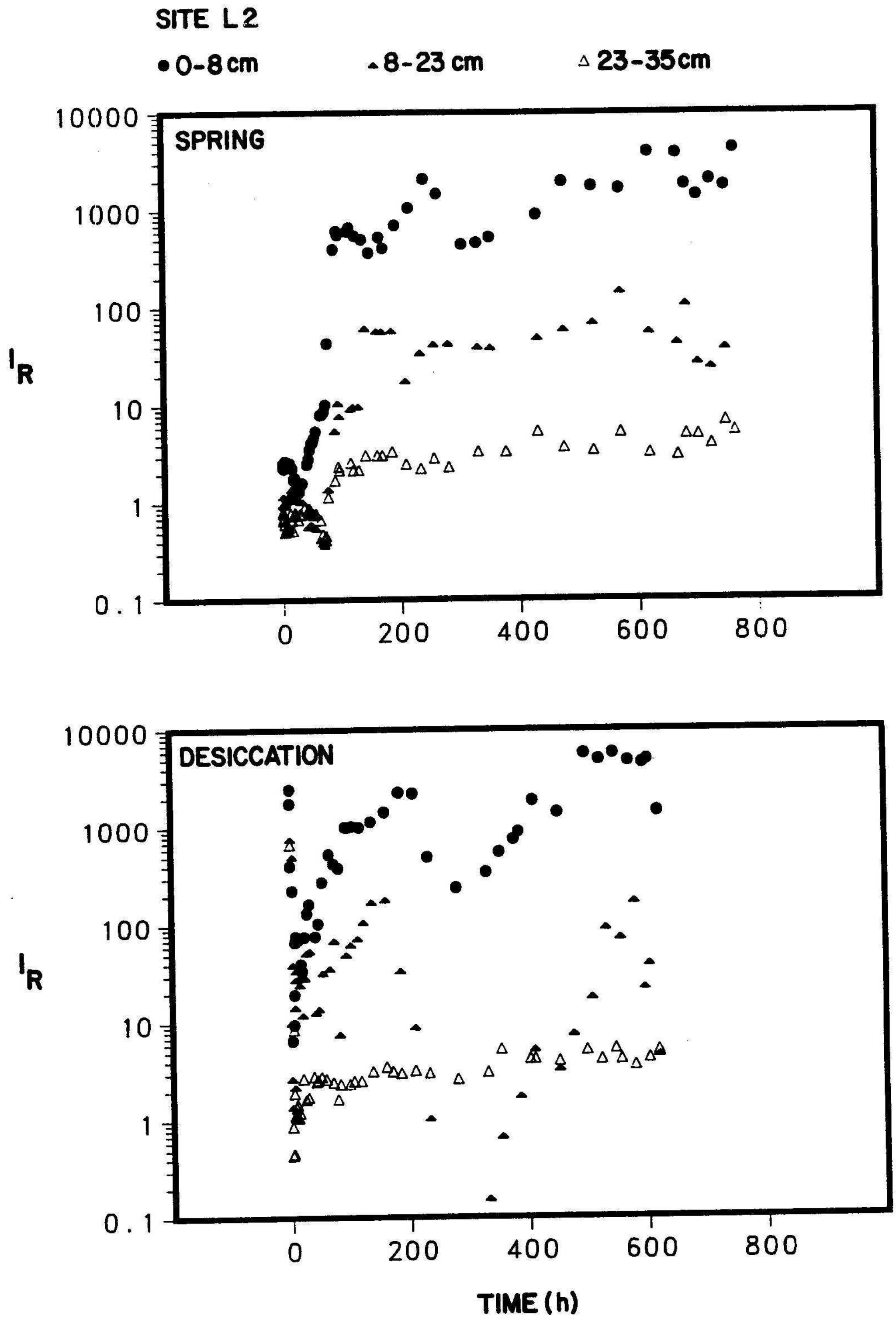


Fig. 38. Impedance ratio measurements for site L2 during the Spring 1987 test and following desiccation.

steeply during early times, and reached a higher final value than was observed during the spring test. No clogging of the layers below 8 cm was indicated. The variable (decreasing, then increasing) hydraulic gradient for the surface layer following 163.5 hours of basin operation was caused by deliberate changes in ponded depth, used to evaluate the effects of basin stage on infiltration rate.

The extent of immediate clogging for the 0 to 8 cm layer (Fig. 38) resulted in impedance ratios two orders of magnitude greater than pre-experimental values. Resealing of the surface occurred quickly after desiccation, and eventually I_R reached 1000 times pre-experimental values. The second layer also indicated little recovery from desiccation, and quickly reached I_R values of nearly 100. Between 200 and 400 hours, a disturbance of the 0 to 8 cm and 8 to 23 cm layers was indicated. The nature of the disturbance is not known. It is possible that the tensiometer comprising the boundary between the two layers was not functioning properly. No change in impedance was indicated for the 23 to 38 cm layer.

Site L3 May 4 to June 5

Slight hydraulic gradient increases (Fig. 39) were indicated at early times for 8 to 23 and 23 to 38 cm layers, but within 10 hours sealing of the surface layer dominated the changes in hydraulic gradient within the basin subsoil profile. The 0 to 8 cm layer reached maximum hydraulic gradient within 50 hours. Slight increase near the end of the spring experiment was caused by increasing the depth of water in the basin.

The impedance ratio data (Fig. 40) indicated no clogging below 23 cm. The 0 to 8 and 8 to 23 cm layers clogged quickly , reaching approximate equilibrium impedance values within 50 hours of operation. The surface layer impedance approached 20,000 to 30,000 times initial pre-experimental values. Clogging at 8 to 23 cm resulted in impedance values approximately 10 times pre-experimental values. Clogging at 8 to 23 cm was not transitory, and remained approximately uniform throughout the period and suction range

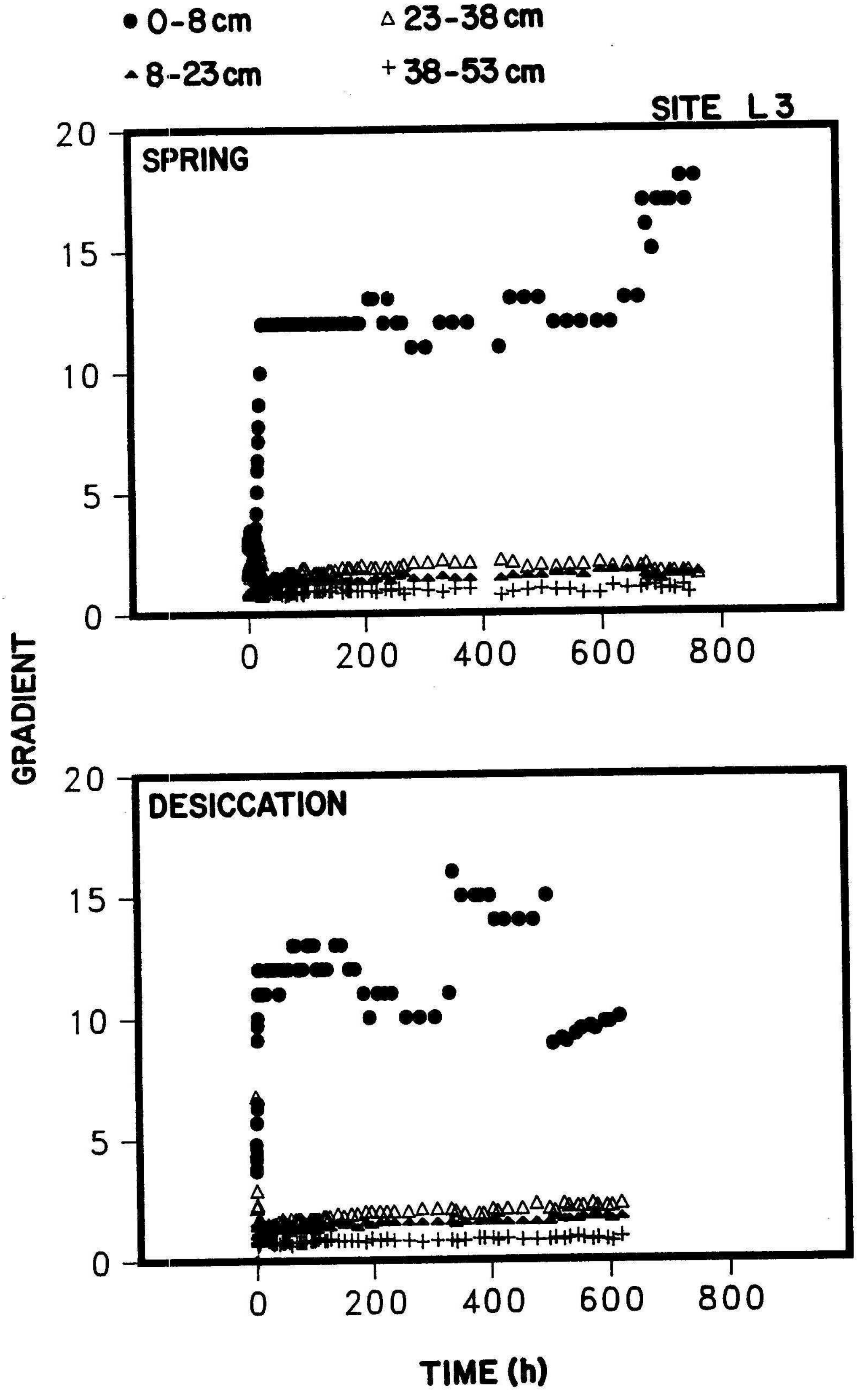


Fig. 39. Hydraulic gradient measurements for site L3 during the Spring 1987 test and following desiccation.

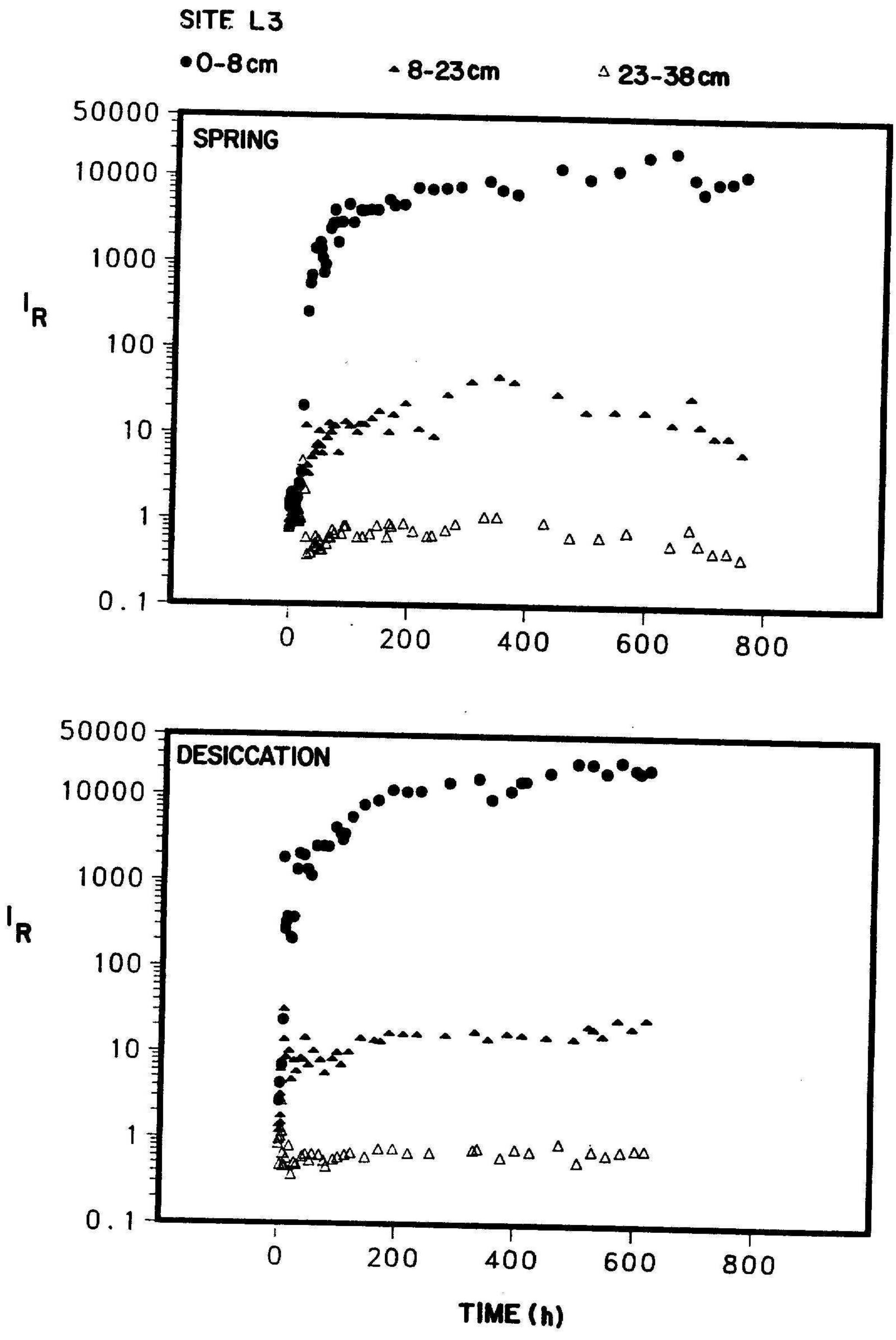


Fig. 40. Impedance ratio measurements for site L3 during the Spring 1987 test and following desiccation.

of the basin experiment.

Site L3 After Desiccation June 15 to July 11

The hydraulic gradient for the 0 to 8 cm layer (Fig. 39) increased at a greater rate following desiccation than during the initial spring operation. Increasing gradients for the 8 to 23 cm and 23 to 38 cm layer were not observed, but would tend to be masked, since a quickly rising gradient for an overlying layer would depress the gradients of underlying layers. The variable (decreasing, then increasing) hydraulic gradient for the surface layer following 163.5 hours of basin operation was caused by deliberate changes in ponded depth, used to evaluate the effects of basin stage on infiltration rate.

The impedance ratio data (Fig. 40) indicated a fast rise to an I_R of 2000 followed by a more gradual rise in I_R, reaching as much as 40,000 times pre–experimental values. Both the rate of initial rise and the final impedance ratio reached indicate a faster and more extensive sealing of the surface layer following desiccation than during the pre–desiccation Spring test. It is evident that partial recovery was achieved, but that resealing of the surface layer proceeded quickly. The 8 to 23 cm layer indicated no recovery. I_R values of 10 times pre–experimental impedance were immediately present upon initiation of recharge following desiccation.

Site L4 May 4 to June 5

The hydraulic gradient data (Fig. 41) indicates a slight early (0 to 50 hour) clogging of the control layer (38 to 53 cm), which would result in a slight overestimation of true flux through the basin subsoil profile. This, in turn, must result in an underestimation of flux if impedance increases for the overlying layers. The agent of clogging is unknown, but the initial falling gradient at 23 to 38 cm indicates that less clogging was occurring in that layer, than in the layer underlying it. Similarly, a slight gradient increase in the 8 to 23 cm layer seems to have been dampened by the increasing gradient of the surface (0 to 8

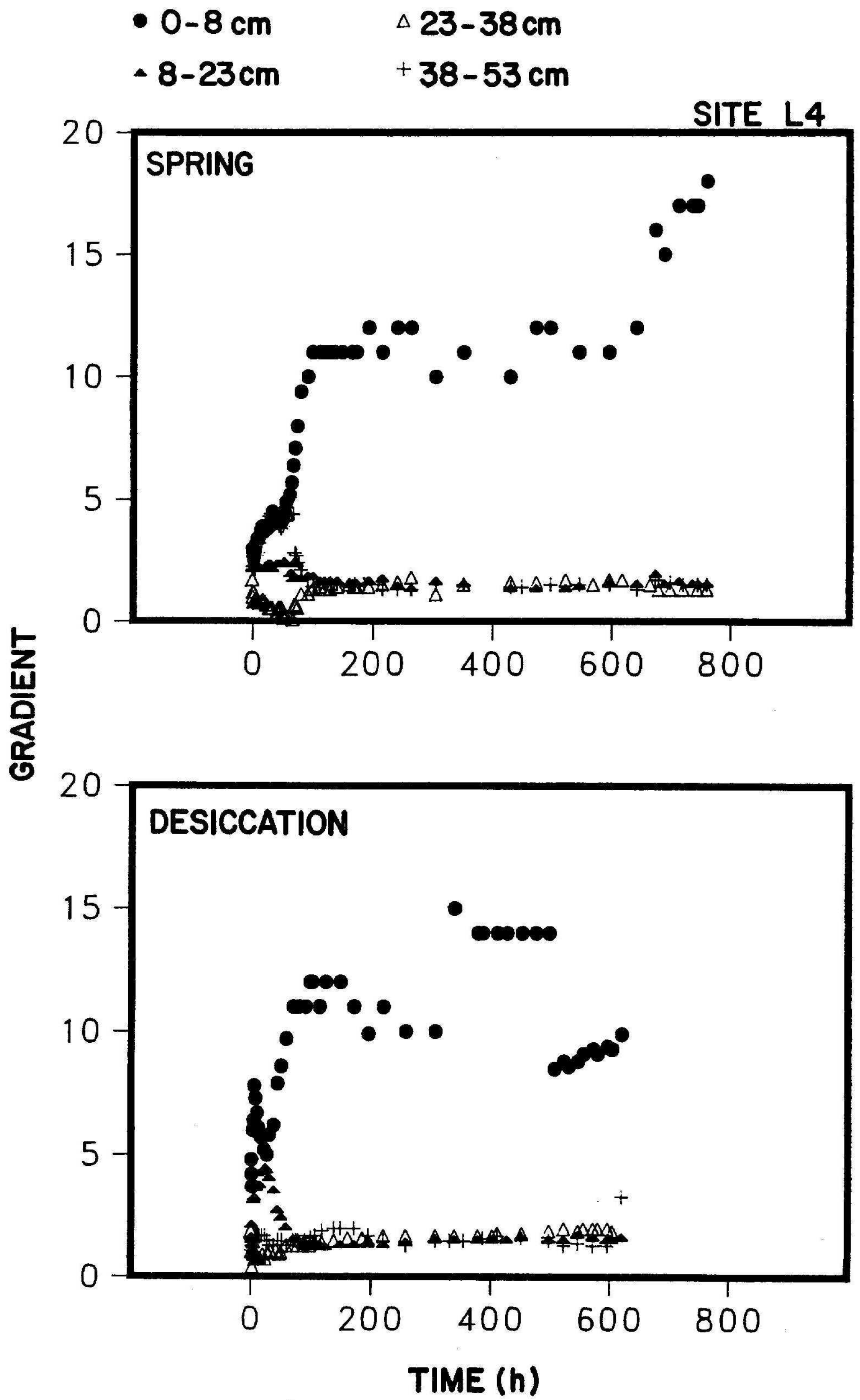


Fig. 41. Hydraulic gradient measurements for site L4 during the Spring 1987 test and following desiccation.

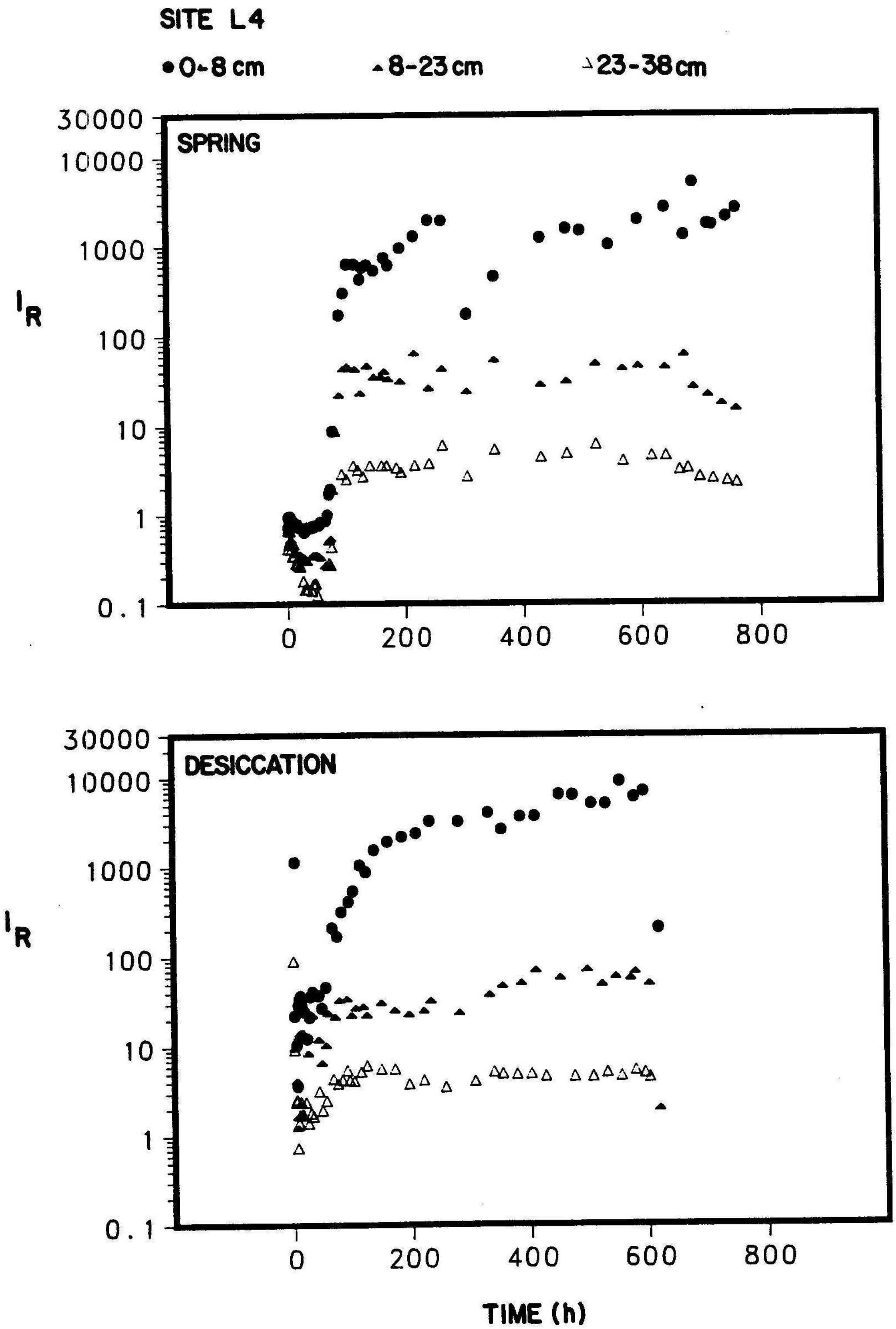


Fig. 42. Impedance ratio measurements for site L4 during the Spring 1987 test and following desiccation.

cm) layer. The increased hydraulic gradient near the end of the test was due to increased ponded depth in the basin which was varied to study the effects of basin stage on infiltration rate.

The early clogging of the 38 to 53 cm layer (Fig. 42) is further indicated by an early decrease of I_R values for all basin subsoil layers above 38 cm to below 1. After 50 hours all basin subsoil layers indicate increasing I_R. The 23 to 38 cm layer exhibited increased I_R to about 3. The 8 to 23 cm layer I_R values increased to roughly 20 or 30 times pre–experimental impedance. The surface (0 to 8 cm) layer increased to 1000 times pre–experimental impedance. Because of evidence of control layer clogging, these estimates are almost certainly low, and represent minimum values.

Site L4 After Desiccation June 15 to July 11

The hydraulic gradient data (Fig. 41) indicate a partial recovery for the 0 to 8 cm layer. The gradient for the surface layer began immediately at a higher value than did the same layer in the spring experiment. It decreased briefly in response to clogging in the 8 to 23 cm layer (to 30 hours), and then increased to a final value similar to that reached during the spring operation. The 8 to 23 cm layer also indicates immediate clogging, followed by a slight increase in gradient. No clogging below 23 cm is conclusively indicated for the post–desiccation experiment. The variable (decreasing, then increasing) hydraulic gradient for the surface layer following 163.5 hours of basin operation was caused by deliberate changes in ponded depth, used to evaluate the effects of basin stage on infiltration rate.

