Hydraulic Characteristics of an Underdrained Irrigation Circle, Muskegon County Waste-Water Disposal System, Michigan

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By M. G. McDONALD

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CONTENTS

ILLUSTRATIONS

HYDRAULIC CHARACTERISTICS OF AN UNDERDRAINED IRRIGATION CIRCLE, MUSKEGON COUNTY WASTE-WATER DISPOSAL SYSTEM, MICHIGAN

By M. G. McDonald

ABSTRACT

Muskegon County, Michigan, disposes of waste water by spray irrigating farmland on its waste-disposal site. Buried drains in the highly permeable unconfined aquifer at the site control the level of the water table. Hydraulic conductivity of the aquifer and drain-leakance, the reciprocal of resistance to flow into the drains, was determined at a representative irrigation circle while calibrating a model of the ground-water flow system. Hydraulic conductivity is 0.00055 meter per second in the north zone of the circle and 0.00039 meter per second in the south zone. Drain leakance is low in both zones: 2.9×10^{-6} meters per second in the north and 9.5×10^{-6} meters per second in the south. Low drain leakance is responsible for waterlogging when irrigation rates are maintained at design levels. The capacity of the study circle to accept waste water is 35 percent less than design capacity.

INTRODUCTION

The Muskegon County, Mich., waste-disposal system is designed to collect, store, and dispose of waste water at the rate of 160,000 m^3/d (cubic meters per day). From spring to late fall, partially treated waste water is sprayed on 22 km^2 (square kilometers) of corn field. Spraying is done with a center-pivot irrigation rig designed to spray 8.9 cm/wk (centimeters per week). The rig irrigates an area that is either a circle or a sector of a circle.[1] During the winter, irrigation ceases and waste water is stored in lagoons.

The disposal site is underlain with drains to prevent subsurface migration of waste water, to maintain 1.5 m of unsaturated zone for effective waste-water treatment, and to provide an unsaturated zone thick enough for corn growth. Effectiveness of drains in maintaining desired ground-water levels is not well known. McDonald and Fleck (1978) found that in some parts of the disposal site clogged drains would cause severe waterlogging problems. Culp and Hinrichs (1978) reported that in 1977, a relatively dry year, only 100,000 m^3/d of waste

[1] For convenience, the term "circle" is used to refer to both sectors and complete circles.

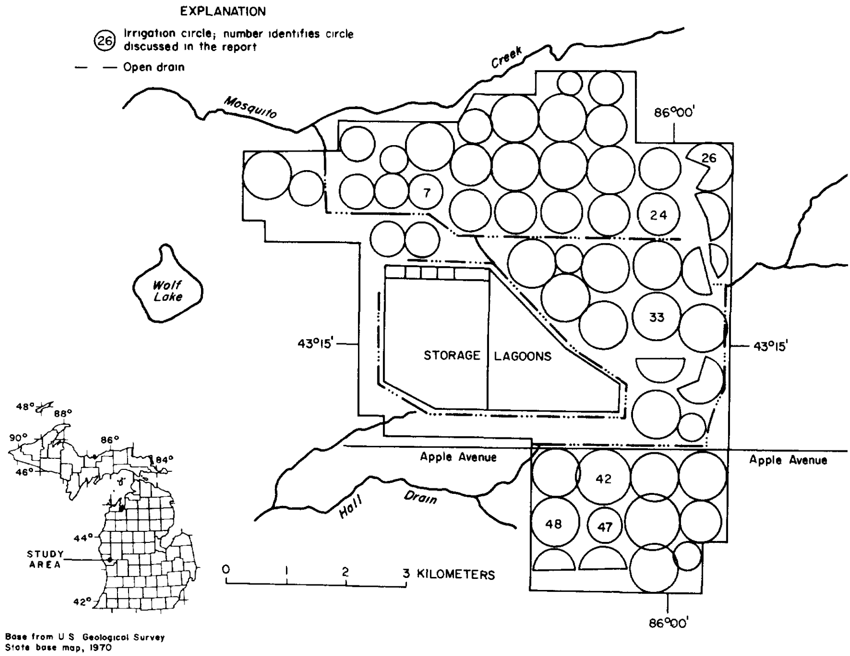


FIGURE 1.—Muskegon County Wastewater Management System.

water could be disposed of by spray irrigation. South of Apple Avenue (fig. 1), waterlogging occurs when the irrigation rate is only 2.5 cm/wk. North of Apple Avenue, drainage is better but is not sufficient to maintain an unsaturated zone 1.5 m thick in all areas.