The impedance ratio for the surface layer reached 8000 (Fig. 42). Whether this was due to increased clogging during the second operation, or whether the control layer had effectively recovered resulting in a representation of a "true" clogged value similar to the initial spring run is uncertain. The 8 to 23 cm layer indicated immediate (I_R = 20,000 to 30,000) clogging upon commencement of recharge. Similarly, the 23 to 38 cm layer reached an I_R indicating an impedance value 2 to 3 times that for a nonclogged subbasin soil. These are identical to those reached during the spring period of operation. It is evident that little if any recovery occurred in the 8 to 38 cm subbasin layer during desiccation. From this similarity, it also seems likely that the greater level of surface clogging reached was due to actual increase in sediment sealing, rather than to recovery of the 38 to 53 cm layer used in calculating I_R.

Variation of Ponded Depth

The hydraulic gradient driving the flux through the subbasin soil profile can be increased by increasing the ponded depth within the basin. The "static head" provided by the water in the basin, however, comprises only one component of the total head controlling flow, and the relative importance of ponding is dependent upon the homogeneity of the soil profile. Factors influencing the effectiveness of increasing the ponded depth of the basin have been discussed previously in this report (Section – INFILTRATION, p. 24). Briefly, at early times on a homogeneous subbasin little effect from increased ponding would be expected because of the dominance of the gravitational gradient. The existence of impeding layers within the subbasin profile would tend to increase the influence of suction head (on the lower boundary of the impeding layer) and ponded head on the surface. The case of a sufficiently thin surficial impeding layer would render the gravitational component negligible, with infiltration almost entirely dependent on ponded depth and on the suction head developed beneath the impeding crust. Because of the suction head component, increases in flux will be approximately proportional to changes in ponded depth, with a proportionality constant of less than 1 or approaching 1.

To examine the sensitivity of changes in flux to changes in the ponded depth under the varying conditions encountered during the clogging of the basin, a digital computer model (Lappala et al. 1987) was used to simulate the final equilibrium flux for 60 cm and 120 cm ponded depths in the basin under conditions of varying surface crust resistance (crust depth = 1 mm) and with a second partially clogged layer. Hydraulic data used for the model were K(S) functions measured during the clogging process, and laboratory moisture retention data for undisturbed samples taken after the completion of the Fall 1986 basin operation period. Details of the model and its conclusions are to be reported separately (Sumner and Schuh, in preparation). A brief summary of conclusions follows.

For a nonclogged homogeneous profile with the hydraulic properties of the subbasin surface, a 14% increase was effected by doubling the the ponded depth. For a three layer system with a surface crust (1 mm), a partially clogged second layer (to 23 cm) , and a homogeneous third layer to the water table; an approximate maximum of 60% increase in infiltration rate was achieved by doubling the depth of the basin from 60 cm to 120 cm. The simulated suction head component (beneath the surface crust) was 25 cm. The simulation also indicated that the subcrust suction did not change greatly with the change in basin depth, although in some soil types and moisture retention ranges it might conceivably do so.

It must be observed that the proportionality constant of less than 1.0 for infiltration rate vs. ponded depth is related to the initial ponded depth tested, since the 25 cm suction is large in proportion to the 60 cm and 120 cm ponded depths. With greater initial ponded depths, the ponded component would be larger in relation to the suction component, and the percent increase in infiltration would thus be greater. Greater ponded pressure might also decrease the suction beneath the crust, enhancing importance of the ponded depth.

An in–situ test of basin response to ponded depth variation was conducted in June, 1987, at the end of the post–desiccation experiment. Tests were conducted only after the formation of the filter–cake layer. Because of rapid changes in the permeability of the basin floor at early times, discernment of early head variation effects alone would have been difficult. For comparison of ponding depth effects, the water surface was first allowed to decrease (to about 0.46 m). Lowering, rather than raising the water was preferred because of less likelihood of disturbing the basin floor from the turbulence of additional water input. The water level was then raised to about 0.87 m.

The results (Table 13) confirm the model conclusions of overall low sub–crust suction response to changes in ponded depth. In addition, excluding the single 0 value, the range of suctions (15 to 39 cm) and the mean overall subcrust suction (22.9 cm) correspond well with value simulated using the model. Using response ratios (ι/η) on Table 13 it can be calculated that by doubling the ponded depth, an approximate average infiltration rate increase of 68% (0.84 x 2 = 1.68) would be effected. Similarly, individual sites vary from 30% to 100% increased infiltration rate for a doubled ponded depth. This compares with the 60% simulated value. Results from raising the ponded depth, however, indicated that infiltration rate response was proportional to basin depth on a 1:1 basis. The latter case was almost certainly due to basin floor disturbance caused by the increased flow from the stilling basin during the raising of the water level. Immediately upon increasing discharge into the basin, the turbidity of the ponded water increased significantly, suggesting agitation of the fragile filter–cake crust deposited on the basin floor. After basin drainage, scour marks were observed near the stilling basin outflow.

Generally, the infiltration rate response to ponded head depth will be least during the early phases of infiltration where the largest rates occur, and will be greatest following the formation of the surface crust, when flux is the slowest. At later times, after the formation of the filter–cake layer, flux increases of 60% or more might be achieved by doubling the basin depth for a 60 cm ponded basin. Greater percent increases (approaching 100%) might be achieved for a basin constructed to operate with a deeper water level. For early times dependence of the infiltration rate of the noncrusted subbasin on local soil homogeneity makes prediction more difficult. The simulated 13% increase provides an approximation for the test area. At other locations, however, actual values may be more or less, depending on the depth to the water table, the layered characteristics of the subbasin soils, and the initial operational depth of the basin.

Table 13. Response of infiltration rate to head changes for in-situ basin positions L1, L2, L3, and L4, June 1987.

VARIABLE HEAD RESPONSE JUNE 1987

SITE	T (h)	H cm	S cm	i cm/h	H2/H1 η	i2/i1 ι	ι/η
S1-F	148	42	38	0.024	0.690	0.690	1.000
	185	29	38	0.017			
S1-R	331	27	37	0.006	2.560	2.300	0.900
	339	70	35	0.015			
S2-F	172	58	00	0.205	0.820	0.780	0.950
	186	48	15	0.160			
S2-R	332	46	36	0.119	1.940	1.940	1.000
	340	89	26	0.230			
S3-F	172	66	18	0.049	0.864	0.567	0.650
	186	57	18	0.028			
S3-R	332	54	19	0.020	1.860	1.790	1.040
	340	97	18	0.037			
S4-F	172	61	19	0.071	0.836	0.623	0.750
	186	51	21	0.044			
S4-R	332	49	21	0.023	1.880	1.920	1.030
	340	92	17	0.044			
	Falling Head			$\bar{X}$	0.80	0.67	0.84
				S	0.08	0.09	0.17
	Rising Head			$\bar{X}$	2.06	1.98	0.99
				S	0.33	0.22	0.06

*F = Falling Head R = Rising Head
T = Time H = Ponded depth
S = Soil water suction i = infiltration rate

Other Observations

The scope of this experiment did not include detailed biological data, although it was suspected that algae would influence the rate of clogging of the basin floor during the warmer months. Two weeks after initiation of the spring basin operation, large amounts of filamentous green algae were observed attached to various objects within the basin. Shortly thereafter the algae were no longer visible. The reasons for disappearance were not clear, but for the duration of the spring operation, and during the post–desiccation experiment, few algae colonies were observed. Upon completion of spring and post–desiccation experiments, large numbers of water fleas of the genus *Daphnia* were identified in the receding water. It is known that *Daphnia* feed on algae, and it is hypothesized that the *Daphnia* may have limited the amount of algae in the basin waters. This is not certain, because surveys of algae in nonfilamentous form were not taken, and the life cycles of the algae and *Daphnia* were not thoroughly considered. These observations are documented because the interaction of *Daphnia* and algae in artificial recharge basins may be of sufficient importance to warrant future investigation.

Algae were observed in the filter–cake layer upon termination of each recharge period. The green color of chlorophyll was observed wherever the basin was still moist at the time of observation. However, analysis of organic carbon content indicated that any increase in organic carbon in the filter cake, compared with the Fall 1986 experiment, was small. Crust from the Fall 1986 operation indicated a range of 2.2% to 3.4% organic carbon (mean 2.83 %) while a sample taken at the end of the post–desiccation period was 3.96 %.

One other factor likely affecting total infiltration through the recharge basin was temperature. Soil hydraulic conductivity is dependent upon fluid density and viscosity, which vary with temperature. James River temperatures recorded at Oakes for 1985 and 1986 indicated an annual range of surface water temperature between 0 and 29^{o}C. Changes in hydraulic conductivity calculated for the range of viscosities and temperatures indicated that a maximum increase of approximately 6% could be expected for i between the coldest and warmest operational periods. This increase would likely be maximized by pumping water near the river surface, or by lengthy retention of the water within the recharge basin, or within conveyance facilities. Other research (Bouwer and Rice, 1984) has indicated that calcium carbonate deposition caused by algal photosynthesis under conditions of high temperature and long retention can cause large decreases in infiltration. Thus, temperature conditions affecting minimum viscosity would likely cause negative impacts that more than offset potential gains.

Summary Spring + Desiccation Basin Operation

During 765 hours of basin operation in the spring of 1987, 2660 cm (87.27 ft.) of recharge was achieved through the large test basin . This compares with 3040 cm (99.7 ft.) for the Fall 1986 test. In 529 hours of operation after desiccation of the basin floor, 1200 cm (39.37 ft.) of water was passed through the basin . This compares with 2470 cm (81 ft.) of water through the large basin over the same time for the completely renovated spring operational period. For early times (before variation of head in the basin) post–desiccation recharge was half that of the spring test.

Physical data indicated clay and organic matter clogging to a depth of 7.6 cm. No silt was deposited in the basin subsoil. The composition of the surface filter–cake layer was higher in silt and lower in clay than the sediment added to the basin in the influent water, supporting the hypothesis of preferential clay movement to greater depths.

For the fully renovated basin (spring operation) the greatest impedance increase was in the 0 to 8 cm layer, with increases of 2 to 4 orders of magnitude. This agrees with particle size distribution data for the subbasin soil profile. After desiccation and cracking of the surface filter cake layer, partial recovery was usually achieved. Partial clogging, ,however, remained for the surface layer after desiccation, as indicated by the final impedance values following desiccation.

Impedance in the 8 to 23 cm layer usually varied from 10 to 100 times measured values before addition of turbid water. In one case an I_R of 5000 was recorded, but clogging in this case was transitory and may have been due to gas entrapment. Clogging, where I_R values between 10 and 100 were recorded, was usually permanent rather than transitory, and was not significantly reversed by a 10 day period of desiccation. This suggests that clogging was caused by a solid agent rather than gas.

Little clogging was observed for the 23 to 38 cm layer. In one instance an extremely high transitory increase in impedance was observed. The large increase was almost fully recovered after desiccation of the basin floor. In one other case a nonreversible clogging of the 23 to 38 cm layer was observed. The magnitude of change was at least 3 times preoperational impedance, but may have been higher due to overestimates of flux caused by a clogged control layer. Indications of clogging for the subbasin below 38 cm were found for one site. Physical parameters indicated that impedance changes in the surface 8 cm were due to increased clay content and organic matter. Sediment deposition below 8 cm was not indicated. Thus, the agent of clogging for subbasin layers below 8 cm is uncertain. The causes of increased impedance may have been effective in quantities smaller than detection limits allowed by our sampling procedures, or they may have been substances not analyzed.

Algae were observed in the basin and were a visible component of the filter–cake layer. However, basin operation during the warm months of May and June did not result in a large deposit of organic matter on the basin floor, and organic carbon measurements did not differ greatly from the Fall 1986 values. Large numbers of *Daphnia* (sp.) beetles may have served to control algae growth.

OPERATION 3: AUGUST 3 TO OCTOBER 5, 1987

(Organic Mat + Desiccation)

Previous research by Jones et al. (1981) indicated that infiltration was significantly enhanced by the use of a surface organic mat. The filter–cake layer observed in the fall and spring basin operations was composed of fine, laminar particles, and was structureless when moist. Both Fall (1986) and Spring (1987) tests indicated that the greatest impedance was reached in the surface layer, including the filter cake. Partial recovery of the surface layer after desiccation indicated that the integrity of the filter–cake layer was an important factor in maintaining high impedance. It was hypothesized that a surface organic mat would serve as a rapid filter (Ives, 1970), removing a portion of the sediment materials before they reached the subbasin soil, and preventing the formation of the laminar filter cake on the soil surface. It was also hypothesized that the irregular surface of the organic mat would interrupt the integrity of the surface filter–cake layer and would thereby decrease the final impedance of the surface filter formed.

The purpose of the third and final basin experiment was to investigate the effect of a well composted organic mat on rates of infiltration. The objectives were to measure: 1) the rate of attenuation of infiltration during turbid water application with a protective surface organic mat; 2) the depth and extent of clogging, and the nature of clogging during turbid water application with a surface organic mat; and 3) the effect of a period of desiccation on the recovery of flow capabilities for a basin with a protective organic surface mat.

Renovation and Preparation

Renovation of the basin prior to the organic mat test was performed in the same manner as described for the Spring 1987 basin operation. The surface 0.46 m (1.5 ft.) of soil was removed and replaced with clean sand. Because of the problems encountered in characterizing in–situ hydraulic properties during the Spring experiment caused by the heterogeneous spoil removed during basin construction, a pit was excavated near the basin and clean sand was removed from the same layer as the original basin surface. The sand was spread on the basin floor. An organic mat was placed over the surface of the sands.

Organic Mat Preparation and Placement

Jones et al. (1981) used cotton–gin trash in forming their organic mat. For potential application in North Dakota a local agricultural by–product was desired. Sunflower–seed hulls were selected because they are locally available in large quantities and are relatively inexpensive ($12.00 to $19.00 per ton). Considerable research concerning the role of organic matter in enhancing soil structure has been published (Martin, 1941; Robinson and Page, 1950; Russel et al., 1952). Martin (1941) has indicated that electrical properties enhancing aggregation are highest on partially composted materials. Since the same properties would likely provide the function of trapping and orienting clay particles, it was decided to compost the seed hulls before use as a filter mat. Under normal conditions, organic materials placed on a basin floor would gradually compost during the aerated portions of the cycle of operation. Due to the time limitations imposed by the test schedule, it was necessary to speed the rate of decomposition.

In mid–March, 16.6 Mg (36,720 lb.) of sunflower seed hulls were placed in a pile 1.8 m (6 ft.) high. Half of the hulls were ground (passing a 60 mesh per square inch sieve) to increase the rate of overall decomposition. Approximately 273 kg (600 lb.) of urea (46–0–0) was mixed with the hulls using a front end loader (125 kg actual N). Topsoil was added and mixed with the organic materials to provide bacterial inoculum. The pile was then thoroughly wetted while stirring with a front–end loader. At the first wetting the sunflower seed hulls were water repellent, and a plastic cover was placed over the piles to prevent blowing. The water repellency declined quickly, however, and soon no cover was necessary, as crusts forming on the wetted piles prevented blowing. The compost was stirred and rewetted (Fig. 43) at time intervals of two to three weeks, until placement on the basin floor.

Organic matter often enhances soil permeability through the formation of structure and increased macroporosity. In some cases, however, it can inhibit permeability through the filling of large pores within the soil matrix. Although Jones et al. (1981) tilled their mat to mix it slightly with the loamy materials of their basin floor, it was considered likely that the mixture of coarse–grained low CEC sands with composted organic materials would serve to decrease the effective porosity of both materials. The composted sunflower–seed hulls were spread over the basin floor to form a 10 cm (4 inch) mat. No tillage was performed.

Samples of the compost were taken at the time of placement, and were air dried for preservation prior to analysis for Kjeldahl total nitrogen (Bremner, 1965) and organic carbon (Allison, 1965). Results (N = 0.56%, C = 13.9%, C:N ration = 25) indicated that mineralization of N due to decomposition of the organic mat would be unlikely during the test basin operation. Low likelihood of mineralization, along with a small nitrate N component (27.4 mg/kg), further indicated that a large accumulation of denitrification gases would not be expected.

Although fractional analysis of the organic mat was not performed, organic acids formed in the process of decomposition are known to be influential in promoting soil structure and aggregation (Martin, 1942). Organic acids are known to
play a structuring role in bonding clay particles through polyvalent cations (aluminum, calcium, magnesium, etc.), which attach to organic ligands and form cation bridges (Giovannini and Sequi, 1976; Mazurak, 1953). The pH of the James River water (7.8 to 8.2) indicated a saturated calcite–dolomite solution, which would enhance flocculation. Because many organic acids are water soluble, their role as flocculants would likely be partially independent of the filtering properties of the organic mat itself, causing precipitation of sediment in the aquatic environment above the organic mat from which

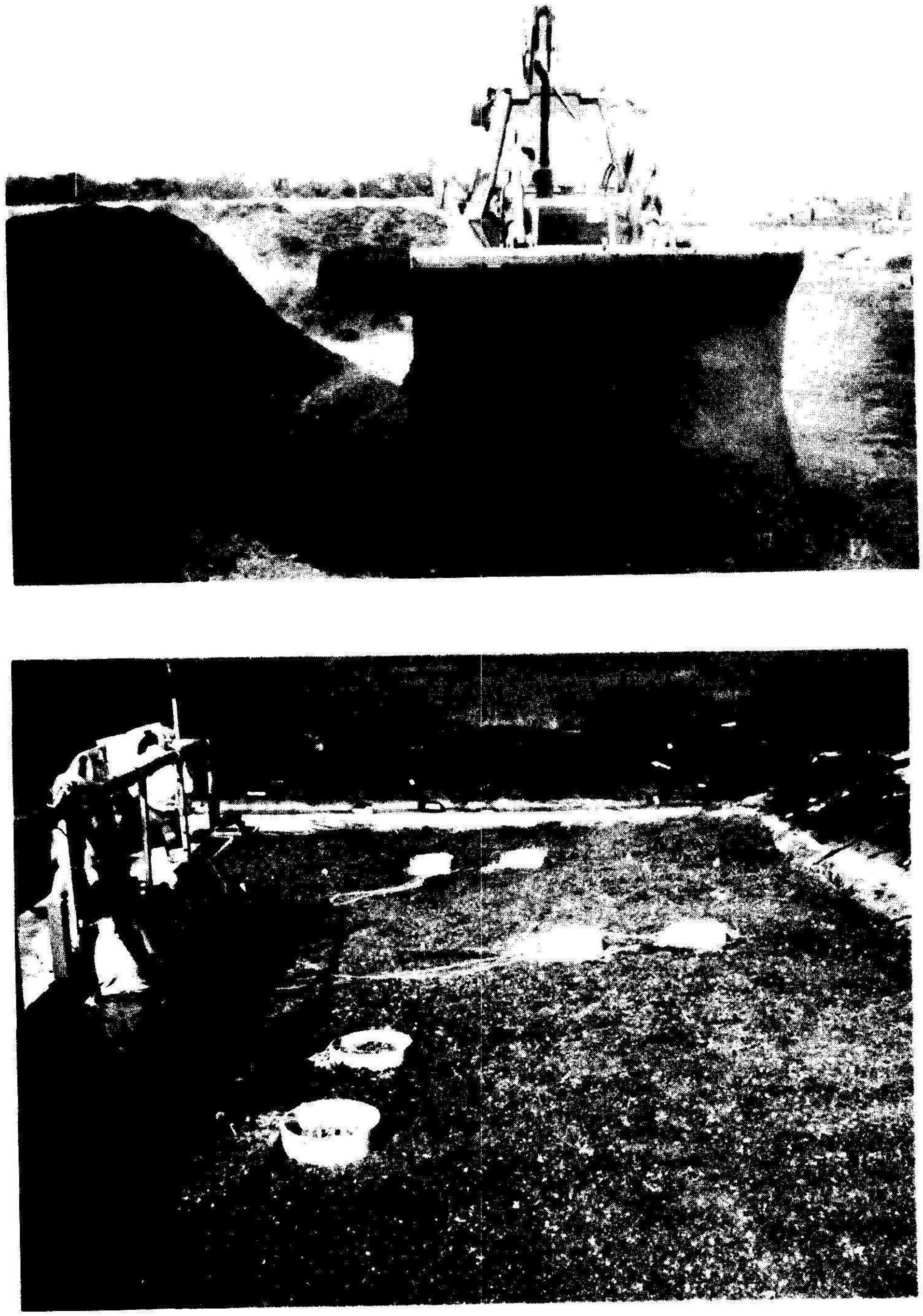


Fig. 43. Photo-illustration of sunflower-seed hulls during preparation and composting.

they have been dissolved.

Soil and Water Samples

Water samples for suspended solids determination were taken daily during basin operation. Additional samples were taken for measurement of sediment particle size distribution (Tables 14 and 15). Soil samples were taken in the same manner and design as described for the Spring + Desiccation tests. Samples were taken before initiation of the first organic mat test and after termination of the second organic mat test. Two sets of bulk density samples were taken – one from each of the two major sampling areas – before and after the organic mat tests. Two sets of ring samples for determination of moisture characteristic curves were also taken before operation of the basin. One set of samples was taken near each set of the paired tensiometer nest installations. A list of soil laboratory samples and procedures for the Organic Mat + Desiccation test is on Table 16.

Hydraulic Parameters

Four paired sets of infiltrometer and tensiometer installations (eight total installations) were established on the basin floor (Fig 44). Each set consisted of one installation covered with a 10 cm (4 inch) organic mat, and a second installation about 1.8 m (6 ft.) away with no organic mat within the inner or outer ring areas. Unsaturated hydraulic conductivities were determined as described for other basin experiments, but with a few changes in method. For the organic mat experiment two additional tensiometers were placed at the 1 cm and 69 cm depths.

One problem encountered was that a layer of low permeability lay somewhere between 38 and 69 cm for each measurement site. This may have been due to compaction during replacement of the basin floor, or it may have been caused by a thin layer of detrital lignite located in that depth interval at several sample sites. The impeding layer resulted in low hydraulic gradients in some of the overlying materials during the period of

Table 14. Grain-size distribution for the basin-floor filter cake and for suspended solids delivered to the large basin during the 1987 Organic Mat test (before desiccation).

ORGANIC MAT (BEFORE DESSICATION) 9/22/1987

FILTER CAKE SAMPLES Location			SUSPENDED SOLIDS Date		
CK	SILT	57%	8/04/87	SILT	29%
	CLAY	43%		CLAY	71%
	OC	7.01%			
			8/09/87	SILT	40%
				CLAY	60%
EAST	SILT	60%			
	CLAY	40%			
	OC	5.65%	8/24/87	SILT	43%
				CLAY	57%
OM	SILT	58%			
	CLAY	42%			
	OC	5.48%			
$\overline{SILT}$ = 58% SD = 1.53 $\overline{CLAY}$ = 42% SD = 1.53 $\overline{OC}$ = 6.07 SD = 0.87 N = 3			$\overline{SILT}$ = 37% SD = 7.4 $\overline{CLAY}$ = 63% SD = 7.4 N = 3		

CRUST/CLAY SEDIMENT RATIO = 0.67
OC = ORGANIC CARBON

CK = No Organic Mat cover (flow cell)
OM = Organic Mat cover (flow cell)
EAST = East Quadrant of Basin

Table 15. Grain-size distribution for the basin-floor filter cake and for suspended solids delivered to the large basin during the 1987 Organic Mat test (after desiccation)

ORGANIC MAT (AFTER DESSICATION) 10/06/1987

FILTER CAKE SAMPLES Location			Location			SUSPENDED SOLIDS Date		
NW	SILT	54%	SE	SILT	50%	8/31/87	38%	SILT
	CLAY	46%		CLAY	50%		62%	CLAY
	OC	6.6%		OC	6.9%			
SW	SILT	58%	A	SILT	54%			
	CLAY	42%		CLAY	46%			
	OC	6.7%		OC	5.1%			
NE	SILT	50%	B	SILT	55%			
	CLAY	50%		CLAY	45%			
	OC	7.5%		OC	6.3%			

$\overline{SILT}$ = 53% SD = 3.08

$\overline{CLAY}$ = 47% SD = 3.08

OC = 6.5% SD = 0.8
N = 6

CRUST/CLAY SEDIMENT RATIO = 0.72   OC = ORGANIC CARBON

Table 16. Basin floor laboratory samples taken for the 1987 Organic Mat + Desiccation Test

LABORATORY SAMPLES (ORGANIC MAT + DESICCATION)

Depth (cm)	Particle Size		Organic Carbon		Moisture Retention (10-120 cm)		Bulk Density	
	T	N	T	N	T	N	T	N
0.0 - 1.3	B/A	8	B/A	8	----		----	
1.3 - 2.5	B/A	8	B/A	8	----		----	
2.5 - 5.1	B/A	8	B/A	8	----		----	
5.1 - 7.6	B/A	8	B/A	8	----		----	
7.6 - 22.9	B/A	8	B/A	8	B	2	B/A	2
22.9 - 38.1	B/A	8	B/A	8	B	2	B/A	2
38.1 - 53.3	B/A	8	B/A	8	B	2	B/A	2
0.0 - 7.6	----		----		B	2	B/A	2
0.0 - 1.3	A-/+	3	A-/+	3	----		----	
1.3 - 2.5	A-/+	3	A-/+	3	----		----	
2.5 - 5.1	A-/+	3	A-/+	3	----		----	
5.1 - 7.6	A-/+	3	A-/+	3	----		----	
7.6 - 22.9	A-/+	3	A-/+	3	----		----	
Suspended Solids	D	4	----		----		----	
Filter Cake	A	9	----		----		----	

T = Time N = Number of Samples D = During Operation
B = Before Operation A = After Operation
+ = With Organic mat - = without organic mat

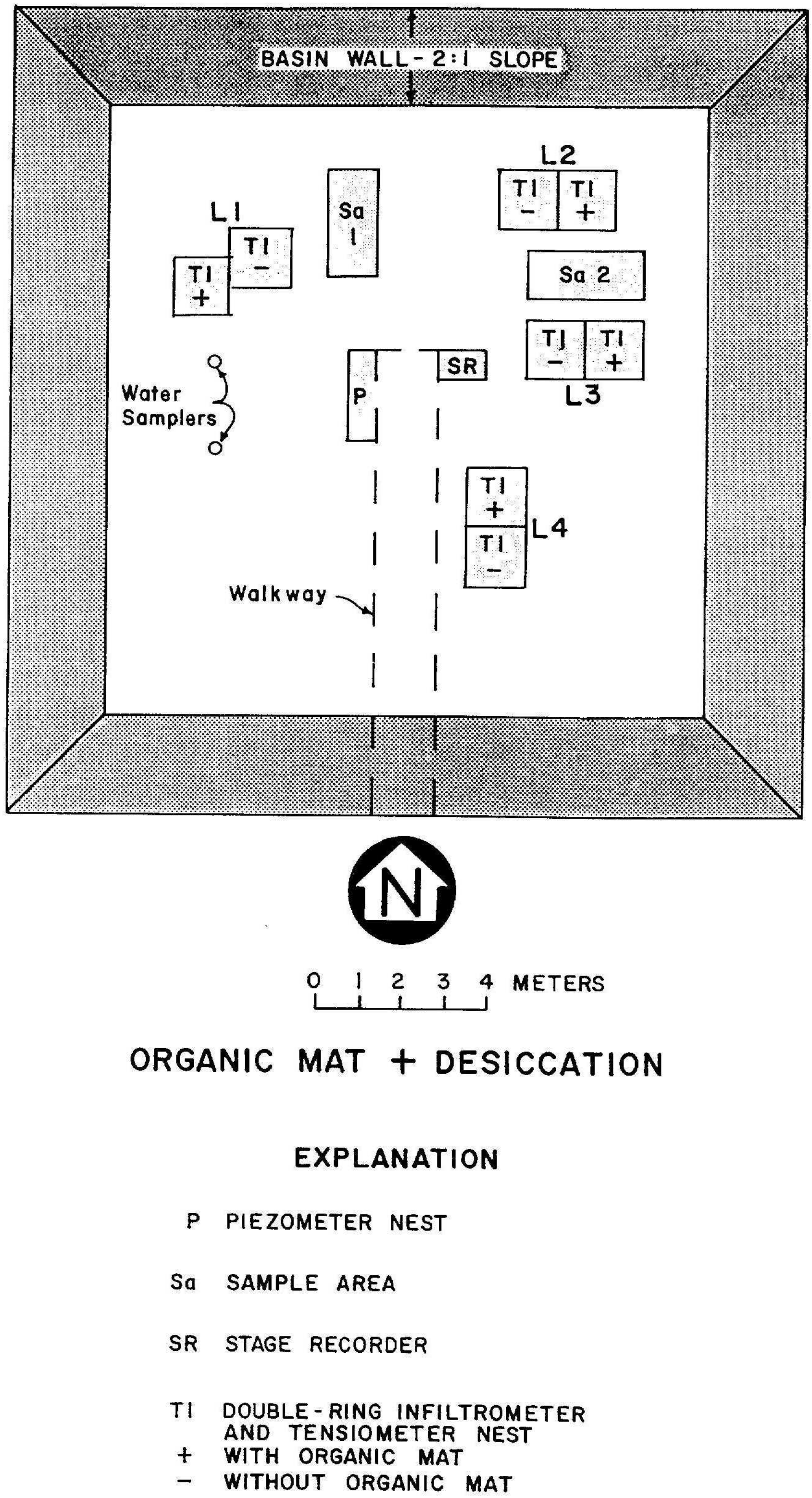


Fig. 44. Organic mat + Desiccation test: Fall 1987 large basin sampling and instrumentation layout.

infiltration. This resulted in low sensitivity for discerning the hydraulic gradients. Because of the importance of the control layer in determining flux through the profile and in calculating the actual impedance of overlying layers during drainage , the control layer was set at a layer of higher sensitivity (higher gradient discernment) , and therefore varied between the 38 to 53 cm layer and the 53 to 69 cm layer, depending on the individual installation.

It was thought that slightly higher hydraulic gradients induced by the 0.61 m (2 ft.) ponded surface water might enhance sensitivity for estimation of K(S) in the surface layers. The steady–state K values used to match the K(S) functions for layers above the control layer were, therefore, determined during the first three hours of basin operation. As soon as the 69 cm tensiometric profile was fully wetted, matching K was determined from measured hydraulic gradients, and from infiltration calculated at the bottom control layer. The advantage in using this altered procedure was undoubtedly slight.

The Ahuja method (1980) requires the use of tensiometers to evaluate the total change in water content from the surface to the layer for which properties are being assessed. No tensiometers had been placed within the organic mat and, because drainage characteristics of the mat were very different from the underlying sands, no similarity could be assumed . This left the quantity of water draining from the organic mat unknown. A column experiment was performed to evaluate the sensitivity of hydraulic conductivity measurement in the subbasin sands to the drainage component from the organic mat.

Two 1.2 m (4 ft.) columns were filled with sand, overlying a 7.8 cm gravel pack on the bottom. An outflow on the bottom allowed free drainage. A 10 cm (4 in.) organic mat was placed above the sand for each column. Tensiometers were placed at 1, 4.8, and 8.7 cm beneath the upper boundary of the sand, and at 2.8 and 6.6 cm above the lower boundary of the organic mat. Each column was ponded and allowed to flow for 4 hours (at which time the drains were flowing freely). The columns were then covered and allowed to drain, while tensiometric profiles were measured in a manner identical to that used in the field K(S) determination. The experiment was repeated for each column.

The results indicated that a log–log relationship existed between the bottom tensiometer in the organic mat and the top tensiometer in the sand – over the range of suctions measured (0 to 60 cm) for each of the columns. They also indicated that, except for a steep gradient across the sand–mat boundary, the hydraulic gradient within the organic mat was very close to unity throughout the experiment. Using this information, a comparative simulation was performed in which field hydraulic conductivity profiles were calculated for cases which: 1) ignored the effect of the surface organic mat, and 2) were adjusted for the effect of the organic mat, using the equations and assumptions determined in the column experiments. It was found that exclusion of the organic mat contribution resulted in about a 50% underestimate of K for the surface layer (to 1 cm). In the 1 to 8 cm layer very little difference was observed. Below 8 cm no differences were detectable. For calculation of field measurements, the effects of the organic mat were ignored, and the 0 to 1 cm layer K(S) determinations were discarded. The organic mats did not influence the rates of infiltration before the addition of sediment to the basin.

Condition of the Basin Floor

Some of the organic mat had been compacted during placement of instruments and preoperational experiments. Those areas were lofted using pitch forks just prior to the delivery of water to the basin. After the first experimental run and the following 21 day desiccation period, the surface crust was further broken by hand raking the basin surface. This was done to simulate a light dragging operation, which would be the simplest and least expensive tillage operation for basin renovation.

Basin Operation

Water was first delivered to the large basin at 14:50 h on August 3, 1987. A 0.61 (2 ft.) water level was established after 1 hour and 7 minutes and maintained as in previous experiments. Tensiometer and piezometer reading frequencies were decreased slightly (initially every 1/2 hour) based on previous experience of clogging rates. The delivery of water was terminated at 07:53 h on September 1, and the basin floor was allowed to dry and crack. The surface filter cake was raked just prior to initiation of the second basin operation period at 15:52 on September 22. The second basin experiment was terminated at 19:45 h on October 2. The planned date for termination of the second basin operation was October 5. On October 1, however, high winds stirred up the sediment of the James River to such an extent that the pump screen was blocked. One sample of discharge water into the basin was collected during the evening of October 1, and indicated that the suspended solids were as high as 785 mg/l.

RESULTS

The initial infiltration rate during basin operation was 35 cm/h (27 ft./d). This declined to 1.65 cm/h (1.3 ft./d) after 713 hours of infiltration using turbid water from the James River (Fig. 45). The total recharge achieved during that time was 5010 cm (164 ft.) of water. This compares with only 2712 cm (89 ft.) for the Spring 1987 first basin operation, and 3040 cm (100 ft.) for the Fall 1986 experiment – both without organic mat. The average sediment load (weighted for discharge) was 90 mg/l, compared with 50 mg/l for the Fall 1986 experiment, and 68 mg/l for the Spring 1987 experiment. It is evident that the organic mat resulted in a substantial increase in total recharge under sediment load conditions which would have been expected to cause a greater degree of clogging. The decrease in infiltration rate occurred much more gradually over time with the organic mat than without the mat, indicating that the disruption of the integrity of the surface filter cake layer was successful.

Following a 21 day desiccation period and a shallow raking of the surface of the organic mat, the initial infiltration rate was 35 cm/h (27 ft./d), and the rate after 219 hours of operation was 3.94 cm/h (3.08 ft./d). Initial infiltration rates were completely recovered (Fig. 45). However, rate of decline in infiltration rate with time was significantly higher during the post–desiccation test. After 219 hours on the first basin operation, the infiltration rate was 7.5 cm/h (5.9 ft./d), almost double the rate following desiccation. The total recharge during the 219 hours of post–desiccation operation was 1400 cm (46 ft.). This compares with 3580 cm (117 ft.) for the same time period during the first operational run. Although the infiltration rate through the dried and raked organic mat exceeded that through the desiccated sand basin floor, the reduction in infiltration between initial and post–desiccation experiments was greater (Tables 12 and 17). Cumulative infiltration following desiccation was 38% of that achieved for comparable times in the fully renovated initial test.

A perched ground–water mound (measured in Piezometer TP1–A) formed after about 25 minutes of basin operation, and reached a maximum height of 0.35 m (1.14 ft.) after 1 hour and 39 minutes. The perched ground–water mound fully dissipated after 50.5 hours. The period of mound persistence was considerably longer than for previous tests. Similarly, tensiometers in the top 0.68 m (2.25 ft.) indicated a longer period of initial saturation compared with previous tests. The 1 to 8 cm layer was unsaturated after 185 hours, the 8 to 23 cm layer after 230 hours, the 23 to 38 cm layer after 306 hours, and the 38 to 53 cm layer after 269 hours. Later desaturation times and the later time to perched ground–water mound dissipation were due to sustained infiltration rates enabled by the organic mat. Following desiccation, desaturation times were 185, 223, 306, and 258 hours, respectively, for the above listed layers. These did not differ greatly from those of the initial run.

Sediment Distribution and Filter–Cake Layer Formation

The filter–cake layer formed on top of the organic mat (Fig. 46). Examination of the boundary between the sand and the organic mat revealed no sign of secondary cake

Table 17. Comparison of Fall 1987 Organic Mat test infiltration before and after natural desiccation.

ORGANIC MAT (Fully Renovated vs. Desiccation)

Time (h)	* Des. Recharge (cm)	** FR Recharge (cm)	Des./FR
24	351	609	.58
48	504	1160	.43
72	653	1640	.40
96	775	2040	.38
120	925	2430	.38
144	1060	2790	.38
168	1180	3110	.38
192	1300	3370	.39

* 10 day Desiccation
** Fully Renovated Basin Floor

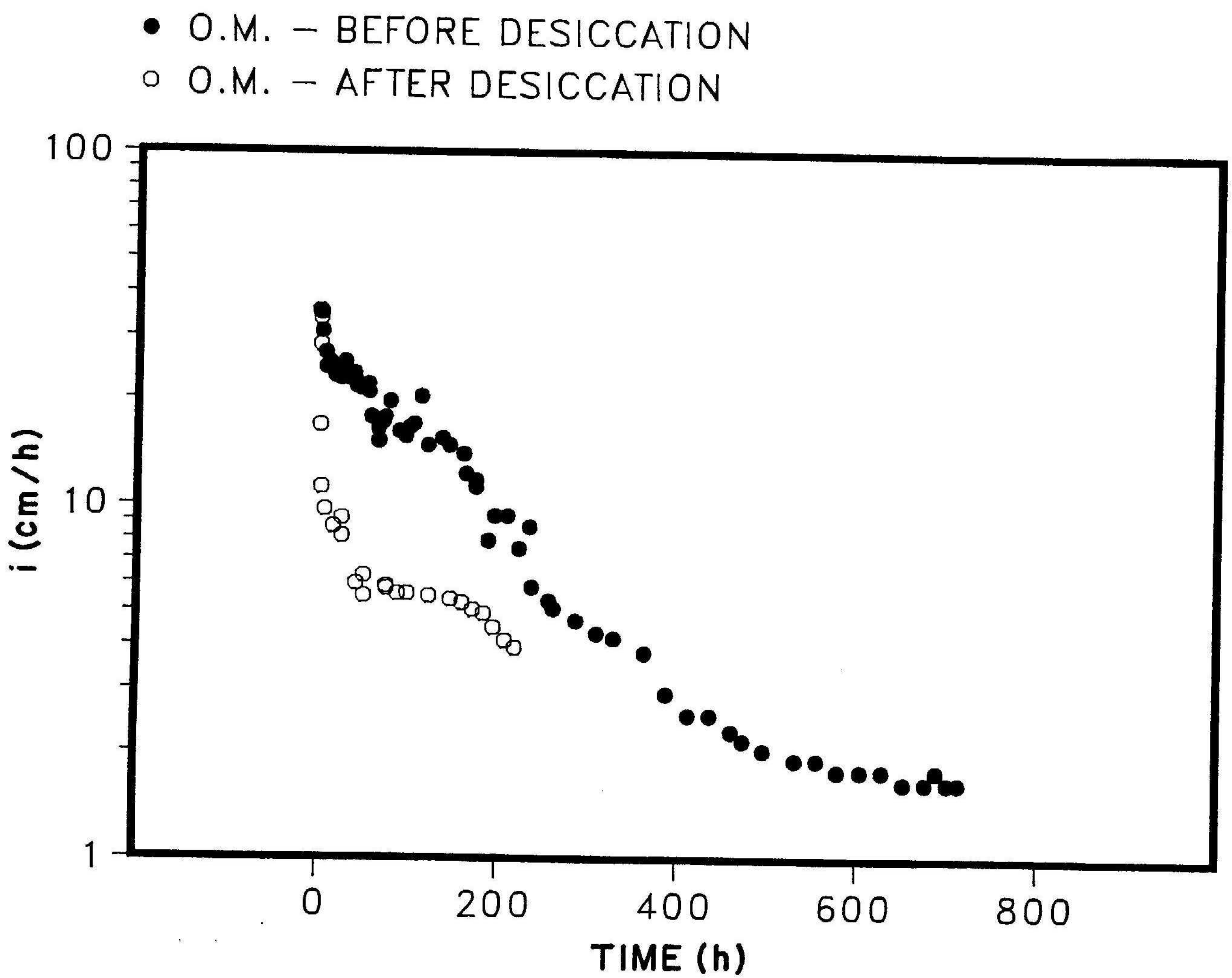


Fig. 45. Infiltration rate measured at the intake for the 1987 Organic-Mat test before and after natural renovation by desiccation.

Fig. 46. Photo-illustration of the filter-cake layer formed above the sunflower-seed hull mat.

formation on top of the sand. The filter cake from the first run (Table 14) indicated 58 % silt composition, while the second (Table 15) indicated 53 % silt. These compare with 53 and 71% silt content, respectively, for the sediment delivered to the basin during the two previous experiments. As with previous experiments, a greater portion of silt deposition near the surface was indicated, with deeper penetration of the clays.

The sediment load grain–size distribution varied within a narrow range during the entire period of measurement beginning in September 1986 and ending in October 1987. Clay percentage was 68% for the spring and desiccation period, 63% for the organic mat first experiment, and 62% for the final organic mat experiment. The 1986 average was highest at 77%, but this may have been influenced by disturbance of river bottom sediment from bridge repairs approximately one mile upriver. In October 1986 the clay content decreased to 66 % – more similar to later measurements.

Physical Data

A comparison of particle–size data from before the organic– mat experiment, and after the organic–mat + desiccation experiment indicated that significant ($P< 0.05$) clay deposition occurred in all materials above 23 cm (Table 18). Some deposition appeared likely to greater depths, but this is not statistically verifiable. Increased organic carbon (Table 19) was noted only for the surface (0 to 1.2 cm) layer. The depth of clay penetration with the 10 cm organic mat exceeded those of the Spring 1987 and Fall 1986 operations without the protective filter. The greater penetration was unexpected, since the hydrochemical environment in and near the organic mat was expected to be conducive to flocculation, and electrical properties of the mat were expected to intercept much of the added sediment.

Reasons for greater clay penetration with the organic mat are not certain. The combination of a higher suspended load in this test, and greater sustained velocities over the duration of the experiments may have caused deeper penetration of the clays. It is

Table 18. Basin subsoil grain-size distribution changes (% clay and % silt) before and after the Organic Mat + Desiccation test (N=8).

ORGANIC MAT + DESICCATION

Percent Clay Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	+ 0.362	0.227	1.60	NS
1.3 - 2.5	+ 1.237	0.329	3.75	0.010
2.5 - 5.1	+ 1.100	0.410	2.68	0.05
5.1 - 7.6	+ 0.925	0.337	2.74	0.025
7.6 -15.2	+ 1.762	0.388	4.54	0.005
15.2 -22.9	+ 2.212	0.480	4.61	0.005
22.9 -38.1	+ 0.787	0.456	1.72	NS(0.2)
38.1 -53.3	+ 1.475	0.790	1.86	NS(0.1)

Percent Silt Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	- 0.475	0.409	1.16	NS
1.3 - 2.5	- 0.650	0.403	1.60	NS
2.5 - 5.1	- 0.662	0.364	1.82	NS
5.1 - 7.6	- 0.387	0.647	0.59	NS
7.6 -15.2	- 1.830	0.942	1.94	NS(0.1)
15.2 -22.9	- 2.550	1.327	1.91	NS(0.1)
22.9 -38.1	- 1.700	1.080	1.57	NS
38.1 -53.3	- 1.662	0.700	2.36	0.05

SE = Standard Error t = Student's t
P = Probability Level

Table 19. Basin subsoil organic carbon changes (% OC) before and after the Organic Mat + Desiccation test (N=8).

ORGANIC MAT + DESICCATION

Percent Organic Carbon Difference Before and After Basin Operation

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	+ 0.563	0.134	4.20	0.005
1.3 - 2.5	- 0.650	0.032	2.00	NS(0.1)
2.5 - 5.1	- 0.008	0.021	0.36	NS
5.1 - 7.6	- 0.004	0.020	0.21	NS
7.6 -15.2	+ 0.000	0.013	----	NS
15.2 -22.9	+ 0.024	0.022	1.09	NS
22.9 -38.1	+ 0.003	0.013	0.19	NS
38.1 -53.3	+ 0.044	0.025	1.76	NS

SE = Standard Error t = Student's t
P = Probability Level

known (McDowell–Boyer et al., 1986; Harmeson et al., 1968) that approach velocity is one of the variables influencing the depth of particle penetration during rapid filtration. It is apparent, moreover, that the porosity of the sunflower–seed hull mat is such that clay particles are not fully and effectively filtered from the passing waters.

After removal of the inner infiltrometer rings and the tensiometers upon completion of the final basin experiment, additional soil samples were taken from three of the four hydraulic measurement sites. For three sites two sets of samples were taken ; one set from the organic mat covered area, and the other from the area not covered (check). Results (Table 20) indicated a greater clay deposition for the 2.5 to 5 cm layer without the organic mat. Significant differences in other areas were not discerned. Organic carbon was slightly higher ($P < 0.05$) for the organic mat area. Greater deposition at the shallow (2.5 to 5.0 cm) depth for the uncovered area is not necessarily inconsistent with deeper penetration on the covered areas. However, the sparse sample numbers used in this comparison ($N = 3$) were not sufficient to characterize overall sediment deposition profiles with confidence.

In comparing check and mat covered areas, it is remembered that the check areas are not entirely isolated from the hydrochemical effects of the surrounding organic mats. Some organic exudates dissolved in the water near the mats would likely be transferred through turbulence, convection, and diffusion to the small noncovered areas. Flocculating effects of organic acids, for example, would likely occur to some degree in the check areas as well as in the mat covered areas. The comparison of check and organic mat area, therefore, are not strictly independent.

Although insufficient bulk density samples of the basin floor were taken for statistical comparison, bulk density does not appear to have increased during the period of basin operation.

Clogging of the Basin Profile

Interpretation of the organic mat experiment hydraulic data is more complex than

Table 20. Basin subsoil grain-size distribution and organic carbon difference between check and organic mat covered areas (N=3).

ORGANIC MAT + DESICCATION

Percent Clay Difference Between Check and Organic Mat Covered Treatments

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	- 0.73	0.24	3.04	NS(0.1)
1.3 - 2.5	- 1.03	0.79	1.30	NS
2.5 - 5.1	- 1.20	0.15	7.89	0.005
5.1 - 7.6	- 0.73	0.81	0.90	NS
7.6 -22.9	+ 0.40	0.81	0.49	NS

Percent Silt Difference Between Check and Organic Mat Covered Treatments

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	- 1.13	0.47	2.40	NS(0.1)
1.3 - 2.5	- 2.80	1.55	1.80	NS
2.5 - 5.1	- 0.03	0.93	0.03	NS
5.1 - 7.6	- 4.30	1.85	2.32	NS
7.6 -22.9	+ 1.17	1.79	0.64	NS

Percent Organic Carbon Difference Between Check and Organic Mat Covered Treatments

Depth (cm)	Change (%)	SE (%)	t	P
0 - 1.3	- 1.13	0.47	2.40	NS(0.1)
0 - 1.3	+ 0.047	0.013	3.61	0.05
1.3 - 2.5	- 0.040	0.021	1.90	NS
2.5 - 5.1	- 0.053	0.030	1.72	NS
5.1 - 7.6	+ 0.007	0.018	0.55	NS
7.6 -22.9	+ 0.000	0.031	****	NS

SE = Standard Error t = Student's t
P = Probability Level

previous experiments due to evidence of deeper clogging in both check and organic mat covered profiles. The nature of the clogging is unclear, but some indications point to a greater likelihood of transitory clogging mechanisms rather than the more permanent sediment clogging. The increased complexity of the organic mat experiments is due at least partially to the addition of large amounts of carbon substrate and nutrients to water percolating through the subbasin profile. The fact that the check profiles also exhibit erratic behavior is not unexpected because of the likely similarity of hydrochemical conditions over the entire basin. A considerable number of clogging agents are likely under the conditions described for this experiment. 1) Organic or mineral particulate sediment may directly clog the subbasin soil pores . 2) Air entrapment ahead of the wetting front at early times would be more likely because of the high impedance layer between 38 and 69 cm which would prevent free air passage, and because of the faster sustained approach velocity of the water which would tend to trap air. 3) Microbial solid products, such as polysaccharides (Nevo and Mitchell, 1967), could form in situ due to the ample carbon substrate and nutrients added in organic mat and water. 4) In–situ production and entrapment of denitrification products (N_2 and NO_2) could result from the combination of carbon substrate, nitrates from the organic mat, and increasing oxygen limitations with depth beneath the basin floor. 5) In–situ production of CO_2 could occur due to ample carbon substrate, and well oxygenated water delivered to the basin.