PURPOSE AND METHOD OF STUDY

The study was made to determine the hydraulic characteristics of an individual irrigation circle having buried drains. Circle 26 (fig. 1) was selected for study. Choice of this circle was made, in part, because the Soil and Crop Science Department of Michigan State University was studying the relation of waste water to soils and field crops at circle 26 and was willing to cooperate in the collection of data. Also, this circle has drainage problems similar to those in other irrigation circles at the site—it becomes waterlogged when irrigated at the design rate. To determine if circle 26 was representative of the entire system, water-level measurements were collected at other irrigation circles.

Hydraulic characteristics of circle 26 were studied by simulating ground-water flow with a digital model. Values of hydraulic conductivity and drain leakance, the reciprocal of resistance to flow into drains, were varied in the model until the water table calculated by the model approximated the actual water table. The model used for this project was a steady-state parameter-estimation model.

COOPERATION AND ACKNOWLEDGMENTS

This study was done in cooperation with the Geological Survey Division, Michigan Department of Natural Resources. In addition to sharing in the cost of the study, the Department of Natural Resources made available well records and other data from their files and provided assistance with field work. The advice and assistance of Dr. A. Earl Erickson and Dr. James Hook, Michigan State University, is gratefully acknowledged.

PHYSICAL SETTING

Circle 26 is underlain by glacial lake and outwash deposits. The lake and outwash deposits consist of an upper layer of highly permeable fine to medium sand that is 5-6 m thick and a lower layer of silty sand interbedded with silty clay that is 10 m thick. Underlying the lower layer is silty clay till. Land surface slopes 0.3 percent to the southwest.

Average annual precipitation at Muskegon is 76 cm ; snowfall is 226 cm. Mean daily temperatures between early December and late March are below 0°C. Mean temperature is −3°C in January; it is 22°C in July (National Oceanic and Atmospheric Administration, 1974).

Five buried drains cross circle 26 in the east-west direction (fig. 2). On the east side of the circle, the drains are 1.5 m below land surface. They have 0.5 percent downward slope to the west. The drains discharge into a concrete collector pipe, which discharges to an open drain south of circle 24 (fig. 1). Buried drains are corrugated polyethylene tubes, 15 cm in diameter, perforated with slots 0.2 by 3.8 cm, and encased in a 0.45-mm-mesh fiberglass fabric.

The north half of circle 26 becomes waterlogged during spring thaw and after periods of intense rain or irrigation. Water either stands on the land surface or flows slowly to the southwest, accumulating around the irrigation rig pivot. During periods of waterlogging, water also flows in open ditches adjacent to the roads on the north and east boundaries of the site (fig. 2).

SIMULATION OF FLOW AT IRRIGATION CIRCLE 26

A model of ground-water flow was used to refine estimates of hydraulic conductivity and drain leakance and to assist in understanding the ground-water flow system under circle 26. A finite-difference parameter-estimation model program developed by Larson (written

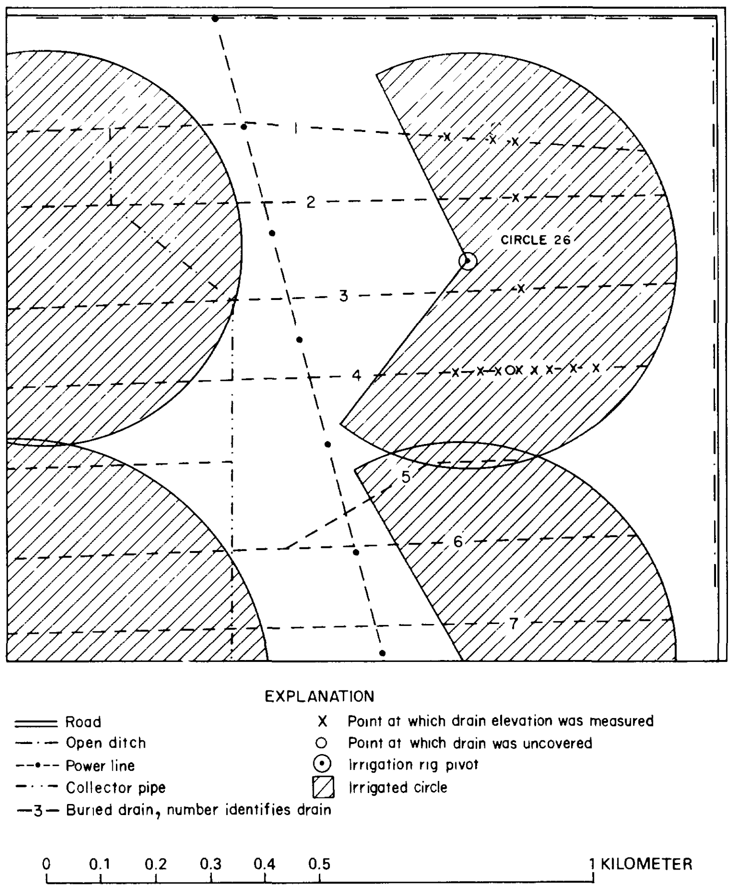


FIGURE 2. – Irrigation circle 26 and adjoining circles.