Of the above listed potential agents, sediment deposition beneath the surface filter cake would be expected to be stable, and resulting hydraulic effects should largely recur following desiccation and cracking. Solid microbial products would be expected to partially decompose during the desiccation period so that substantial recovery of the flow capabilities of the clogged layer should result. Gas entrapment would almost certainly be characterized by substantial recovery during a desiccation period. Trapped gases could also be transitory during a single operational period, dissolving or moving as tiny bubbles in the basin water. Of the gases listed, N_2 and O_2 have similar solubilities, while NO is much more soluble than the other two. In–situ denitrification would likely be least prevalent immediately beneath the filter cake because of oxygen content in the water delivered to the pit. Denitrification gas production would be expected to increase with depth as oxygen is depleted. Carbon dioxide (CO_2) is also highly soluble. Its clogging effects would be expected to be transitory, followed by rapid dissolution in subbasin waters. Preliminary geochemical work (R. Huff, personal communication) has indicated that the vadose zone beneath the basin with organic mat is predominantly aerobic and that CO_2 evolution would likely be considerable.

In interpreting the I_R profiles, it is important to remember that a true I_R value less than one is not possible unless the conductive properties of the medium increase. This would require a disturbance of the subbasin matrix, and is unlikely. The only other likely cause would be the occurrence of clogging in the control layer. This would result in overestimation of flux through the subbasin profile and, in turn an overestimation of $K(S)_t$ for each layer. The final result would be an underestimate of the true I_R because of a falsely small numerator in Eq. 6. One possible component of the overestimation of flux from clogging of the control layer would be a gradient increase, which would result in a greater calculated flux. Another possibility, however, would be in the direct overestimation of K(S) due to gas entrapment. Norum and Luthin (1968) have discussed the effect of air bubble entrapment as a component of hysteresis in determining K(S). Hydraulic conductivity is a direct function of conducting porosity, while suction is related to the miniscus of the atmosphere and pore water interface, which would not be sensitive to entrapped air within the water column. Because flux calculations are based on K(S), the result of air bubble entrapment would be a decrease in K for a given suction [lower K(S)]. This could result in an overestimate of flux during the period of entrapment.

Site L1A

A rising hydraulic gradient did not occur in the control layer (53 to 69 cm) or in the overlying layer (38 to 53 cm). Rising gradients for 1 to 8, and 22 to 38 cm layers (Fig. 47) occurred prior to 75 hours, indicating initial clogging at those depths. Thereafter, decreasing gradients for both layers occurred. All hydraulic gradients were stable within 200 hours of the initiation of the experiment.

Early rises in I_R for 0 to 1, 1 to 8, and 23 to 38 cm layers agreed with hydraulic gradient data in indicating early clogging for those depths (Fig. 48). Reasons for the decrease in I_R between 75 and 200 hours are not certain, but the extent of the decrease (I_R < 1) indicates that either a temporary or transitory failure of the method for calculating I_R occurred. Although no increase in control layer hydraulic gradient was observed, one possible cause could be hysteresis of the control layer K(S) function caused by gas bubble entrainment. The upward bulge of flux values calculated for site L1A at 75 hours (Fig. 49) is consistent with this hypothesis. However, physical and chemical supporting evidence is insufficient to fully define the causes of the observed hydraulic phenomena. A similar I_R profile occurred for site L3A, with falling I_R between 75 and 200 hours, and the behavior of these two sites may be related.

If the falling I_R was due to transitory causes, then the extent of clogging was 1000 times pre–test impedance for the surface 1 cm , and 35 times pre–test impedance for the 1 to 8 cm layer, with no clogging indicated for the subbasin beneath 8 cm. If the decreasing I_R was due to a stable clogging agent, then these estimates are conservative and some clogging below 8 cm may have occurred. Following desiccation and raking of the filter–cake layer, almost total recovery occurred in all layers (Fig. 50). The degree of recovery supports the hypothesis of transitory (solid or gaseous) inducing a significant portion of the clogging below 1 cm.

Site L1B

Hydraulic gradient data (Fig. 47) indicated two transitory clogging phases for the control layer (38 to 53 cm in this case). The first phase was from initiation to 45 hours,

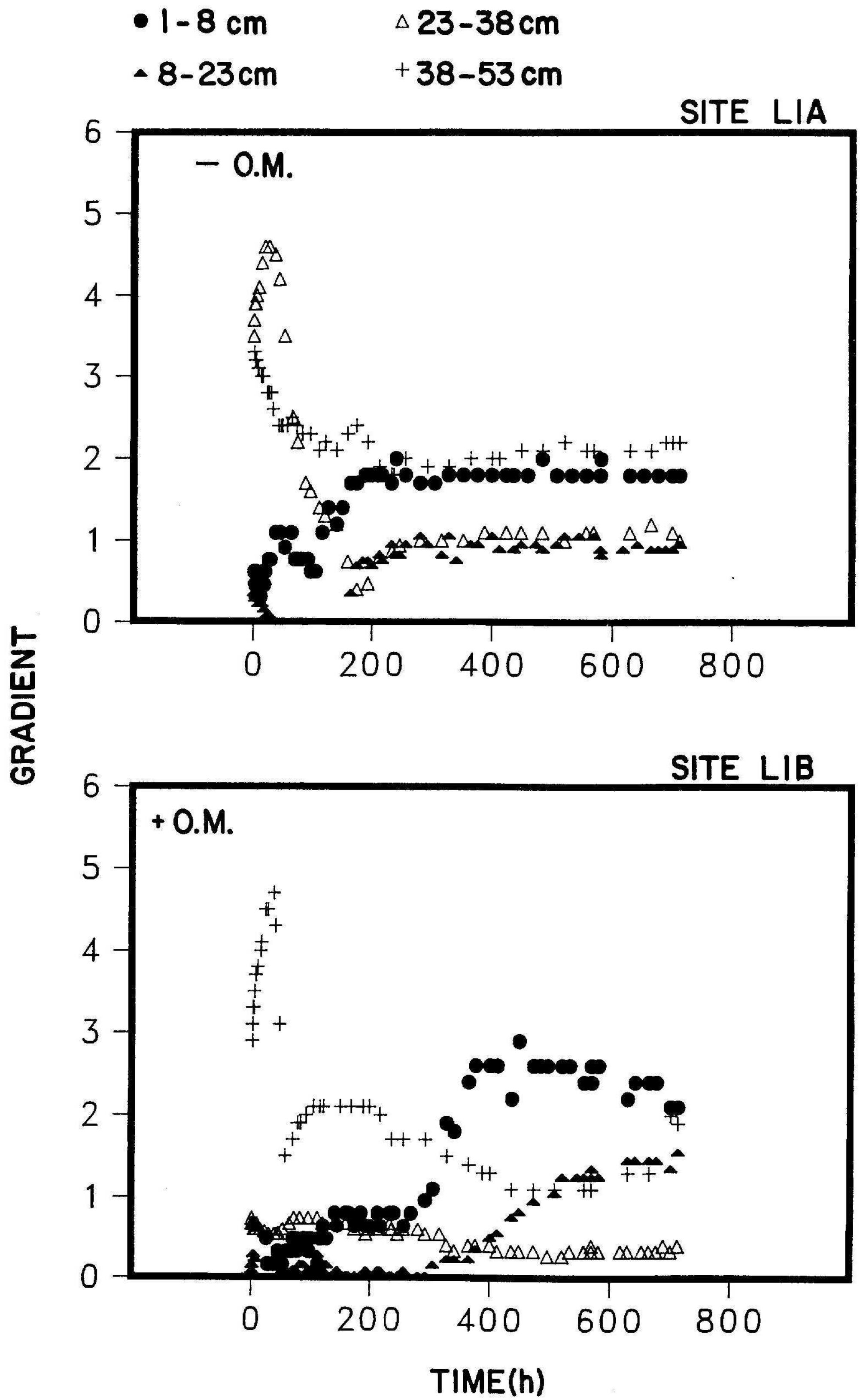


Fig. 47. Hydraulic gradient measurements for paired check (L1A) and organic mat covered (L1B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M. = with organic mat. - O.M. = check.

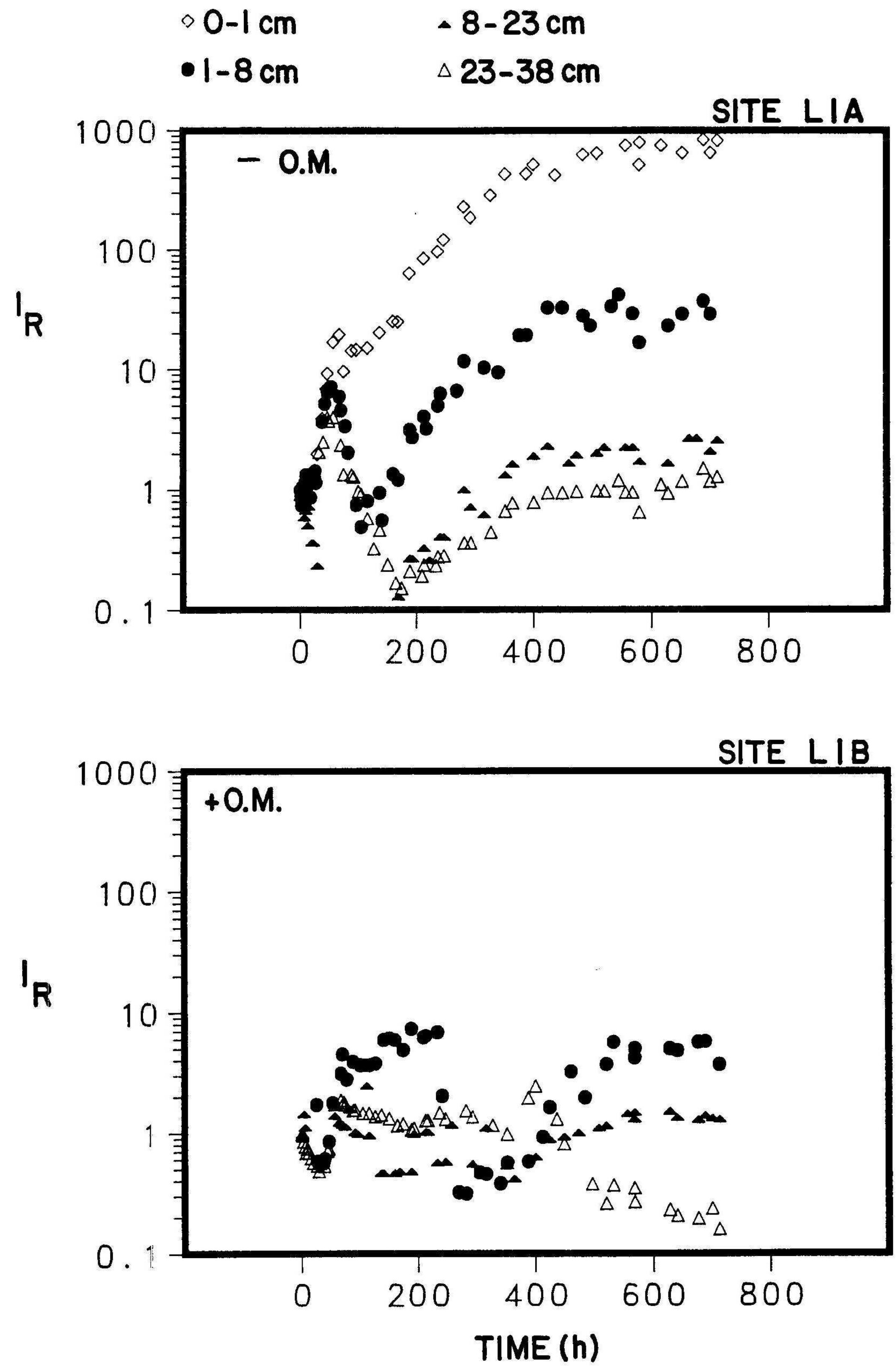


Fig. 48. Impedance ratio measurements for paired check (L1A) and organic mat covered (L1B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M. = with organic mat, - O.M. = check.

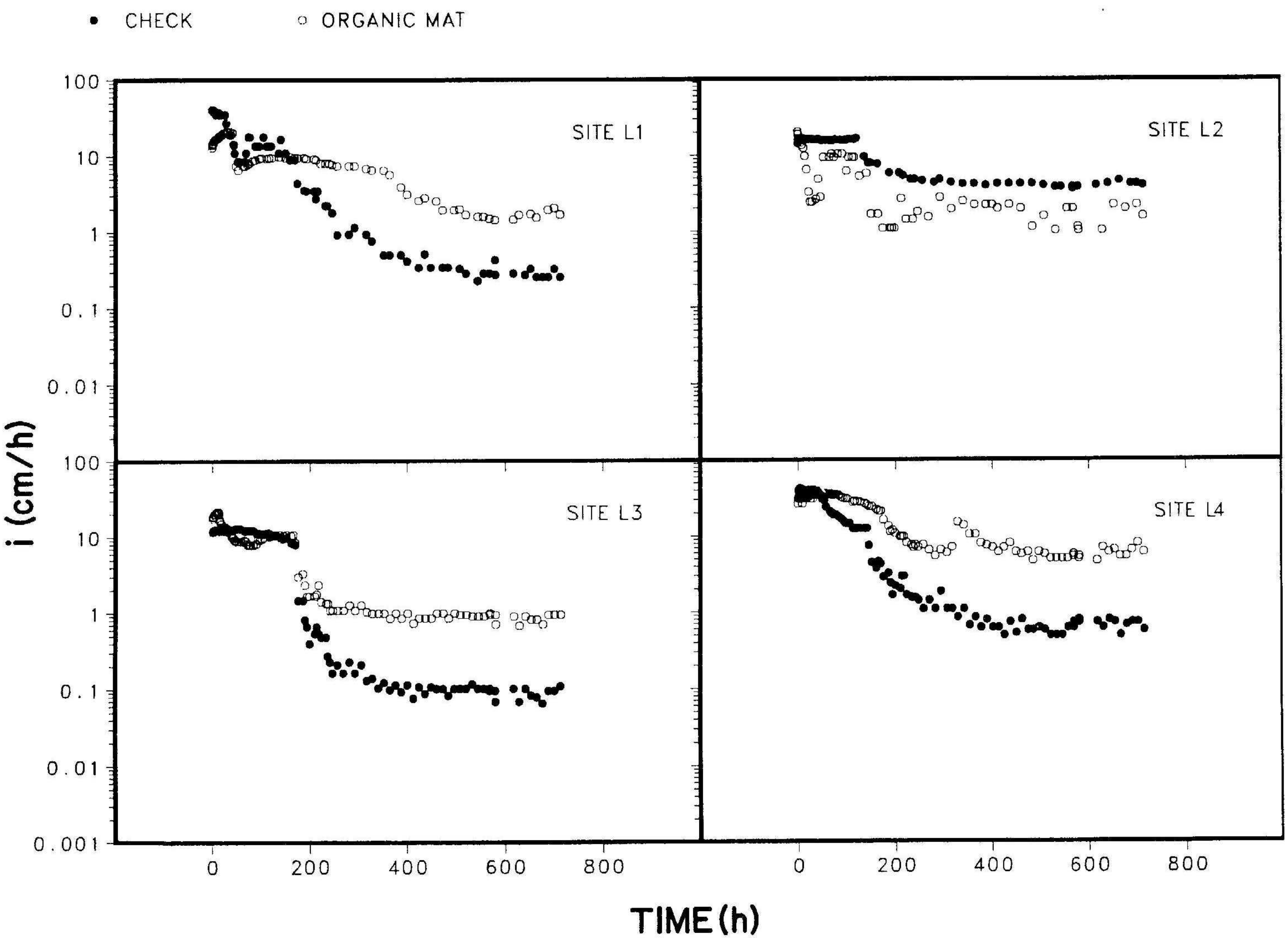


Fig. 49. Infiltration rate measured at in-situ basin monitoring sites L1, L2, L3, and L4 for check (non-covered) and organic-mat covered treatments.

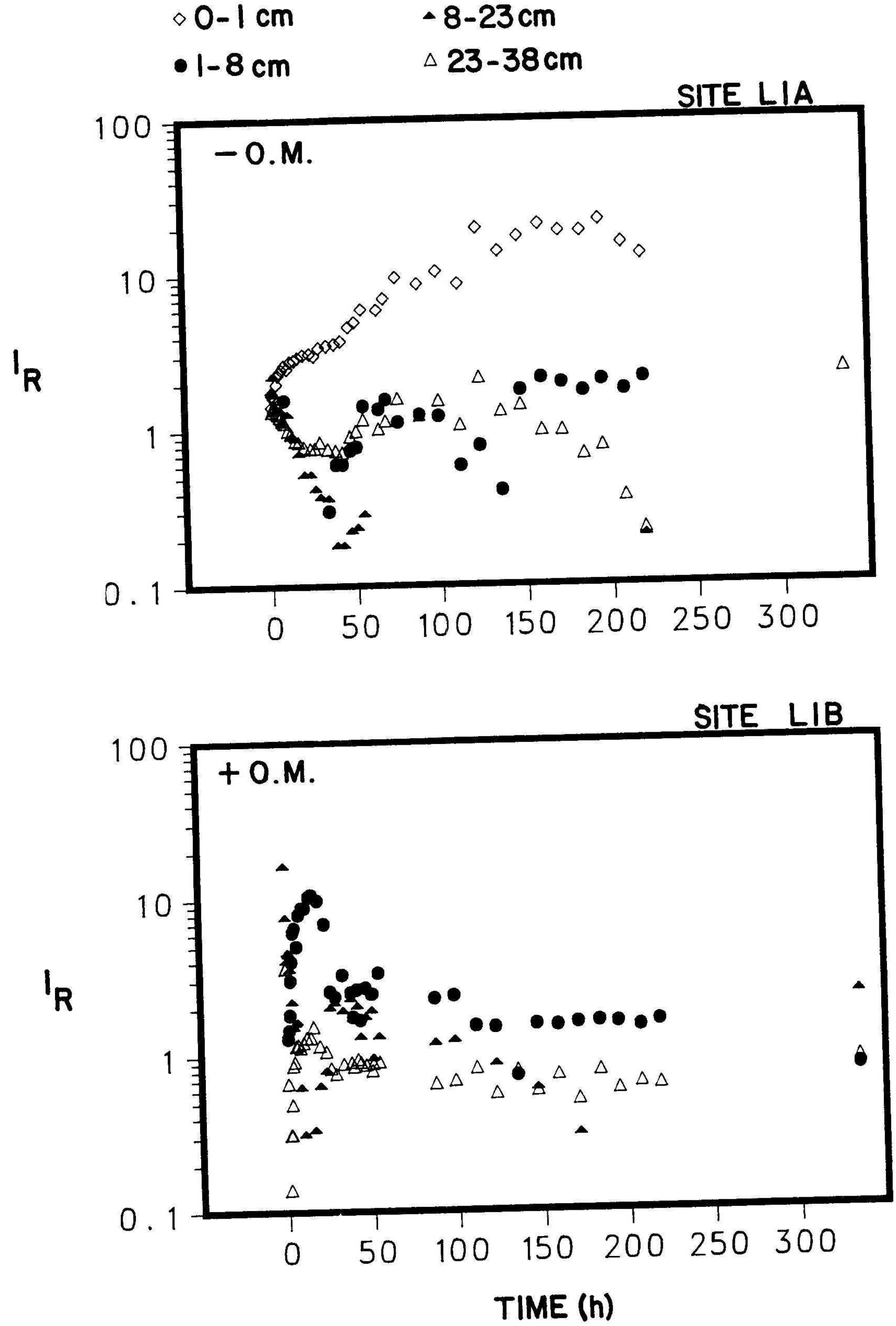


Fig. 50. Impedance ratio measurements for paired check (L1A) and organic mat covered (L1B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test - after natural renovation by desiccation. + **O.M.** = with organic mat, - **O.M.** = check.

followed by a sudden drop in gradient. The abrupt fall in hydraulic gradient at 45 h was caused by the intersection of a rising perched ground–water mound (initiated beneath the zone of tensiometer instrumentation) with the 53 cm tensiometer. The mound thus formed was shortlived, and began to dissipate immediately. The second rising phase was from 60 to 150 hours, and was gradual. After 150 hours clogging occurred in the 1 to 8 cm layer. After 400 hours clogging was indicated by increasing gradient in the 8 to 23 cm layer.

Impedance ratio data for all layers exhibit decreased I_R for times corresponding to the clogging peaks indicated for the control layer (Fig. 48). The 1 to 8 cm layer underwent an I_R increase by a factor of 10 (compared with 40 for the check profile) and layers beneath 8 cm exhibited little evidence of clogging. After desiccation, no clogging was indicated below 8 cm (Fig. 50). The 1 to 8 cm layer retained some large pore obstruction, effective at early operational times. During the basin operation, substantial recovery was indicated from desiccation for smaller, later draining pores.

Site L2A

Hydraulic gradient data (Fig. 51) indicate no clogging of the 'control' layer (38 to 53 cm). The 23 to 38 cm layer exhibited no initial clogging, followed by a sudden abrupt increase in gradient at 150 hours and then a steeply falling gradient. The abruptness of the gradient changes suggests a transitory clogging agent. Clogging of the 1 to 8 and 8 to 23 cm layers is indicated by increasing gradients following 325 hours of operation.

The surface 1 cm increased from 1 to 500 times pre–test impedance during the first 300 hours of basin operation (Fig. 52). A transitory increase in the impedance of the 23 to 38 cm layer corresponded with the period of rising gradient (at 200 hours). Similarly, I_R increased by a factor of 10 for 1 to 8 cm and 8 to 23 cm layers after 325 hours of operation. Following desiccation, complete recovery of the 23 to 38 cm layer occurred (Fig. 53), supporting the likelihood of a transitory agent such as microbial solid products or gas production during the initial basin operation. Little recovery was observed for the 8 to 23

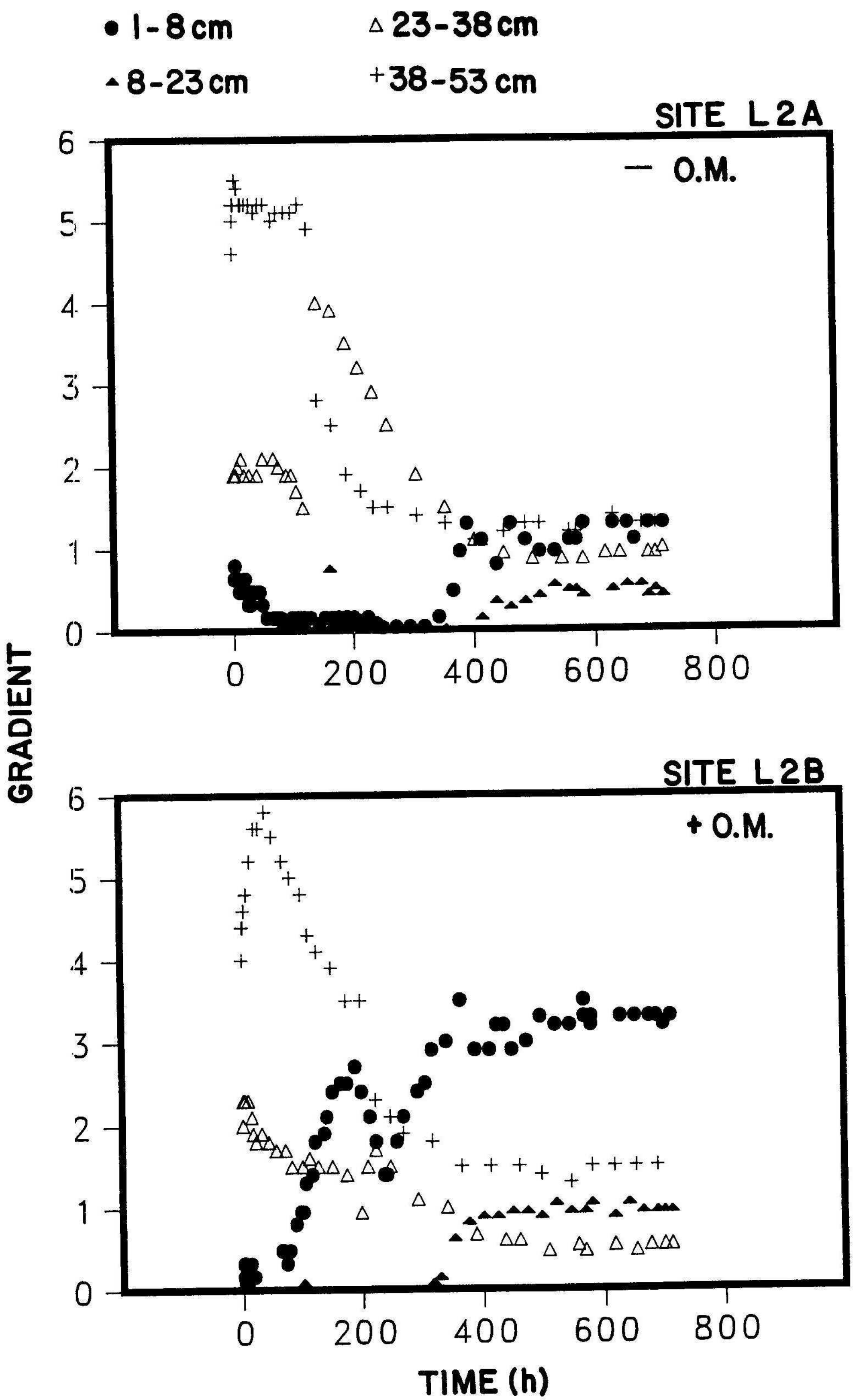


Fig. 51. Hydraulic gradient measurements for paired check (L2A) and organic mat covered (L2B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M. = with organic mat, - O.M. = check.