commun., 1978), based on techniques of Cooley (1977), was used. The model determines values of hydraulic parameters that will cause the difference between calculated and measured water levels to be minimized. The measure of the difference is

$$M = \sum_{i=1}^{m} W_i(O_i - C_i)^2, \qquad (1)$$

where

M is the weighted sum of squared deviations,

O_i is the measured water level at well i,

C_i is the calculated water level for well i,

W_i is the weighting factor associated with well i, and

m is the number of observation wells.

Seepage of water into a drain is affected by convergence of flow toward the drain, resistance to flow caused by low permeability material immediately around the drain, and resistance to flow caused by the drain walls. These three effects were treated as a lumped parameter, referred to as drain leakance in this report. The effects on drain leakance of convergence of flow is negligible compared with the effects of low permeability material around the drains and resistance to flow through the drain walls. However the latter two effects cannot be evaluated independently.

The equation that was used to represent flow into a unit length of buried drain is

$$Q = C(H_A - H_D), \tag{2}$$

where

Q is the flow into the drain per unit length,
C is drain leakance,
H_A is the altitude of the water level in the aquifer at the drain, and
H_D is the altitude of the drain.

The study area is divided into two zones -- north and south (fig. 3). The north zone is lightly irrigated, whereas the south is heavily irrigated. Frequent waterlogging in the north limits irrigation.

The parameter-estimation model was used to determine hydraulic conductivity and drain leakance in each zone. The model program required that initial estimates of each of these parameters be made. Drain leakance for drain 4 was estimated on the basis of measured water levels and recharge rates to be 6.5×10^{6} m/sec. The value was used as the initial estimate of drain leakance in both zones. Hydraulic conductivity was estimated from work by McDonald and Fleck (1978) to be 0.00030 m/sec. That value is comparable with values of 0.00031 m/sec and 0.00018 m/sec determined from aquifer tests at other irrigation circles at the waste-water site (Muskegon County, 1970).

The boundary of the area that was simulated is shown in figure 3. Constant water levels were considered to exist at the north and east boundaries. The west boundary is at a collector pipe. The impermeable collector pipe, buried 4 m below land surface, is at the lower end of buried drains, which discharge into it from both the east and the west. Consequently the west boundary, as well as the south boundary, which is at a buried drain, were considered to have no flow across them. The bottom boundary was the top of the lower layer of lake and outwash deposits.

Ground-water conditions that were approximately at steady state prevailed during the first week of August 1978. Those conditions were simulated as steady-state conditions. The open drains on the north and east boundaries were dry. Water levels and amounts of precipitation and irrigation had been relatively steady for four weeks (fig. 4).