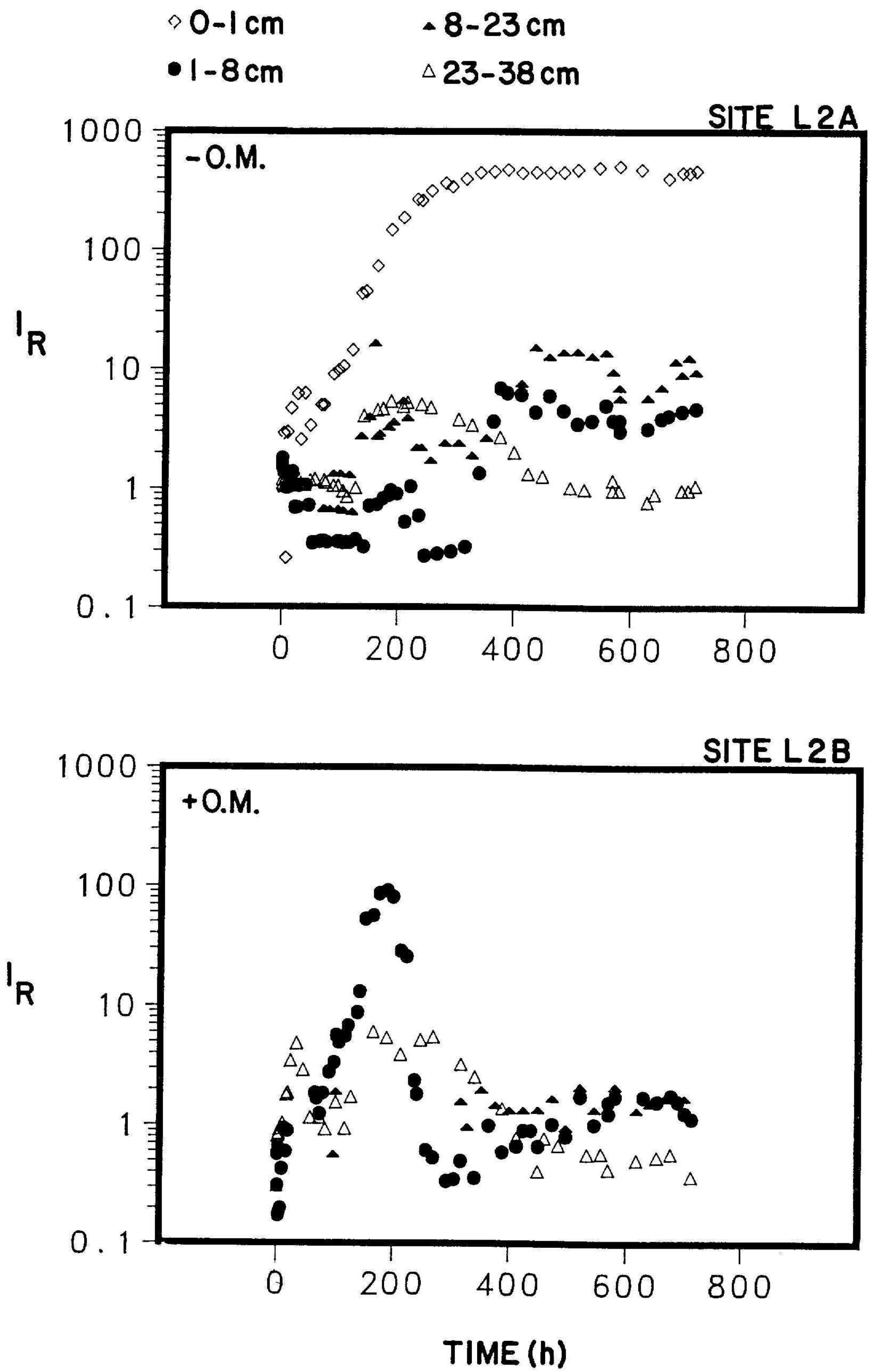


Fig. 52. Impedance ratio measurements for paired check (L2A) and organic mat covered (L2B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test.

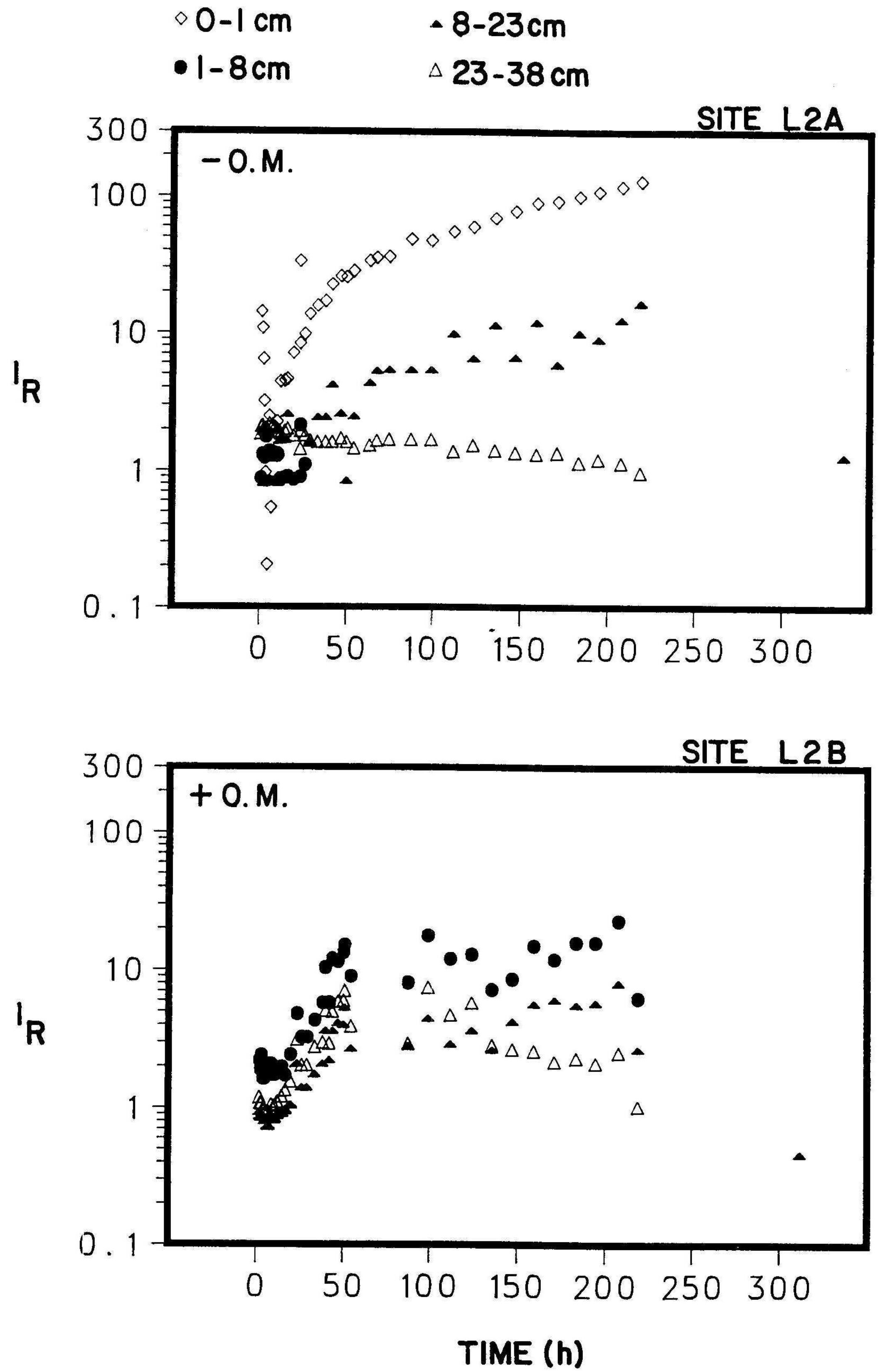


Fig. 53. Impedance ratio measurements for paired check (L2A) and organic mat covered (L2B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test - after natural renovation by desiccation. + O.M. = with organic mat, - O.M. = check.

cm layer following desiccation. I_R values were slightly higher than for comparable times in the preceding operation. The surface 1 cm data indicated a substantial initial recovery, but I_R values increased much more rapidly than in the preceding basin operation (reaching 30 at 50 hours, compared with 6 at 50 hours for the pre–desiccation experiment).

Site L2B

No gradient increase for the control layer (53 to 69 cm) was observed (not illustrated.). However, an increasing gradient for the 38 to 53 cm layer occurred during the first 50 hours (Fig. 51). The initial increase in hydraulic gradient at 38 to 53 cm resulted from an increasing pressure head at 38 cm. This increase was caused by a rising ground–water mound perched on a layer of high impedance between 38 and 53 cm. It was not caused by clogging. The 23 to 38 cm layer exhibited a falling gradient throughout the basin operation, except for a minor rise at 200 to 225 hours. Increased gradients for the 1 to 8 cm layer occurred up to 400 hours.

The I_R data (Fig. 52) indicated an increase in impedance by a factor of 6 for the 23 to 38 cm layer between 100 and 200 hours. An increase in I_R (up to 100 times pretest impedance) for the 1 to 8 cm layer occurred between initiation and 200 hours. No clogging of the 8 to 22 cm layer was indicated. Following desiccation, substantial recovery of the 1 to 8 cm layer occurred (Fig. 53). Reclogging occurred more quickly, but did not reach the extent of the previous experiment. The I_R profile for the 23 to 38 cm layer following desiccation was similar to the pre–desiccation I_R. The 8 to 23 cm layer also indicated some clogging during the period following desiccation.

Site L3A

Hydraulic gradient data did not indicate clogging of the control layer (53 to 69 cm). Clogging occurred at early times for the 38 to 53 cm layer, and ended at 50 hours (Fig. 54). Gradients for overlying layers appear to have dropped in response to the initial rise at 53 cm. Significant clogging for the 1 to 8 cm layer was indicated up to 200 hours.

Reasons for the falling I_R values (below 1) for the 1 to 8 and 8 to 23 cm layers prior to 200 hours are not certain (Fig. 55). The trough was similar to that seen for site 1A, and occurred at the same time, indicating a possible relationship between the events on the two sites.

If interference with the control layer did not occur, or if the clogging agent was transitory and gaseous, then no increase in impedance occurred in the 23 to 38 cm layer; a five fold increase occurred in the 8 to 23 cm layer; a 35 fold increase occurred at 8 to 23 cm; and the surface layer reached an impedance 1000 times measured before the experiment. If interference with the control layer due to a stable agent such as sediment clogging was the cause for the fall in I_R, then the above estimates are low, and constitute minimum values. It appears certain, however, that significant clogging occurred as deep as 23 cm.

Following desiccation, the surface 1 cm layer recovery was substantial, and reclogging of that layer occurred more slowly during the second operation (Fig.56). The I_R profiles for 1 to 8 , 8 to 23, and 23 to 38 cm layers were similar to the first experiment , prior to desiccation.

Site L3B

Hydraulic gradients (Fig. 54) indicate initial clogging at 23 to 38 cm, ending at about 75 hours. A slight rise in gradient from 85 to 150 hours was noted for the control layer (38 to 53 cm). Rising gradients in the 1 to 8 and 8 to 23 cm layers were observed after 200 hours.

Clogging of the 1 to 8 cm layer resulted in impedance values more than 100 times pre–test values (Fig. 55). Impedance between 3 and 4 times pre–test values was observed for the 8 to 23 and 23 to 38 cm layers.

After desiccation, substantial but incomplete recovery of permeability occurred for each of the clogged layers (Fig. 56). The 1 to 8 cm layer retained impedance at two to five

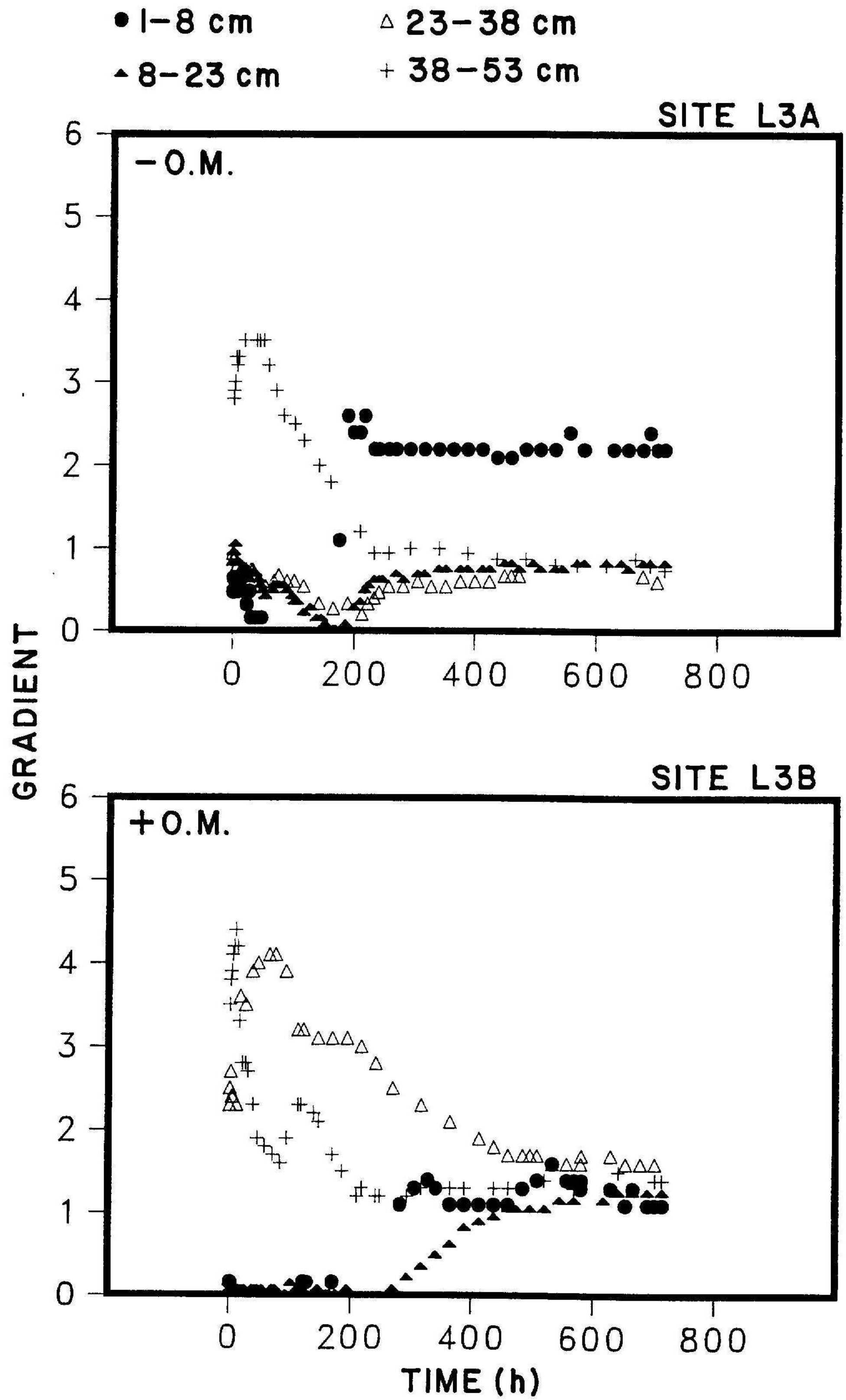


Fig. 54. Hydraulic gradient measurements for paired check (L3A) and organic mat covered (L3B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M. = with organic mat, - O.M. = check.

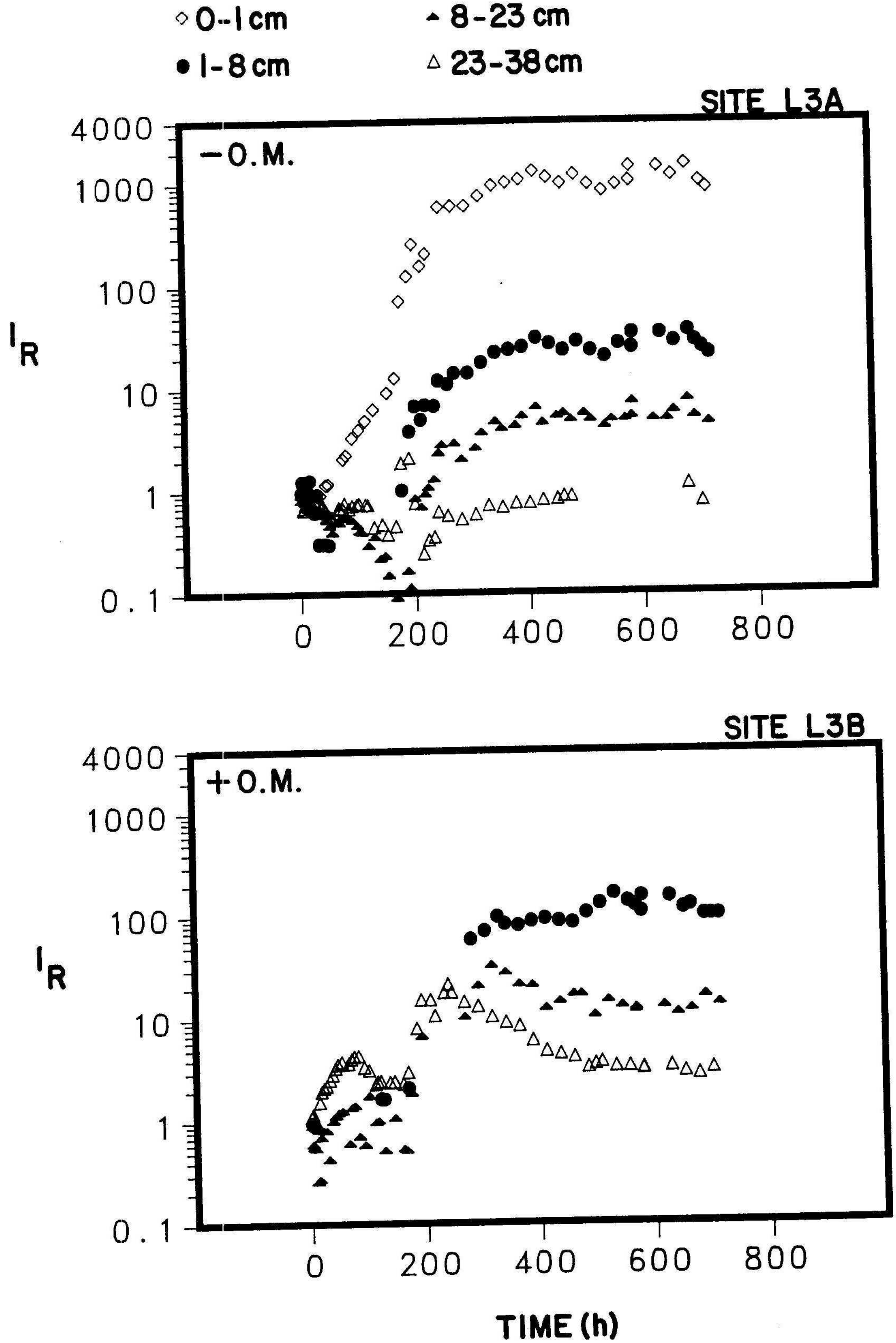


Fig. 55. Impedance ratio measurements for paired check (L3A) and organic mat covered (L3B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M. = with organic mat, - O.M. = check.

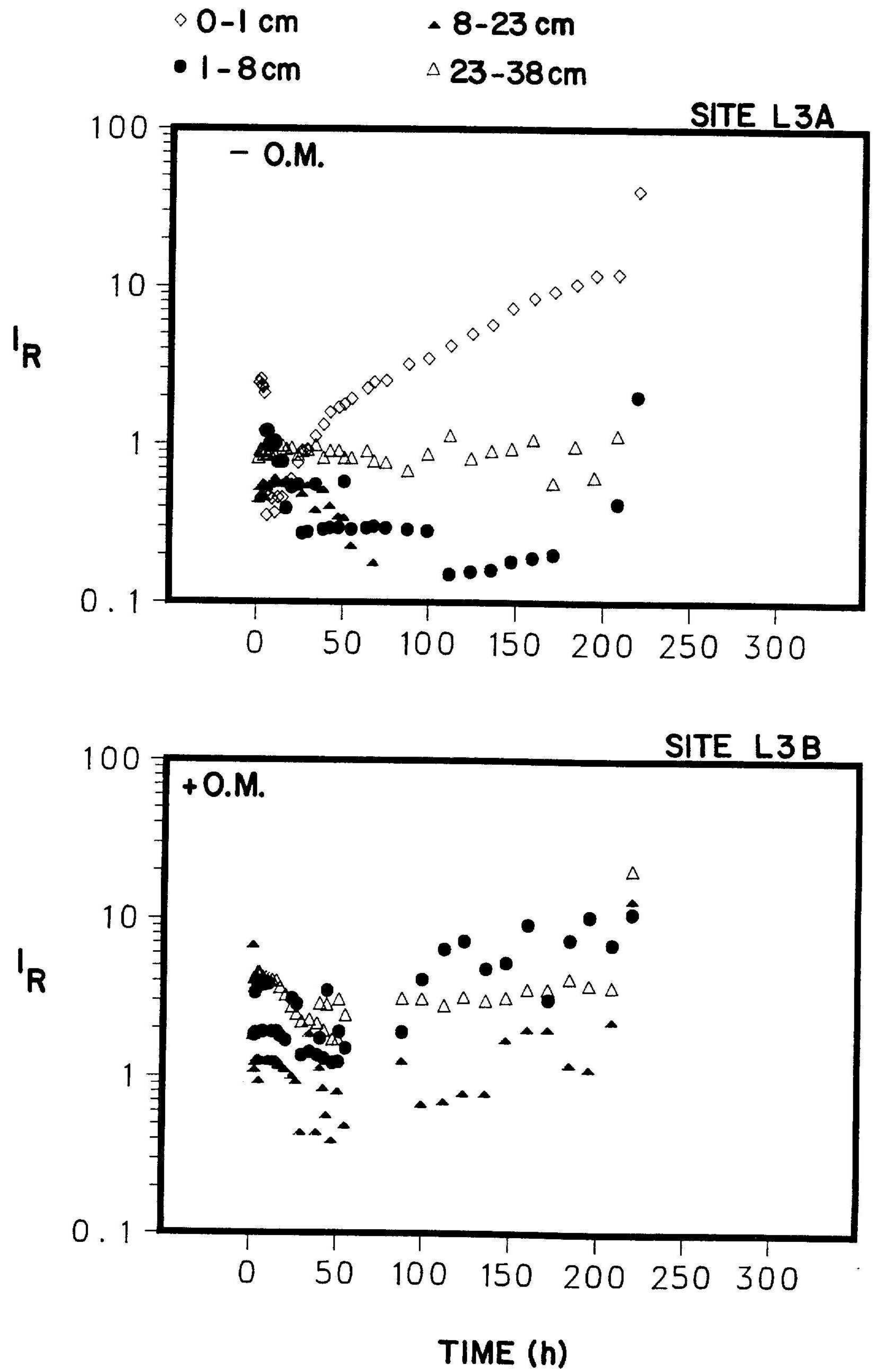


Fig. 56. Impedance ratio measurements for paired check (L3A) and organic mat covered (L3B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test - after natural renovation by desiccation. + O.M. = with organic mat, - O.M. = check.

times pre–test values, and the 23 to 38 cm layer began the post–desiccation operation with impedance five times that measured before the experiment.