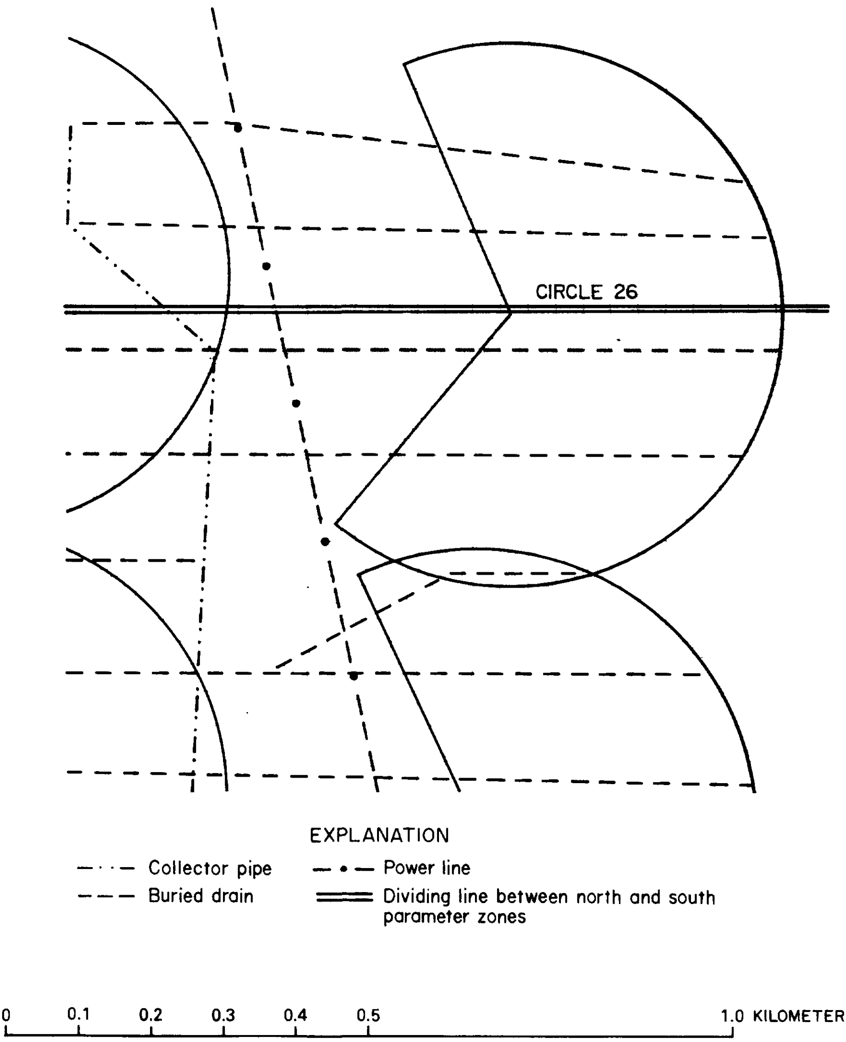


FIGURE 3.—Finite-difference grid spacings and parameter zones used in parameter-estimation model.

Total recharge in the irrigated areas was calculated by using the following formula and was determined to have been 2.8 cm/wk in the north zone and 4.1 cm/wk in the south:

$$R = P + I - ET, \tag{3}$$

where

R is the ground-water recharge rate,

P is precipitation rate,

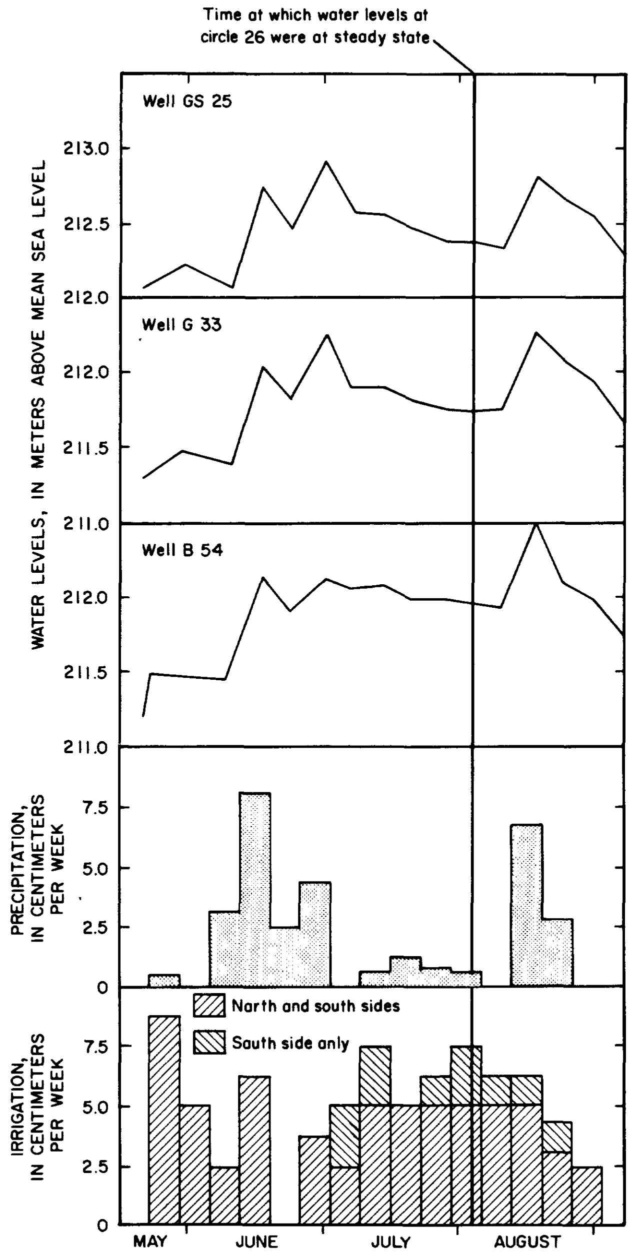


FIGURE 4.–Precipitation, irrigation, and water levels during the summer of 1978.

I is irrigation rate, and
ET is evapotranspiration rate.

A precipitation rate of 0.5 cm/wk and an irrigation rate of 5.1 cm/wk in the north zone and 6.4 cm/wk in the south zone were used. Evapotranspiration in the irrigated area was assumed to be 2.8 cm/wk, the potential evapotranspiration as calculated using the Thornthwaite equation (Chang, 1968). Evapotranspiration outside of the irrigated areas was assumed to be equal to precipitation because potential evapotranspiration was much greater than precipitation and the water table was below the root zone of vegetation.

The four northernmost buried drains were located, and where feasible, altitudes were measured (fig. 2). Locations and altitudes were found to differ from those indicated on construction plans. Some locations were different by as much as 70 m, and altitudes were 0.6-1.5 m higher than those indicated on the plans. The slopes of drains 1 and 4 are 0.5 percent. Therefore all drains were assumed to have a slope of 0.5 percent. The drains for which altitude measurements were not made were assumed to be 0.6 m higher than elevations shown in the plans.

Water levels used in the model to calculate the weighted sum of squared deviations, as described in equation 1, were collected at 22 wells. The locations of the wells are shown in figure 5. To minimize the influence of imprecise boundary conditions the weighting factor for wells outside the irrigated area was set to 0.2, whereas the weighting factor for wells inside the irrigated area was set to 1.0.

The values, in meters per second, of hydraulic conductivity and drain leakance and their standard errors as calculated by the model are as follows:

Zone	Hydraulic conductivity		Drain leakance	
	Value	Standard error	Value	Standard error
North	0.00055	0.00010	2.9×10^{-6}	0.27×10^{-6}
South	.00038	.00006	9.5×10^{-6}	$.59\times10^{-6}$

The standard error is proportional to the range over which the parameters can be varied without significantly altering the calculated water-level distribution. Thus, the smaller the standard error the better the estimate. Figure 6 shows water levels measured in the study area in August 1978 and the water table calculated by the model using the parameters given in the foregoing table.

DRAIN PERFORMANCE IN OTHER IRRIGATION CIRCLES

The water table in the vicinity of drains in irrigation circles 7, 33, and 47 was also studied. Unfortunately only one drain– in circle 33– could be