Site L4A

Hydraulic gradient data (Fig. 57) indicate no clogging of the control layer (38 to 53 cm). Substantial clogging at 1 to 8 cm was indicated between 0 and 175 hours. Impedance ratios (Fig. 58) showed a 5000–fold increase in impedance over pre–test measurements for the top 1 cm, and nearly 700 times the pre–test impedance in the 1 to 8 cm layer. No impedance increase was found beneath the 8 cm depth.

Partial recovery of flow capabilities of the surface 8 cm was affected by the period of desiccation (Fig. 59). Immediate impedance values 10 to 20 times pre–test measurements were observed for 0 to 1 and 1 to 8 cm layers during the post–desiccation trial.

Site L4B

The clogging profile for site 4B is similar to site 4A, but is characterized by deeper clogging (23 to 38 cm) and by less intense clogging in the 1 to 8 cm layer. Impedance values 10 to 20 times pre–test measured values (Fig. 57) were observed for the 1 to 8 and 23 to 38 cm layers under the organic mat, while no increase in impedance was found for the 8 to 23 cm layer. An abrupt rise in control layer hydraulic gradient at about 300 h indicates some form of later clogging occurring at that depth. This may have resulted in underestimation of I_R and flux at later times. Little recovery of the 1 to 8 cm layer was affected by desiccation of the basin floor (Fig. 58). After desiccation I_R values of 10 were immediately found (Fig. 59). No initial clogging below 8 cm was observed after desiccation. Falling I_R values for deeper layers (below $I_R = 1$) may have been due to clogging of the control layer (38 to 53 cm) as indicated by the slight rise in gradient between 0 and 50 hours for the post–desiccation run. Clogging of the control layer was likely caused by a microbial product (solid or gas), since it is believed that sediment

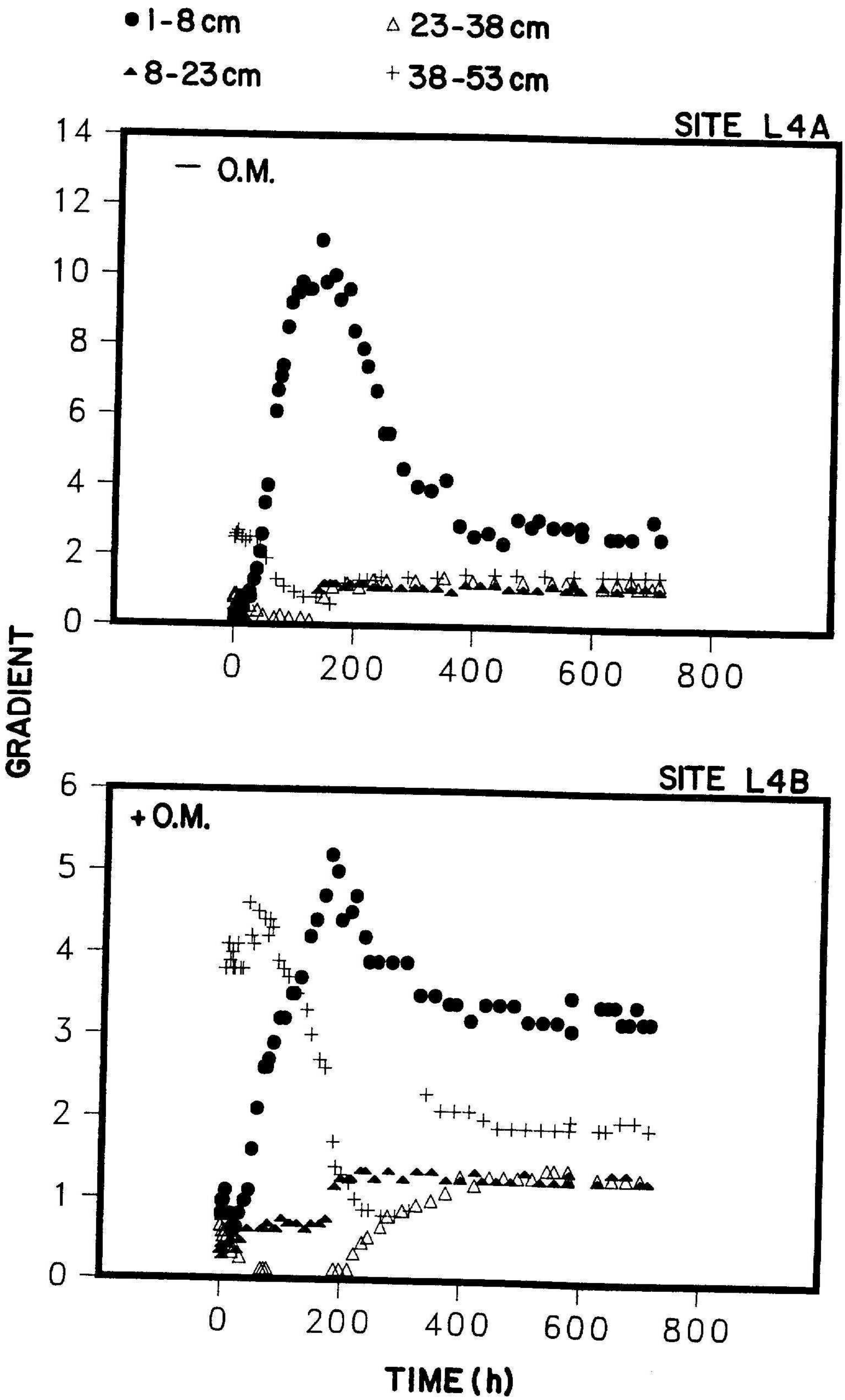


Fig. 57. Hydraulic gradient measurements for paired check (L4A) and organic mat covered (L4B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M. = with organic mat. - O.M. = check.

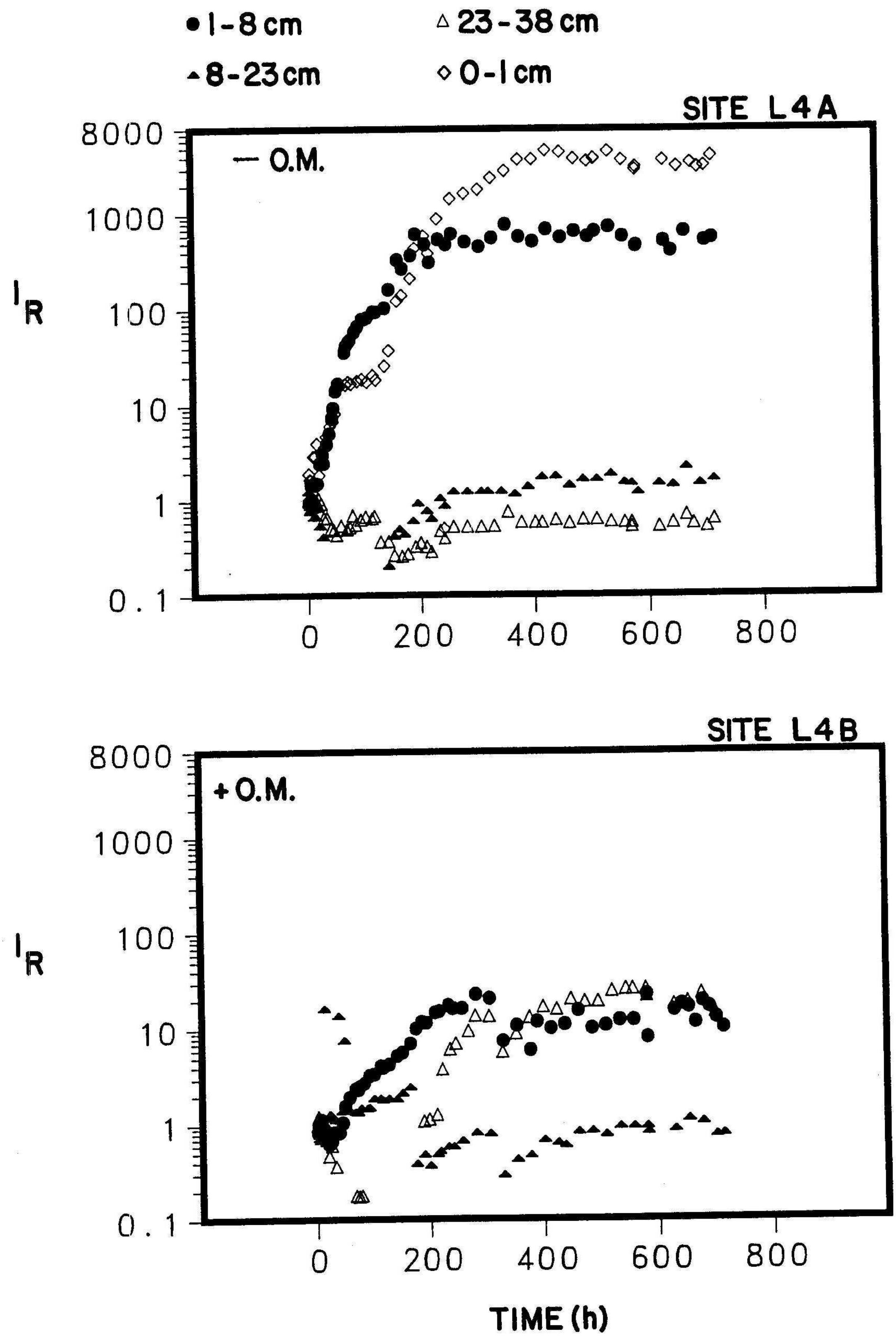


Fig. 58. Impedance ratio measurements for paired check (L4A) and organic mat covered (L4B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test. + O.M = with organic mat, - O.M. = check.

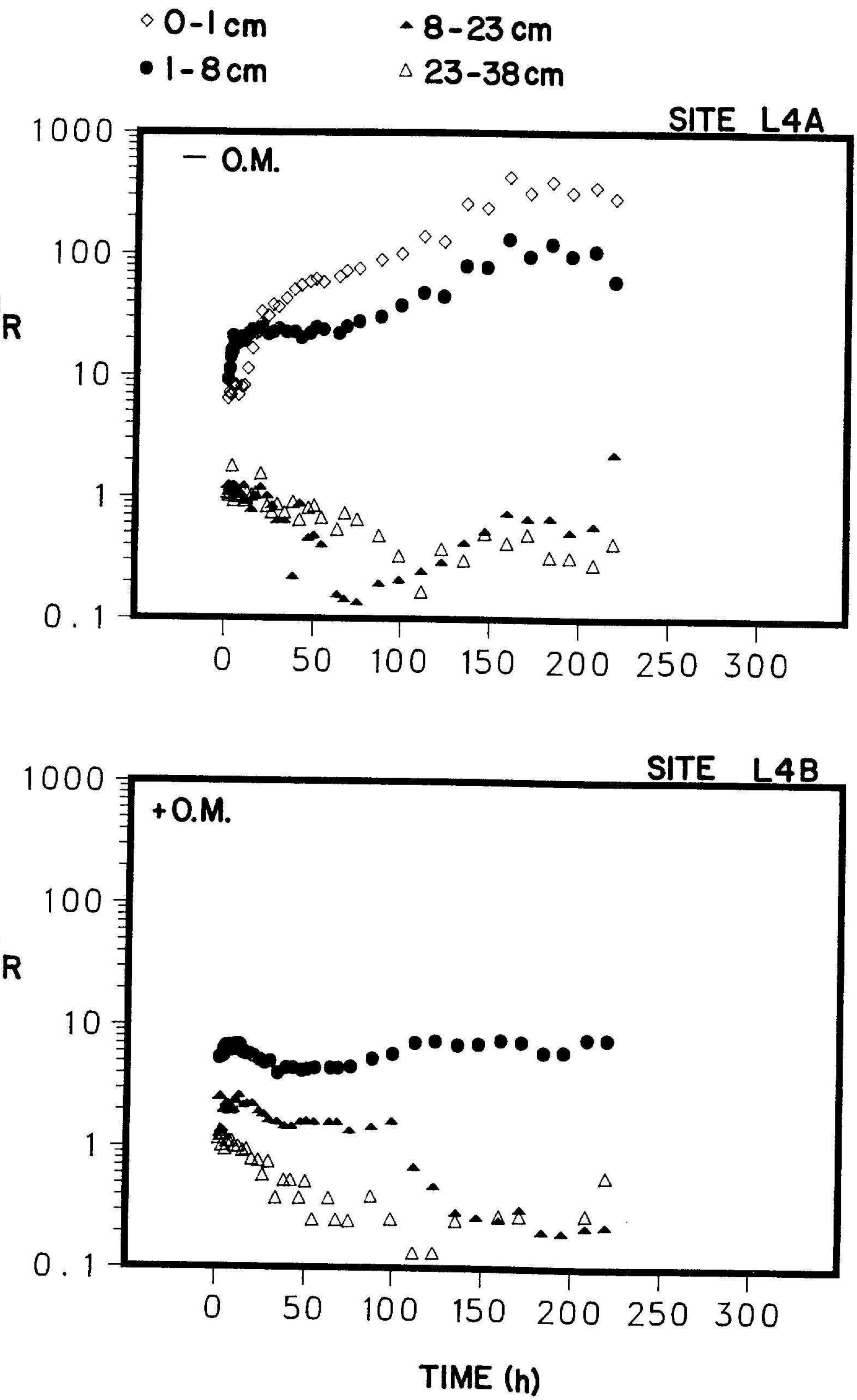


Fig. 59. Impedance ratio measurements for paired check (L4A) and organic mat covered (L4B) in-situ hydraulic monitoring sites during the 1987 Organic Mat test - after natural renovation by desiccation. + O.M. = with organic mat, - O.M. = check.

deposition would exhibit some continuity from the surface to the maximum depth of deposit.

Flux Comparison for In–Situ Sites

Infiltration rates calculated for in–situ measurement sites of check and organic mat covered areas are compared on Fig. 49. Initial infiltration rates for each pair are similar at early times, but for three of the four measured sites the filter covered areas sustained greater infiltration rates than the check areas for most of the operational period. Slight upward bulges in the calculated infiltration functions are believed to be due to gas entrainment within the control layers used to calculate flux and they are believed to represent a temporary overestimate of flux. If the cause of the bulge is due to a permanent clogging agent, then the entire flux vs. time relationship may be slightly high. The differences illustrated between mat covered and check positions are substantial, however, and should be well in excess of inaccuracies introduced by transient clogging within the subbasin.

Summary for Organic Mat Operation Tests

The use of a 10 cm (4 in.) composted sunflower–seed hull organic mat resulted in a substantial increase in the recharge capability of the test basin over a 30 day operational period – compared with Fall 1986 and Spring 1987 operations without mats. Despite sediment loads nearly double those of earlier tests, the organic mat resulted in total recharge more than 1.8 times that achieved under previous experiments without the organic mat filter. Comparisons between filter covered and non covered areas within the basin also indicated substantial increases in sustained infiltration rates through the filtered areas. Following a 21 day period of desiccation and a light raking (to simulate a light dragging operation)of the surface filter cake which formed on top of the mat, a complete initial recovery of infiltration rate was effected. The recovery, however, was brief and the post–desiccation infiltration quickly declined to levels beneath those of the initial run. In terms of total recharge at comparable operation times, only a 38 % recovery was effected. The investigators believe that a greater level of recovery would be likely with deeper tillage (and lofting) of the organic mat layer.

A filter cake similar in composition to previous tests formed on the surface of the organic mat. Silt particles were preferentially intercepted on the surface, while clay particles penetrated more deeply into the soil profile. A secondary filter cake did not form at the boundary of the organic mat and the underlying sand. The organic mat failed to fully filter clay particles, and clay penetrated deeper into the subbasin sand than in previous experiments without the organic mat filter. Clay penetration was statistically verifiable to 23 cm, but may have been deeper still. Organic carbon penetration was significantly greater only to 1.3 cm. A sample comparison of filter covered areas of the basin with uncovered (check) areas indicated a higher portion of shallow clay deposition without the mat. The deeper deposition of clay with the organic mat may have been due to greater sustained approach velocities of the particles, and to higher total load added to the basin during the organic mat operation.

Characterizing impedance development within the subbasin profile was more difficult than in previous tests due to apparent clogging of the control layer in some cases, and due to what appeared to be transient clogging within some deeper subbasin layers. In some cases impedance increases occurred deep in the measured profile, without apparent clogging in overlying layers. It is probable that the addition of the carbon substrate and nutrient enrichment supplied by the organic mat resulted in the proliferation of clogging agents other than particulate matter supplied by the suspended load of the James River water.

A comparison of in–situ hydraulic property changes of organic mat covered areas with check areas yielded ambiguous results, with greater depth of impedance development in organic mat layers in some cases and greater depths of clogging in check layers in others.

In general, 8 cm was the greatest depth indicated for significant impedance from a stable agent (nonrecoverable with desiccation). Clogging was indicated for underlying layers (23 to 69 cm) but seemed to be transient during the period of basin operation, and was largely recoverable during the period of desiccation, which suggests a nonstable (gaseous or solid microbial biproduct) agent . Overall, the greatest increases in impedance were above the 8 cm depth.

Although the recharge capability of the basin was greatly enhanced by the use of a surface organic mat, long–term implications of the use of a mat filter need further investigation. First–run recharge enhancement was excellent. The post–desiccation recovery was somewhat disappointing and indicated that the mat itself might lose conductive capabilities. However, further management, such as drying of the entire layer (rather than just the surface) or deeper tillage to loft the mat and restore porosity, might well enhance the usefulness of an organic mat filter. Possible deeper penetration of sediment beneath the organic filter would impact the cost effectiveness of long–term restoration of the facility, and bears further examination.

FLUX ATTENUATION DUE TO TURBID WATER: OVERVIEW

Infiltration vs. Time

Loss of infiltration capacity during basin operation varied between tests and was influenced by specific sediment loads and management practices. Results have been discussed in detail for each test. However, it is useful to briefly compare all of the tests to illustrate the variation encountered during the basin investigations. No simple functional relationship (linear, semi–log, log–log, etc.) was found to be appropriate for the full operational time on all of the tests conducted. However, it was observed that on all of the tests an approximate linear rate of flux attenuation was established within one day of test initiation, and was maintained until further changes in flux became almost negligible. A comparison of flux attenuation slopes for all tests is provided on Figures 60 and 61.

Fall 1986, Spring 1987, and Spring 1987 + Desiccation tests (Fig. 60) indicate a range of 3.5 to 5.2 cm/h^2 for flux attenuation under conditions of full renovation, compared with more than double that rate of attenuation (13.1 cm/h^2) for the test following natural desiccation, without removal of filter–cake materials. Average suspended solids for each basin operation were 64, 56, 56 mg/l, respectively. For the initial test with the organic mat (Fig. 61) the rate of flux attenuation is less than half that without the mat, indicating a significant prolongation of higher levels of infiltration. Suspended solids averaged 99 mg/l. Following desiccation (with the organic mat) initial recovery of infiltration rate was limited. However, the rate of further flux attenuation following desiccation was very slight, resulting in sustained delivery of recharge water to the water table. Following desiccation suspended solids averaged 59 mg/l.

Sediment Distribution Curves

Attenuation of infiltration rates has been discussed as a function of time. It would

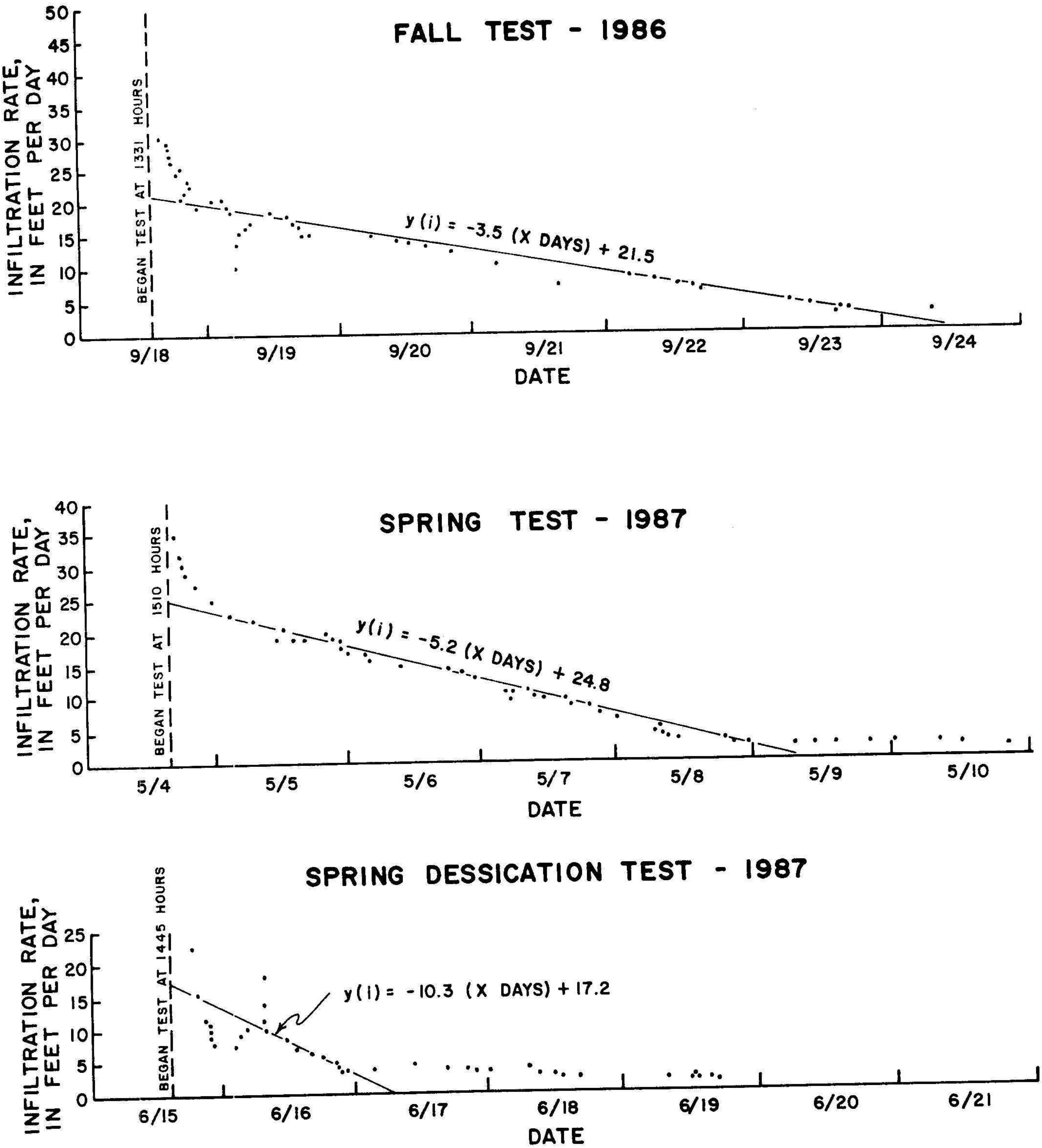


Fig. 60. Comparison of Fall 1986 and Spring 1987 (before and after desiccation) infiltration rates vs. time.

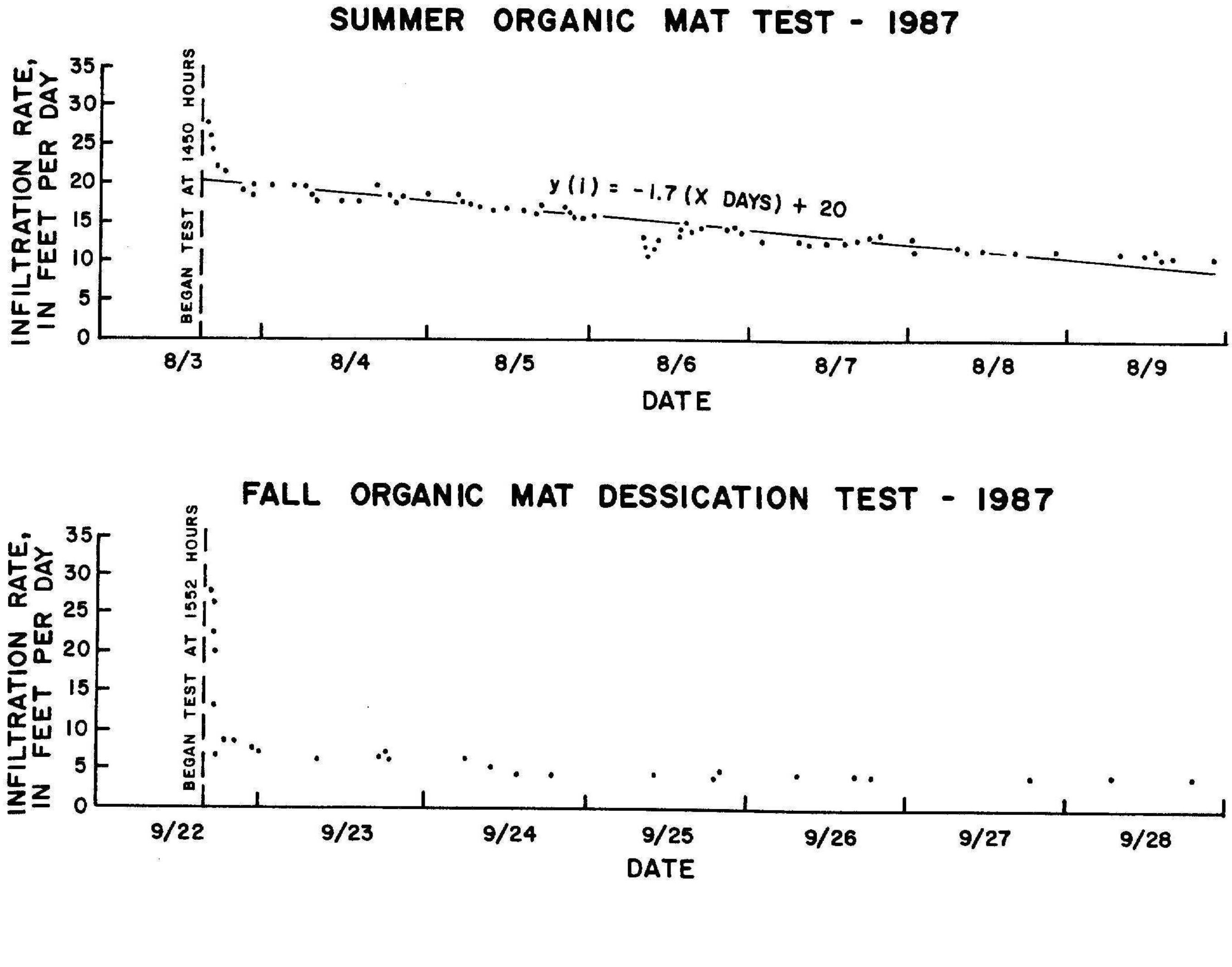


Fig. 61. Comparison of infiltration rates for 1987 Organic Mat tests before and after desiccation.

be most useful, however, to establish a predictive relationship between decreasing infiltration rates and the agents causing flux attenuation. While the importance of biological clogging has been well documented (Ripley and Saleem, 1973; Okubo and Matsumoto, 1979; Allison, 1947), suspended solids have been found to dominate the clogging process when present (Rice, 1974). Establishing transferable relationships for describing clogging phenomena can be difficult, however. Theoretically–based models have been developed by Iwasaki (1937), Ives (1970), and others to describe filtration through materials of uniform composition. Simple empirical models have also been derived (Harmeson et al., 1968; Behnke, 1969). McDowell–Boyer et al. (1986) have presented a comprehensive review of research on porous media filtration. Attempts to relate recharge rate to accumulated suspended solids in predictive models in a consistent and transferable manner have met with limited success. Jones et al. (1974) reported poor results in attempting to use cumulative suspended sediment delivered as a predictor of infiltration rate. For this experiment, the model of Behnke (1969) was used for each basin operation. Predictive results were poor in all cases.

Basin average, and local in–situ infiltration rates vs. specific deposit (mg/cm^2) are shown for the 1986 large basin test on Figure 62. As with i vs. t, there was large spatial variability within the basin. For the Spring 1987 test, Fig. 63 illustrates the difference in i attenuation due to sediment deposition before and after desiccation. The amount of sediment required after desiccation to effect a degree of clogging comparable to that of the first (fully renovated) spring operation is nearly an order of magnitude less. This is not surprising, considering that all of the sediment from the first operation remains on the basin floor, and would be expected to increase basin floor sealing after rewetting and repositioning. The rate of infiltration rate attenuation for the Organic Mat test (Fig. 64) is much less than for the Spring fully renovated test. It is noted that i still exceeds 1 cm/h after nearly 500 mg/cm^2, compared with less than 0.3 cm/h for the Spring test with less than 150 mg/cm^2 specific deposit. The large early decrease of i for the Organic Mat test

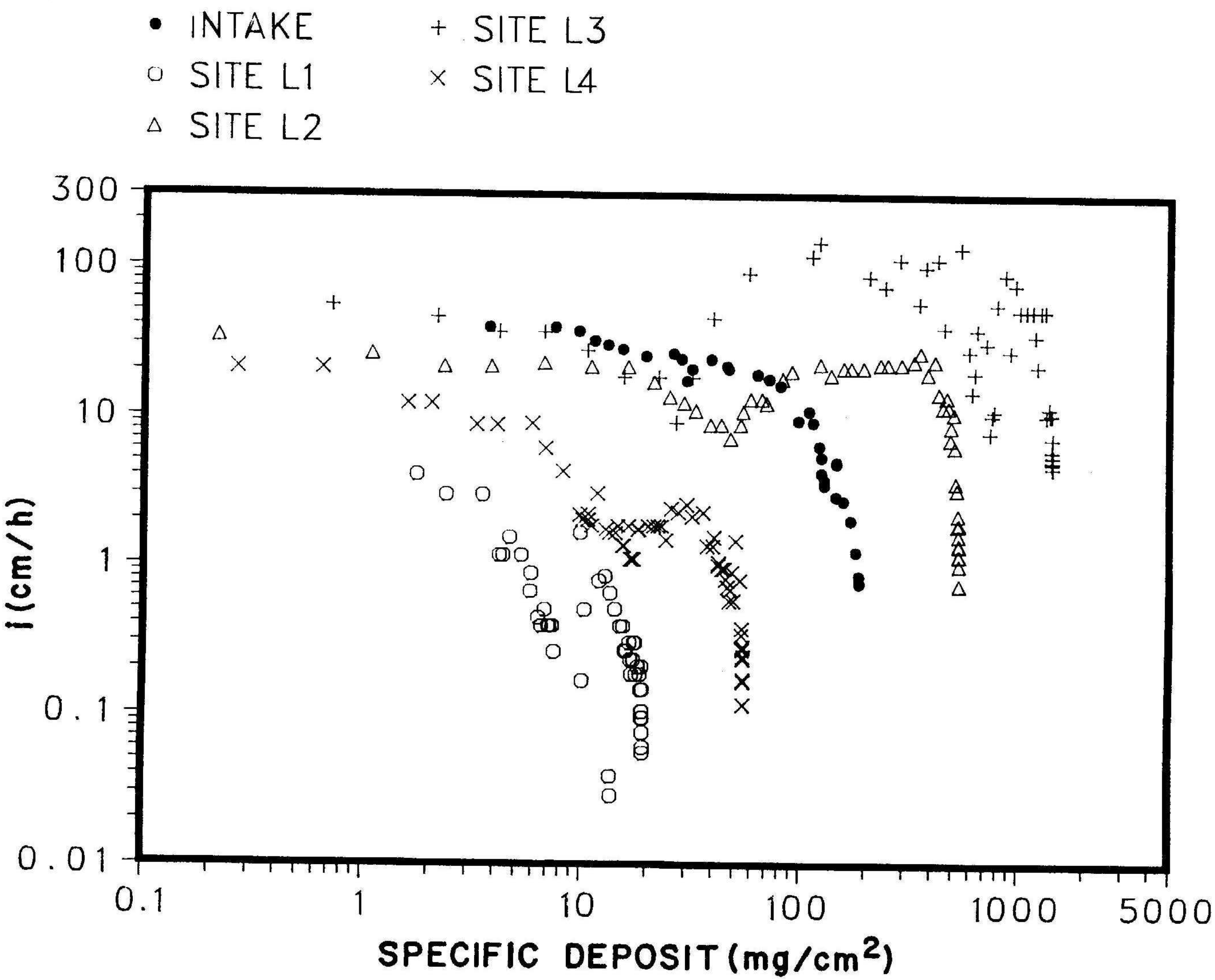


Fig. 62. Infiltration rate vs. cumulative suspended solids delivered to the basin during the Fall 1986 test.

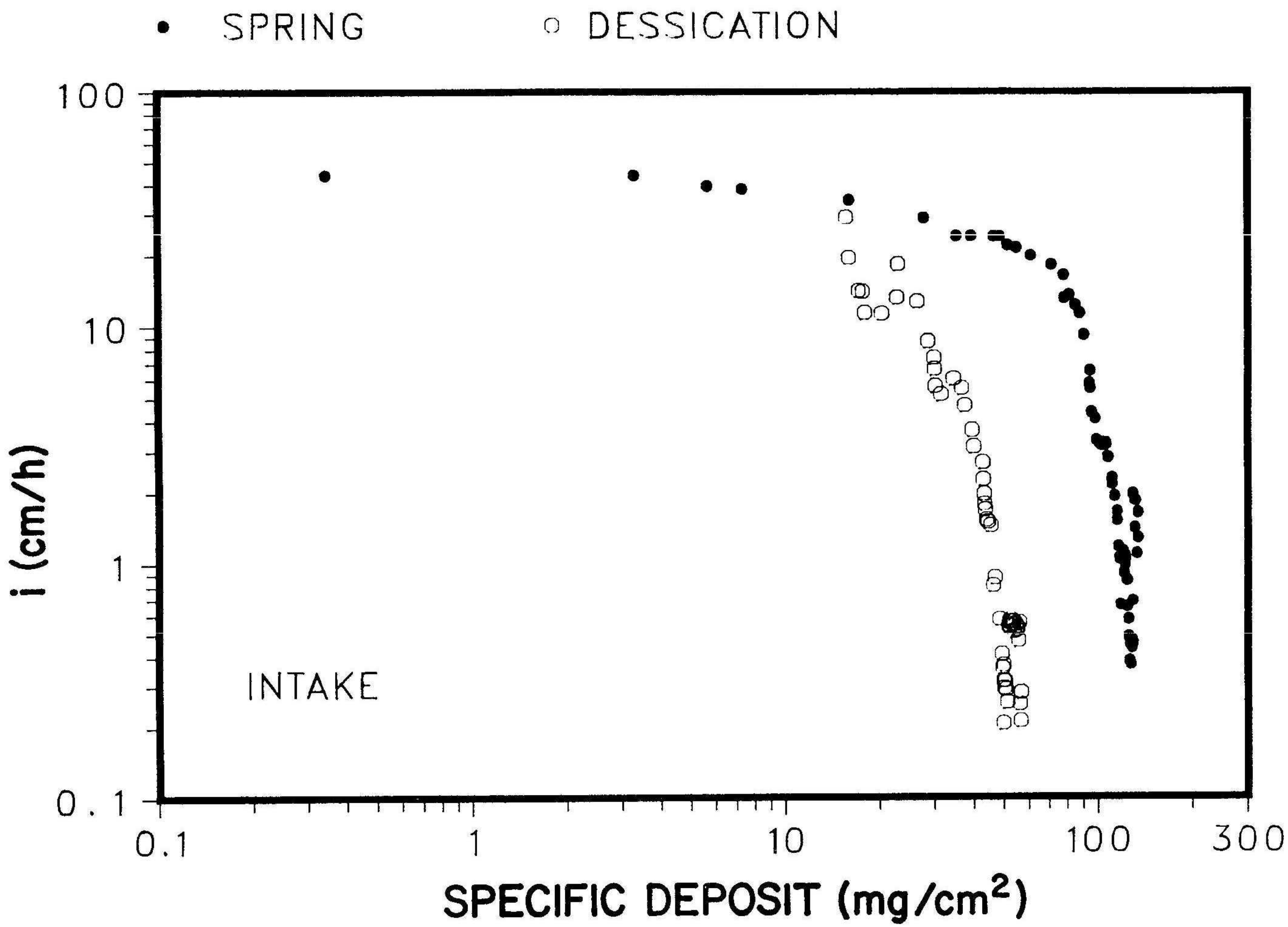


Fig. 63. Infiltration rate vs. cumulative suspended solids delivered to the basin, before and after desiccation during for the Spring, 1987, basin test.

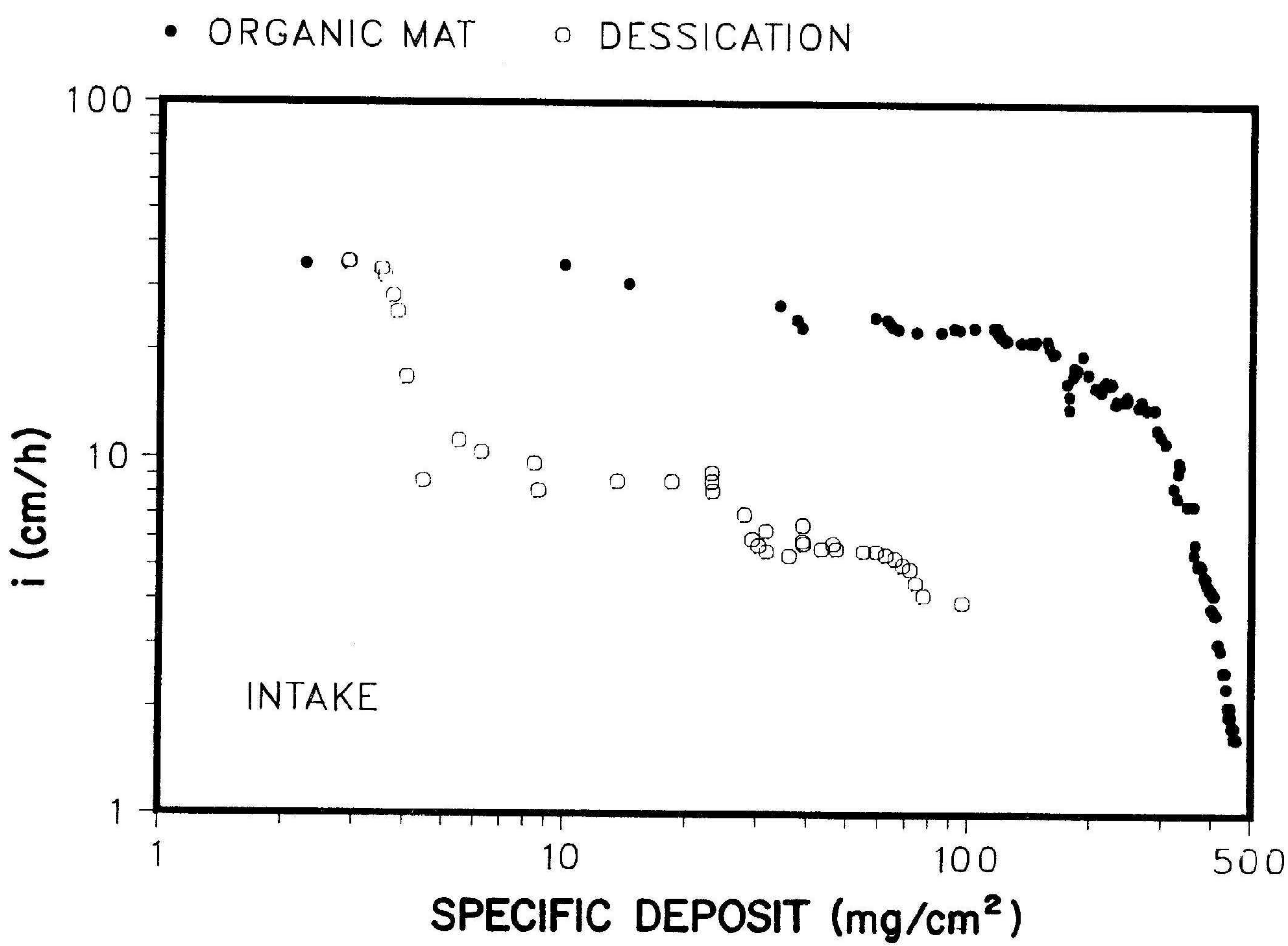


Fig. 64. Infiltration rate vs. cumulative suspended solids delivered to the basin, for the Organic Mat, and Organic Mat + Desiccation tests.

following desiccation (Fig. 64) may be due to compression and consolidation of the mat, as well as due to sediment interception within the mat. It is thought that further drying and tillage of the mat might increase the degree of recovery.

Although modeling may provide a future means of evaluating potential attenuation of infiltration rates, i vs specific deposit relationships are, at present, impractical to predict on a wide scale. The authors agree with Bianchi and Muckel (1970) that there is no substitute for an on site pilot project, as a part of the implementation of large scale facility design and operation. A design based on conservative capability criteria should be prepared. It should then be implemented in stages, working with management technique options to optimize recharge for each stage of completion. At each stage of completion the total needs of the project should be reassessed, paring away any unnecessary planned facilities or measures.

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SUPPLEMENTAL DATA

SUPPLEMENT 1

Test Hole and Observation Well Record

Location: 131-59-29DDCB1

Use of well: test hole

Owner and number: SWC V1-1

Principal aquifer: Oakes

Depth drilled (in.): 197

Altitude of land surface (ft., msl): 1312.4

Screened interval (ft.): none

Lithologic log from: SWC

Casing diameter: none

Comments: $DDCB_1$ is 100 feet north of $DDCB_2$

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, slightly clayey, dark brown	7	7
Sand, very fine to fine, very silty, slightly clayey, medium brown	4	11
Sand, very fine to very coarse, predominantly fine, very slightly gravelly, yellow brown	13	24
Sand, very fine to very coarse, predominantly medium, moderately gravelly, lots of quartz, yellow brown	12	36
Sand, very fine to very coarse, predominantly medium, slightly gravelly, yellow brown	23	59
Sand, very fine to very coarse, predominantly coarse, slightly gravelly, yellow brown	16	75
Sand, very fine to fine, predominantly fine, slightly silty, well sorted	20	95
Sand, very fine to medium, predominantly fine to medium, good sorting, yellow brown	40	135
Sand, very fine to medium, predominantly fine, mottled	62	197

SUPPLEMENT 2

Test Hole and Observation Well Record

Location: 131-59-29 DDCB2

Use of well: test hole

Owner and number: SWC V1-2

Principal aquifer: Oakes

Depth drilled (in.): 186

Altitude of land surface (ft., msl): 1312.3

Screened interval (ft.): none

Lithologic log from: SWC

Casing diameter: none

Comments: $DDCB_2$ is 100 feet south of $DDCB_1$

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey	8	8
Sand, very fine to coarse, very silty, moderately to very clayey, plastic	10	18
Sand, very fine to coarse, very silty, very clayey, light gray	2	20
Sand, very fine to very coarse, predominantly medium, slightly gravelly	20	40
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, pale yellow brown, composed of quartz, carbonates, and shale	40	80
Sand, very fine to very coarse, predominantly medium, slightly gravelly	25	105
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly, very slightly clayey	8	113
Sand, very fine to fine, predominantly fine, silty, mottled	73	186

SUPPLEMENT 3

Test Hole and Observation Well Record

Location: 131-59-29DDCC1

Use of well: test hole

Owner and number: SWC V1-3

Principal aquifer: Oakes

Depth drilled (in.): 198

Altitude of land surface (ft., msl): 1311.7

Screened interval (ft.): None

Lithologic log from: SWC

Casing diameter: none

Comments:

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to medium, predominantly very silty, moderately clayey, dark brown	25	25
Sand, very fine to very coarse, predominantly medium, slightly gravelly, very slightly silty, very slightly clayey	18	43
Sand, very fine to very coarse, predominantly medium to coarse, moderately gravelly, yellow brown	19	62
Sand, very fine to very coarse, predominantly medium, slightly gravelly, yellow brown	18	80
Sand, very fine to very coarse, predominantly coarse, slightly gravelly, yellow brown, composed of quartz, carbonates, and shale	31	111
Sand, very fine to very coarse, predominantly medium, yellow brown, composed of quartz, carbonates, and shale	31	142
Sand, very fine to coarse, predominantly medium, slightly gravelly, yellow brown, composed of quartz, carbonates and shale	56	198

SUPPLEMENT 4

Test Hole and Observation Well Record

Location: 131-59-29 DDCB3

Owner and number: SWC V2-2

Depth drilled (in.): 200

Screened interval (ft.): none

Casing diameter: none

Date completed: 6/5/86

Use of well: test hole

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1312.3

Lithologic log from: SWC

Comments: $DDCB_3$ is 141 feet southwest of DDCA

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, clayey, dark brown	8	8
Sand, very fine to fine, very silty, slightly clayey	4	12
Sand, very fine to medium, predominantly fine, pale yellow brown	12	24
Sand, very fine to medium, predominantly fine, dark brown	5	29
Sand, very fine to medium, predominantly fine, pale yellow brown	15	44
Sand, very fine to very coarse, predominantly medium, slightly gravelly, pale yellow brown	7	51
Clay, sandy, silty, pale greenish gray, plastic	2	53
Sand, very fine to very coarse, predominantly medium, slightly gravelly, yellow brown	13	66
Sand, very fine, very silty, slightly clayey, brown	7	73
Sand, very fine, moderately silty, moderately clayey	7	80
Sand, very fine to fine, predominantly fine, pale yellow brown, mottled	41	121
Sand, very fine to fine, predominantly fine, pale yellowish brown	4	125
Sand, very fine to medium, predominantly fine, silty, slightly clayey, dark brown	2	127

SUPPLEMENT 4 CON'T.