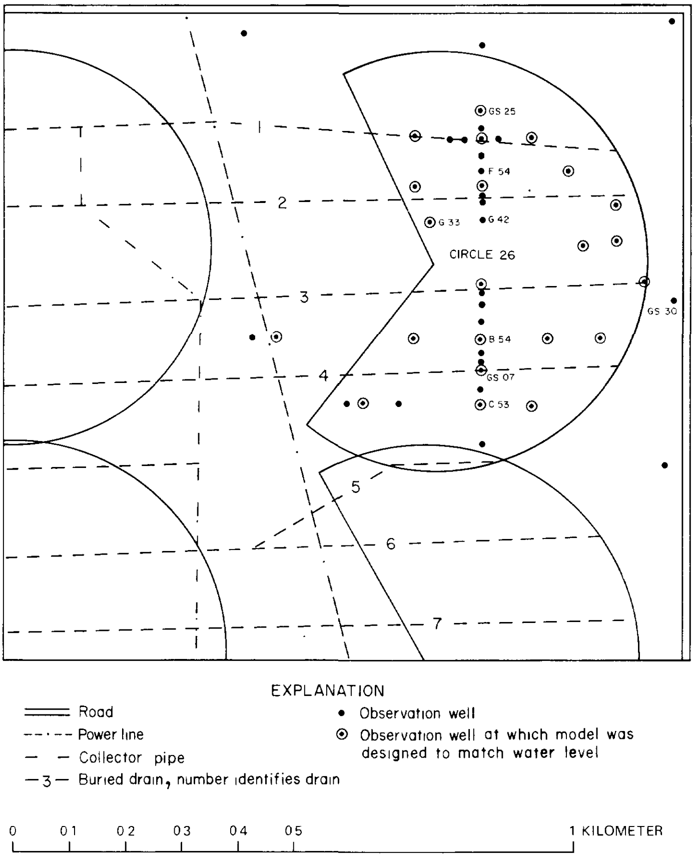
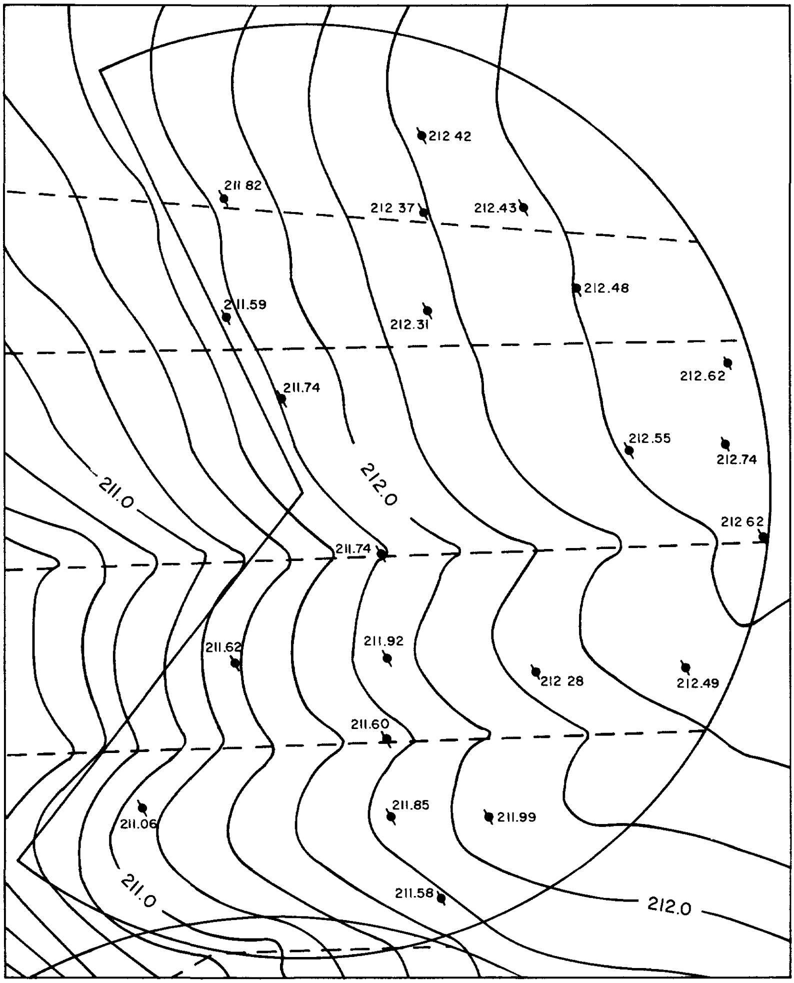


FIGURE 5. - Location of observation wells at irrigation circle 26.

located. Locations of other drains were estimated using aerial photographs. Thus, the altitudes of most drains are uncertain. At each of the three circles, 10-15 wells were installed on a line near and perpendicular to the estimated location of a drain.

At circle 7 the only drain south of the irrigation-rig pivot appeared to have no effect on the water table. In August 1977, after 3 weeks during which irrigation plus precipitation was 10 cm/wk, the water table was 0.3 m below the estimated altitude of the drain. It is likely that the drain at this particular point may always be above the water table.

At circle 47 the water table on the edge of the irrigated area ranged from 1 to 1.5 m above the drains after a 3 week period when irrigation plus precipitation was 4.4 cm/wk (fig. 7).



EXPLANATION

— — — Buried drain

—211.0— Contour showing ground-water level calculated by the model, in meters above mean sea level

211.2 Site at which water level was measured, in meters above mean sea level

0 0.1 0.2 0.3 0.4 0.5 KILOMETER

CONTOUR INTERVAL .2 METERS

FIGURE 6.–Calculated and observed water levels at irrigation circle 26, August 1978.

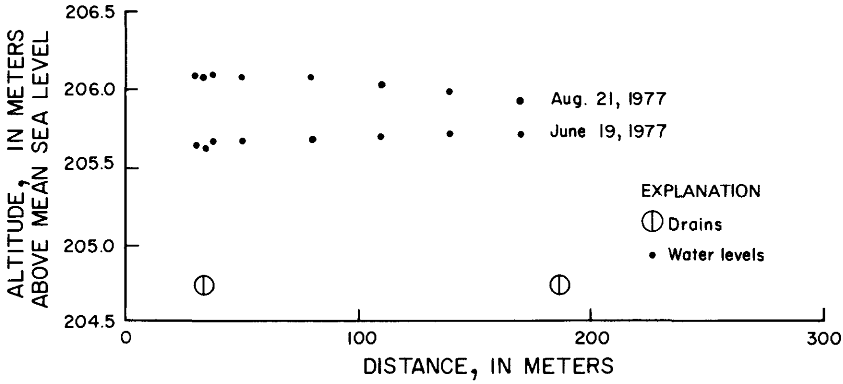


FIGURE 7.– Relation of water levels to two drains in irrigation circle 47 in June and August 1977.

At circle 33 the shape of the water table between two drains at four times in 1978 is shown in figure 8. Water levels on May 7 were measured after a period during which there was no irrigation and precipitation was 2.0 cm/wk. Water levels on June 4 were measured after a month of precipitation and irrigation that together averaged 4.8 cm/wk. The low spot shown over the drain on the right (fig. 8) suggests that the drain is at or below an altitude of 206.8 m. Water levels on July 2, were measured after four weeks of precipitation and irrigation that together averaged 8.8 cm/wk. During the five weeks immediately preceding August 5 water-level measurements, irrigation plus precipitation was 8.1 cm/wk. If evapotranspiration is assumed to be 2.8 cm/wk (the potential evapotranspiration as calculated using the Thornthwaite equation) then, from equation 2, the recharge rate was 5.3 cm/wk.

DISCUSSION

The altitude of the water table at midpoint between parallel drains is the determining factor in the design of a buried drainage system. That altitude is generally regarded as a function of the geometry of the flow system, the hydraulic conductivity of the aquifer material, and the recharge rate (U.S. Soil Conservation Service, 1973). At Muskegon, another factor, resistance to flow into the drain, influences the effectiveness of the drain. This factor has a greater effect on the water table between drains at circle 26 than does hydraulic conductivity. For example, the head loss from the midpoint between two drains to the vicinity of a drain is one third of the head loss from the vicinity of the drain to the inside of the drain (fig. 9).

A drain on circle 26 adjacent to well GS07 (fig. 5) was uncovered and examined. The mesh fabric and the sand within several centimeters of

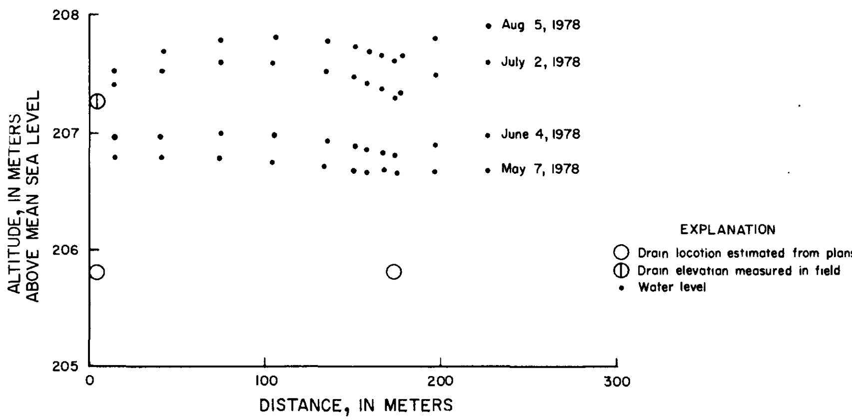


FIGURE 8. - Relation of water levels to two drains in irrigation circle 33 in spring and summer 1978.

the drain were highly discolored by what appeared to be iron precipitate. This precipitate is probably causing increased resistance to flow, as has occurred at other places in the United States (MacKenzie, 1962). If so, it must be inferred that drain leakance has been reduced since the drains were installed and that it may continue to be reduced in the future. Decreasing effectiveness of the drainage system was observed by Culp and Hinrichs (1978), who stated that "* * * circles 42 and 48 are now experiencing drainage problems in areas that had no such problem in the past."

The resistance to flow into drains limits the rate at which irrigation can be applied while maintaining a specified unsaturated thickness. To illustrate the effects of resistance, the model was used to determine how much thicker the unsaturated zone on circle 26 would have been, in August 1978 if the drain leakance had been increased by a factor of 10 and the irrigation left unchanged. At well B54 (fig. 5) the thickness of the unsaturated zone would have been increased from 0.8 m to 1.7 m. Similarly, at well G42, reduced resistance to flow into the drains would have increased the thickness of the unsaturated zone from 0.3 m to 1.4 m. Thus at these two locations resistance to flow into the drains was responsible for not meeting the goal of "* * * 5 feet (1.5 m) of free draining aerobic soil" (Demirjian, 1975). Irrigation rates in circle 26 were kept below the design rate of 8.9 cm/wk to prevent waterlogging. In the summer of 1978, irrigation rates were 5.1 cm/wk in the north part of the circle and 6.4 cm/wk in the south. The model showed that if the irrigation rate had been maintained at design rates of 8.9 cm/wk and if resistance to flow into drains had been 90 percent lower than it was in August 1978, the unsaturated zone at wells B54 and F54 would