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, predominantly fine, gray, well sorted, predominantly quartz	18	145
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	7	152
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, slightly clayey	8	160
Sand, very fine to very coarse, predominantly coarse, slightly gravelly, silty, very slightly clayey, composed of quartz, carbonates, and shale	40	200

SUPPLEMENT 5

Test Hole and Observation Well Record

Location: 131-59-29DDCC2

Use of well: test hole

Owner and number: SWC V2-3

Principal aquifer: Oakes

Depth drilled (in.): 192

Altitude of land surface (ft., msl): 1312.0

Screened interval (ft.): none

Lithologic log from: SWC

Casing diameter: none

Comments: $DDCC_2$ is 100 feet west of $DDCB_2$

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, dark brown	9	9
Sand, very fine to fine, very silty, slightly clayey, yellow brown	7	16
Sand, very fine to medium, predominantly fine, silty, yellow brown	3	19
Sand, very fine to very coarse, predominantly fine to medium, yellow brown	7	26
Sand, very fine to very coarse, predominantly medium, slightly gravelly, yellow brown	7	33
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, yellow brown	30	63
Sand, very fine to very coarse, predominantly medium, slightly gravelly, gray	39	102
Sand, very fine to very coarse, predominantly fine to medium, slightly clayey	2	104
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, mottled	6	110
Sand, very fine to medium, predominantly fine, gray, mottled	52	162
Sand, very fine to very coarse, predominantly coarse to very coarse, moderately gravelly	30	192

SUPPLEMENT 6

Test Hole and Observation Well Record

Location: 131-59-29DDCA

Use of well: test hole

Owner and number: SWC V3-1

Principal aquifer: Oakes

Depth drilled (in.): 194

Altitude of land surface (ft., msl): 1314.2

Screened interval (ft.): none

Lithologic log from: SWC

Casing diameter: none

Comments: DDCA is 141 feet northeast of $DDCB_3$

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine, very silty, slightly clayey, dark brown	9	9
Sand, very fine to fine, very silty, moderately clayey, plastic	6	15
Sand, very fine to medium, predominantly fine, slightly silty	11	26
Sand, very fine to very coarse, predominantly fine to medium, slightly gravelly, slightly silty, slightly clayey	6	32
Sand, very fine to very coarse, predominantly medium to coarse, very gravelly	13	45
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	23	68
Sand, very fine to fine, predominantly fine, gray, good sorting, predominantly quartz	96	164
Sand, very fine to very coarse, slightly gravelly, predominantly coarse	30	194

SUPPLEMENT 7

Test Hole and Observation Well Record

Location: 131-59-29 DDCD1

Use of well: test hole

Owner and number: SWC V3-3

Principal aquifer: Oakes

Depth drilled (in.): 193

Altitude of land surface (ft., msl): 1312.9

Screened interval (ft.): none

Lithologic log from: SWC

Casing diameter: none

Comments: $DDCD_1$ is 100 feet east of $DDCC_2$

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, predominantly fine, very silty, slightly clayey, dark black	9	9
Sand, very fine to fine, predominantly fine, slightly silty, very slightly clayey	11	20
Sand, very fine to very coarse, predominantly fine to medium, slightly silty, very slightly clayey, pale yellow brown	10	30
Sand, very fine to coarse, predominantly fine to medium, well sorted	11	41
Sand, very fine to very coarse, predominantly medium, slightly gravelly, pale yellow brown	14	55
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, pale yellow brown	63	118
Silt, clayey, very slightly sandy, yellow brown	1	119
Sand, very fine to fine, slightly silty	12	131
Sand, very fine to medium, slightly silty, predominantly medium	6	137
Silt, clayey, sandy	1	138
Sand, very fine to fine, predominantly fine, gray, predominantly quartz	26	164
Sand, very fine to very coarse, predominantly medium to coarse, composed of quartz and shale	20	184
Sand, very fine to very coarse, predominantly coarse to very coarse, moderately gravelly, composed of quartz, carbonates, and shale	9	193

SUPPLEMENT 8

Test Hole and Observation Well Record

Location: 131-59-29DDCC3

Owner and number: SWC S-1

Depth drilled (in.): 192

Screened interval (ft.): none

Casing diameter: none

Date completed: 6/4/86

Use of well: test hole

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1310.8

Lithologic log from: SWC

Comments:

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Organic matter, dark brown to black	2	2
Sand, very fine to fine, very silty, very slightly clayey, pale yellow brown	1.5	3.5
Sand, fine, light gray	3.5	7
Sand, very fine to medium, predominantly medium, very silty, very slightly clayey	14	21
Sand, very fine to very coarse, predominantly medium, slightly gravelly, composed of quartz, shale	23	44
Sand, very fine to medium, very silty, very slightly clayey	15	59
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, pale yellow brown	14	73
Sand, very fine to very coarse, predominantly medium, slightly gravelly	23	96
Sand, very fine to medium, very silty, slightly clayey	2	98
Sand, very fine to very coarse, predominantly medium to coarse, mottled	10	108
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, composed of quartz, and shale	6	114
Sand, very fine to very coarse, predominantly medium to coarse, gravelly, composed of quartz and shale	11	125

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to very coarse, predominantly fine to medium, very silty, very slightly clayey	10	135
Sand, fine to very coarse, predominantly fine to medium, very silty, very slightly clayey	57	192

SUPPLEMENT 9

Test Hole and Observation Well Record

Location: 131-59-29DDCC4

Owner and number: SWC S-3

Depth drilled (in.): 200

Screened interval (ft.): None

Casing diameter: none

Date completed: 6/4/86

Use of well: test hole

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1313.4

Lithologic log from: SWC

Comments: S-3 is 200 feet east of S-1

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Organic matter, dark brown to black	1	1
Sand, very fine to fine, very silty, very slightly clayey	21	22
Sand, very fine to fine, silty, clayey	4	26
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly, silty	22	48
Sand, very fine to very coarse, predominantly coarse, moderately gravelly, mottled	12	60
Sand, very fine to very coarse, predominantly coarse, very gravelly, mottled	2	62
Sand, very fine to very coarse, predominantly medium, slightly gravelly, slightly clayey, silty	18	80
Sand, very fine to very coarse, predominantly medium to coarse, silty, very slightly gravelly, slightly clayey	15	95
Sand, very fine to very coarse, medium to coarse, slightly silty, very slightly gravelly	15	110
Sand, very fine to very coarse, predominantly fine to medium, silty, very slightly gravelly, mottled	28	138
Sand, very fine to fine, predominantly fine, silty, mottled	30	168
Sand, very fine to very coarse, predominantly fine to medium, silty, very slightly clayey	12	180
Sand, very fine to very coarse, predominantly medium, slightly silty	20	200

SUPPLEMENT 10

Test Hole and Observation Well Record

Location: 131-59-29 DDCD2

Owner and number: SWC S-5

Depth drilled (in.): 204

Screened interval (ft.): none

Casing diameter: none

Date completed: 6/4/86

Use of well: test hole

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1314.0

Lithologic log from: SWC

Comments: S-5 is 200 feet east of S-3

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Organic matter, dark brown to black	2	2
Sand, very fine to fine, silty, clayey black	7	9
Sand, very fine to fine, silty, clayey, gray	3	12
Sand, very fine to medium, predominantly fine, silty, slightly clayey	12	24
Sand, fine to medium, predominantly fine, very silty, clayey	8	32
Sand, fine to coarse, predominantly medium, slightly gravelly, mottled	6	38
Sand, fine to coarse, predominantly medium, slightly gravelly, slightly clayey	7	45
Sand, fine to coarse, predominantly medium, slightly gravelly	7	52
Sand, very fine to medium, predominantly fine, silty	8	60
Sand, fine to coarse, predominantly medium, slightly gravelly, slightly silty, slightly clayey, lots of detrital shale fragments	68	128
Sand, fine to coarse, predominantly medium, very slightly gravelly	54	182
Sand, fine to coarse, predominantly coarse, gravelly, slightly clayey	4	186
Sand, fine to coarse, predominantly coarse, moderately gravelly	18	204

SUPPLEMENT 11

Test Hole and Observation Well Record

Location: 131-59-29 DDDC

Owner and number: SWC S-7

Depth drilled (in.): 200

Screened interval (ft.): none

Casing diameter: none

Date completed: 6/4/86

Use of well: test hole

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1315.6

Lithologic log from: SWC

Comments: S-7 is 200 feet east of S-5

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Organic matter, dark brown to black	1	1
Sand, very fine to fine, very silty, clayey	10	11
Sand, very fine to coarse, predominantly fine to medium, silty, slightly clayey	13	24
Sand, very fine to medium, predominantly fine, very silty, clayey	19	43
Sand, fine to coarse, predominantly medium, very silty, clayey	11	54
Sand, medium, slightly gravelly, slightly silty, slightly clayey, weathered detrital shale	3	57
Sand, medium to coarse, predominantly coarse, gravelly, mottled	18	75
Sand, very fine to medium, predominantly fine, slightly clayey	21	96
Sand, fine to coarse, predominantly medium, few mottles	12	108
Sand, fine to coarse, predominantly medium, slightly gravelly, slightly clayey, some detrital shale fragments	30	138
Sand, very fine to fine, predominantly fine, mottled	42	180
Sand, fine to coarse, predominantly medium, slightly gravelly, slightly silty, slightly clayey	20	200

SUPPLEMENT 12

Test Hole and Observation Well Record

Location: 131-59-29DDCD3

Use of well: test hole

Owner and number: SWC N-6

Principal aquifer: Oakes

Depth drilled (in.): 196

Altitude of land surface (ft., msl): 1316.3

Screened interval (ft.): none

Lithologic log from: SWC

Casing diameter: none

Comments:

Date completed: 6/5/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, very clayey, dark brown	5	5
Sand, very fine to coarse, predominantly fine, slightly silty, yellow brown	1	6
Sand, very fine to fine, very silty, slightly clayey, dark brown	22	28
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	16	44
Sand, very fine to coarse, predominantly fine	6	50
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	16	66
Sand, very fine to very coarse, predominantly medium, mottled	35	101
Sand, very fine to fine, predominantly fine, mottled	95	196

SUPPLEMENT 13

Test Hole and Observation Well Record

Location: 131-059-29DDCD1

Use of well: Observation

Owner and number: SWC P-1

Principal aquifer: Oakes

Depth drilled (in.): 342

Altitude of land surface (ft., msl): 1316

Screened interval (in.): 238-298

Lithologic log from: SWC

Casing diameter: 2-inch pvc

Comments: Water-table well. Located at center of preliminary test basin.

Date completed: 6/19/86

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, slightly clayey, dark brown	12	12
Sand, very fine to very coarse, predominantly fine to medium, slightly gravelly, moderately clayey, very silty, pale yellow brown, oxidized	12	24
Sand, very fine to very coarse, predominantly medium, slightly gravelly, slightly clayey	12	36
Sand, very fine to very coarse, predominantly medium, slightly gravelly, moderately clayey, pale yellow brown, oxidized	12	48
Sand, very fine to very coarse, predominantly medium, slightly gravelly, silty, slightly clayey	12	60
Sand, very fine to very coarse, predominantly medium, slightly gravelly, red-yellow brown, oxidized	12	72
Sand, very fine to very coarse, predominantly fine, red-yellow brown, oxidized	12	84
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, yellow brown, oxidized	24	108
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly, quartz, carbonates, and shale	24	132
Sand, very fine to fine, light gray, mottled, pale yellow brown, oxidized	48	180

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to medium, predominantly fine to medium, pale yellow brown, oxidized	36	216
Sand, very fine to very coarse, predominantly medium to coarse, slightly to moderately gravelly, quartz, carbonates, and shale, water table at about 240 inches	126	342

SUPPLEMENT 14

Test Hole and Observation Well Record

Location: 131-059-29DDCB4

Owner and number: SWC OL-1

Depth drilled (in.): 276

Screened interval (in.): 250-276

Casing diameter: 2-inch pvc

Date completed: 8/19/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1313

Lithologic log from: SWC

Comments: Water-table well. Located at center of large test basin.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, slightly clayey, dark brown, numerous roots	6	6
Sand, very fine to fine, very silty, very slightly clayey, pale yellow brown	6	12
Sand, very fine to medium, predominantly very fine to fine, silty, very slightly clayey, pale yellow brown	8	20
Sand, very fine to fine, very silty, very clayey, soft weathered detrital shale fragments, moderately cohesive, dark brown to yellow brown	3	23
Sand, very fine to medium, predominantly fine to very fine, pale yellow brown	12	35
Sand, very fine to very coarse, slightly gravelly, predominantly medium, yellow brown, quartz, detrital shale and carbonates	25	60
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, composition as above	16	76
Sand, very fine to coarse, slightly gravelly, predominantly fine to medium, yellow brown, thin dark grey to black detrital lignite layers	9	85
Sand, very fine to coarse, predominantly very fine to fine, medium to coarse grained is detrital shale, detrital shale in layers a few millimeters thick	18	103

SUPPLEMENT 14 CON'T.

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to coarse, predominantly fine to medium, red-yellow-brown, oxidized, quartz, detrital shale and carbonates	3	106
Sand, very fine to fine, yellow brown, oxidized, red-yellow stringers, lots of quartz and some detrital shale	25	131
Sand, very fine to very coarse, predominantly coarse, slightly gravelly, yellow brown, oxidized	13	144
Sand, as above, pale gray, quartz, carbonates, and detrital shale, water table at about 180 inches	80	224
Sand, very fine to very coarse, predominantly medium, slightly clayey, layers of dark brown to black detrital lignite	31	255
Sand, very fine to very coarse, slightly gravelly, predominantly medium, quartz, detrital shale, and carbonates	21	276

SUPPLEMENT 15

Test Hole and Observation Well Record

Location: 131-059-29DDCB5

Owner and number: SWC OL-1A

Depth drilled (in.): 106

Screened interval (in.): 80-106

Casing diameter: 2-inch pvc

Date completed: 8/19/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1313

Lithologic log from: SWC

Comments: Well completed in unsaturated zone to monitor perched ground-water mound. Located at center of large test basin.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OL-1		

SUPPLEMENT 16

Test Hole and Observation Well Record

Location: 131-059-29DDCB6

Owner and number: SWC OL-2

Depth drilled (in.): 276

Screened interval (in.): 250-276

Casing diameter: 2-inch pvc

Date completed: 8/21/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1313

Lithologic log from: SWC

Comments: Water-table well. Located 35 feet south of center of large test basin. West well of three.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, moderately cohesive, black, numerous roots, vitreous quartz	9	9
Sand, very fine to medium , predominantly fine, moderately silty, very slightly clayey, slightly cohesive, pale yellow brown, oxidized	19	28
Sand, very fine to very coarse, predominantly medium, moderately gravelly, pale yellow brown, oxidized	12	40
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, pale yellow brown, oxidized, quartz, carbonates and detrital shale	34	74
Sand, very fine to fine, very silty, moderately clayey, dark black layers of weathered detrital lignite, some weathered detrital shale, moderately cohesive	6	80
Sand, very fine to fine, slightly silty, light gray with yellow brown stringers, oxidized	56	136
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, quartz, detrital shale and carbonates	14	150
Sand, very fine to very coarse, predominantly coarse to very coarse, moderately gravelly, composition as above	15	165
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, water table at about 180 inches	25	190

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to coarse, predominantly fine to medium, very slightly gravelly	10	200
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, numerous thin weathered dark black detrital lignite zones	76	276

SUPPLEMENT 17

Test Hole and Observation Well Record

Location: 131-059-29DDCB7

Owner and number: SWC OL-2A

Depth drilled (in.): 216

Screened interval (in.): 190-216

Casing diameter: 2-inch pvc

Date completed: 8/21/86

Use of well: USGS Water Sample Well

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1313

Lithologic log from: SWC

Comments: Water-table well. Located 35 feet south of center of large test basin. East well of three.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OL-2		

SUPPLEMENT 18

Test Hole and Observation Well Record

Location: 131-059-29DDCB8

Owner and number: SWC OL-2B

Depth drilled (in.): 74

Screened interval (in.): 48-74

Casing diameter: 2-inch pvc

Date completed: 8/21/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1313

Lithologic log from: SWC

Comments: Well completed in unsaturated zone. Located 35 feet south of center of large test basin. Middle well of three.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OL-2		

SUPPLEMENT 19

Test Hole and Observation Well Record

Location: 131-059-29DDCC5

Owner and number: SWC OL-3

Depth drilled (in.): 276

Screened interval (in.): 250-276

Casing diameter: 2-inch pvc

Date completed: 8/21/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1312

Lithologic log from: SWC

Comments: Water-table well located 50 feet south of center of large test basin. East well of pair.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, dark black, moderate to strongly cohesive, numerous roots, vitreous quartz	9	9
Sand, very fine to medium, moderately silty, slightly clayey, gray brown, slightly to moderately cohesive, numerous roots	14	23
Sand, very fine to very coarse, predominantly fine to medium, slightly gravelly, pale yellow brown, oxidized, quartz, shale, and carbonates	22	45
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, as above	14	59
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, as above	27	86
Sand, very fine to fine, very silty, moderate to very clayey, cohesive, numerous dark black layers of weathered detrital lignite	3	89
Sand, very fine to fine, silty, light gray with yellow brown stringers	37	126
Sand, very fine to very coarse, predominantly coarse, slightly gravelly, quartz, detrital shale, carbonates and silicates. Bottom 48 inches with numerous thin detrital lignite and shale layers	150	276

SUPPLEMENT 20

Test Hole and Observation Well Record

Location: 131-059-29DDCC6

Owner and number: SWC OL-3A

Depth drilled (in.): 86

Screened interval (in.): 60-86

Casing diameter: 2-inch pvc

Date completed: 9/10/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1312

Lithologic log from: SWC

Comments: Well completed in unsaturated zone. Located 50 feet south of center of large test basin. West well of pair.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OL-3		

SUPPLEMENT 21

Test Hole and Observation Well Record

Location: 131-059-29DDCC7

Owner and number: SWC OL-4

Depth drilled (in.): 276

Screened interval (in.): 250-276

Casing diameter: 2-inch pvc

Date completed: 8/21/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1312

Lithologic log from: SWC

Comments: Water-table well located 67 feet south of center of large test basin. East well of pair.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, moderately cohesive, numerous roots, vitreous quartz	17	17
Sand, very fine to medium, predominantly fine, moderately silty, slightly clayey, pale yellow brown, oxidized	13	30
Sand, very fine to very coarse, predominantly medium to coarse, moderately gravelly, yellow brown, oxidized, quartz, shale, and carbonates	28	58
Sand, very fine to very coarse, predominantly medium, slightly gravelly, pale yellow brown	22	80
Sand, very fine to fine, very silty, moderately clayey, dark black, lots of weathered detrital lignite, slightly to moderately cohesive	2	82
Sand, very fine to very coarse, predominantly fine to medium, light gray with yellow brown stringers, oxidized, quartz, shale, and carbonates	12	95
Sand, very fine to fine, light gray, with yellow brown stringers, lots of quartz	61	156
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, shale, quartz, and carbonates, water table at about 180 inches	24	180

SUPPLEMENT 21 CON'T.

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to very coarse, predominantly coarse to very coarse, gravelly, quartz, shale, silicates, carbonates, and lignite	48	228
Sand, very fine to very coarse, predominantly medium, slightly gravelly, composition as above	48	276

SUPPLEMENT 22

Test Hole and Observation Well Record

Location: 131-059-29DDCC8

Owner and number: SWC OL-4A

Depth drilled (in.): 80

Screened interval (in.): 54-80

Casing diameter: 2-inch pvc

Date completed: 9/10/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1312

Lithologic log from: SWC

Comments: Well completed in unsaturated zone. Located 67 feet south of center of large test basin. West well of pair.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OL-4		

SUPPLEMENT 23

Test Hole and Observation Well Record

Location: 131-059-29DDCC9

Owner and number: SWC OL-5

Depth drilled (in.): 276

Screened interval (in.): 250-276

Casing diameter: 2-inch pvc

Date completed: 8/21/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1312

Lithologic log from: SWC

Comments: Water-table well located 117 feet south of center of large test basin.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, dark black, moderately cohesive, numerous roots, vitreous quartz	10	10
Sand, very fine to fine, very silty, slightly clayey, brown gray, very slightly brittle, numerous roots	12	22
Sand, very fine to very coarse, predominantly fine, silty, very slightly clayey, very slightly gravelly, yellow brown, oxidized	14	36
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, silty, very slightly clayey, yellow brown, oxidized, quartz, shale, and carbonates	44	70
Sand, very fine to very coarse, predominantly fine to medium, slightly gravelly	11	81
Sand, very fine to very coarse, predominantly fine, light gray with red-yellow stringers oxidized	15	96
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, pale yellow brown, oxidized, quartz, shield silicates, shale, carbonates and detrital lignite	105	201
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, composition as above, water table at about 180 inches	75	276

SUPPLEMENT 24

Test Hole and Observation Well Record

Location: 131-059-29DDCD3

Owner and number: SWC OS-1

Depth drilled (in.): 336

Screened interval (in.): 310-336

Casing diameter: 2-inch pvc

Date completed: 8/19/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1316

Lithologic log from: SWC

Comments: Water-table well. Located at center of small test basin. Reamed test hole N-6.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, dark brown	5	5
Sand, very fine to very coarse, predominantly fine, slightly silty, yellow brown, oxidized	1	6
Sand, very fine to fine, very silty, slightly clayey, dark brown	8	14
Sand, very fine to fine, very silty, slightly clayey	14	28
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	16	44
Sand, very fine to very coarse, predominantly fine	6	50
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	16	66
Sand, very fine to very coarse, predominantly medium, mottled	35	101
Sand, very fine to fine, predominantly fine, mottled	95	196
Sand, very fine to coarse, predominantly fine to medium, lots of detrital shale, water table at about 220 inches	52	248
Sand, very fine to very coarse, slightly gravelly, predominantly medium to coarse, quartz, carbonates, shale, gray	28	276
Sand, very fine to very coarse, very slightly gravelly, predominantly medium, composition as above	60	336

SUPPLEMENT 25

Test Hole and Observation Well Record

Location: 131-059-29DDCD4

Owner and number: SWC OS-1A

Depth drilled (in.): 101

Screened interval (in.): 75-101

Casing diameter: 2-inch pvc

Date completed: 8/19/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1316

Lithologic log from: SWC

Comments: Well completed in unsaturated zone. Located at center of small test basin.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for OS-2		

SUPPLEMENT 26

Test Hole and Observation Well Record

Location: 131-059-29DDCD5

Owner and number: SWC OS-2

Depth drilled (in.): 276

Screened interval (in.): 250-276

Casing diameter: 2-inch pvc

Date completed: 8/20/86

Use of well: USGS Water Sample Well

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1316

Lithologic log from: SWC

Comments: Water-table well. Located 18 feet west of center of small test basin. North well of three.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, dark brown to black, numerous roots, moderately cohesive	10	10
Sand, as above, slightly clayey, gray, slightly cohesive	7	17
Sand, very fine to fine, moderately silty, very slightly clayey, slightly cohesive, pale yellow brown	26	43
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	6	49
Sand, very fine to fine, pale yellow brown, oxidized	6	55
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, pale yellow brown, oxidized	9	64
Sand, very fine to very coarse, predominantly coarse, slightly to moderately gravelly	8	72
Sand, very fine to very coarse, predominantly medium, slightly gravelly, pale yellow brown, oxidized	17	89
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly	25	114
Sand, very fine to fine, very silty, yellow brown, oxidized, slightly cohesive	1	115
Sand, very fine to fine, very silty, slightly cohesive, pale yellow brown, oxidized, possibly slightly clayey	9	124
Sand, very fine to fine, very slightly silty, gray with yellow-brown stringers, water table at about 216 inches	92	216

SUPPLEMENT 26 CON'T.

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to very coarse, predominantly medium, very slightly gravelly, lots of detrital shale	19	235
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly, quartz, shale and carbonates	15	250
Sand, very fine to very coarse, predominantly medium to coarse, quartz, shale, and carbonates	86	336

SUPPLEMENT 27

Test Hole and Observation Well Record

Location: 131-059-29DDCD6

Owner and number: SWC OS-2A

Depth drilled (in.): 336

Screened interval (in.): 310-336

Casing diameter: 2-inch pvc

Date completed: 8/20/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1316

Lithologic log from: SWC

Comments: Water-table well. Located 18 feet west of center of small test basin. Middle well of three.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OS-2		

SUPPLEMENT 28

Test Hole and Observation Well Record

Location: 131-059-29DDCD7

Owner and number: SWC OS-2B

Depth drilled (in.): 114

Screened interval (in.): 88-114

Casing diameter: 2-inch pvc

Date completed: 8/20/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1316

Lithologic log from: SWC

Comments: Well completed in unsaturated zone. Located 18 feet west of center of small test basin. South well of three.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
See log for SWC OS-2		

SUPPLEMENT 29

Test Hole and Observation Well Record

Location: 131-059-29DDCD8

Owner and number: SWC OS-3

Depth drilled (in.): 336

Screened interval (in.): 310-336

Casing diameter: 2-inch pvc

Date completed: 8/20/86

Use of well: Observation

Principal aquifer: Oakes

Altitude of land surface (ft., msl): 1316

Lithologic log from: SWC

Comments: Water-table well. Located 25 feet west of center of small test basin.

Lithologic Log

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to fine, very silty, moderately clayey, black	6	6
Sand, very fine to fine, very silty, slightly clayey, gray, slightly cohesive, numerous roots	9	15
Sand, very fine to fine, slightly silty, pale yellow brown, oxidized, numerous roots	10	25
Sand, very fine to fine, very silty, moderately clayey, moderately cohesive, light gray	4	29
Sand, very fine to fine, moderately silty, very slightly clayey, slightly cohesive	8	37
Sand, very fine to very coarse, predominantly medium, slightly gravelly, quartz, carbonates, and shale, pale yellow brown, oxidized	23	60
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly	9	69
Sand, very fine to very coarse, predominantly medium, yellow brown with red-yellow stringers, oxidized, quartz, carbonates, and shale	6	74
Sand, very fine to fine, yellow brown with red-yellow stringers, oxidized	110	184
Sand, very fine to very coarse, predominantly medium to coarse, slightly gravelly, quartz, shale, and carbonates, water table at about 228 inches	98	282
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly, quartz, carbonates, and shale	30	312

SUPPLEMENT 29 CON'T.

Unit description	Thickness (in.)	Depth (in.)
Sand, very fine to very coarse, predominantly fine to medium, very slightly gravelly, with thin silty clay layers, quartz, carbonates, and shale	24	336