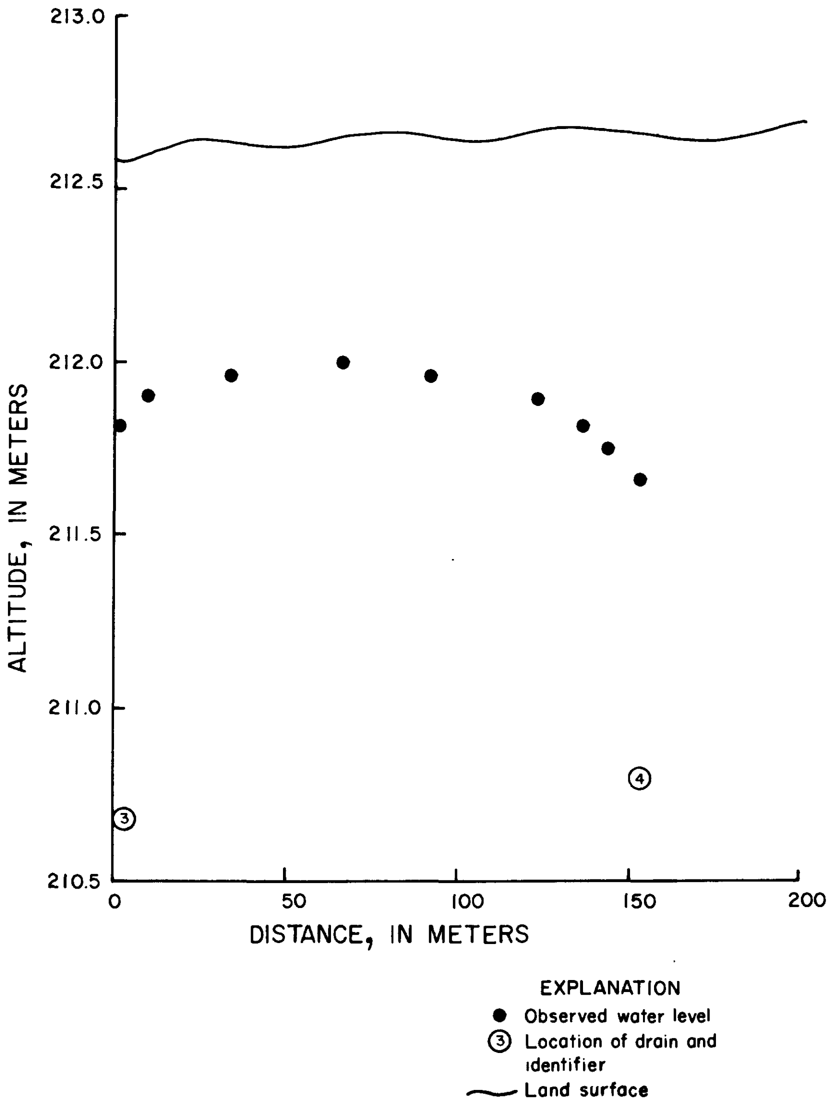


FIGURE 9. - Relation of water levels to drains in a cross section perpendicular to two drains in irrigation circle 26 in August 1978.

have been 1.5 m and 1.1 m thick, respectively, rather than the 0.8 m and 0.3 m actually observed. Thus the resistance to flow into the drains reduced the capacity of circle 26 by more than 35 percent.

CONCLUSIONS

The hydraulic characteristics of circle 26 that have significant impact on ground-water flow and water-table altitude are drain leakance and hydraulic conductivity. Given the prevailing recharge rate, the thinness of the unsaturated zone midway between drains in circle 26 is caused primarily by low drain leakance. Thus low drain leakance has limited the rate at which circle 26 can be safely irrigated.

Low drain leakance is believed to be caused by mineral precipitates, especially iron, clogging the mesh fabric and the pore spaces in the sand surrounding the drain. If mineral deposits continue to accumulate around the drains, leakance will continue to decrease, thereby reducing the capacity of the irrigation circle to accept waste water. Other circles at the disposal site that have poor drainage are believed to have drain-leakance problems similar to those in circle 26. If so, low drain leakance will be responsible for significantly reducing the capacity of the entire waste-water disposal system.

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