A STUDY OF CLOGGING BY SUSPENDED CLAY PARTICLES IN SURFACE SPREADING OPERATIONS FOR ARTIFICIAL GROUNDWATER RECHARGE

By

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ARTIFICIAL GROUNDWATER RECHARGE

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CHAPTER I

INTRODUCTION

A. General

Much attention has been given to the utilization of flood water as an additional source of supply in both arid regions and areas of dense population. Surface storage of these waters is often infeasible due to unfavorable topography, high rates of evaporation, and the inundation of large areas of expensive surface lands. Therefore, recharge into underground storage has been found to be the only feasible method of utilizing these waters.

Research in artificial recharge has centered on the economics of the various recharge methods. The economics of recharge is directly related to the maintenance of high infiltration rates. Studies have been carried out in development of suitable design procedures for recharge of turbid flood waters, as well as reclamation of sewage effluents. Studies undertaken have been concerned with the quality of recharge waters and their response to treatment, analysis of the infiltration capacity of spreading grounds, and the clogging process, its prevention and corrective measures.

B. Quality of Flood Waters

One unfortunate characteristic of excess surface waters associated with high intensity rainfall is the considerable concentration of suspended solids. In Israel extensive work has been done toward conserving storm runoff by artificially recharging this water into underground storage (1). The flood waters generally contain 3,000 to 8,000 mg/l (milligrams per liter) of suspended material (95 to 99 percent of which is mineral matter). Concentrations in the southern part of the country run as high as 25,000 mg/l because of the presence of loess soils, sparse vegetation, and high intensity rainfall. This obviously represents an extreme in suspended solids concentration due to the arid conditions prevalent. However, in the same report the authors state that only moderately turbid flood waters (hundreds of mg/l suspended matter), whether naturally occurring or obtained by some treatment process, are still of insufficient clarity for recharging.

Biological quality of stream flow would vary greatly from basin to basin dependent upon the nature of the watershed and the sewage effluents disposed of in the stream. High flood flows would tend to dilute the pollutants, but the possibility of harmful organisms entering the ground water system is always present. Tests were conducted at the Whittier Narrows Wastewater Reclamation Test Basin by the California State Water Quality Control Board to determine the effect that percolation through an engineered soil system has on pathogenic and nonpathogenic microorganisms (2). Fecal coliforms were found to be removed by filtration, but nonfecal coliforms found the soil environment favorable and actually multiplied. Nonfecal coliform organism concentration increased from 190 mg/l at the surface to 20,000 mg/l at a depth of 8 feet. Fecal streptococci were virtually removed within a few feet of percolation. Enteric (intestinal) viruses were not detected in one liter samples that had percolated through 2 feet of soil which was spread with waste water containing between 102-250 PFU per liter (PFU = plague forming units).

C. The Infiltration Process and Site Selection

The infiltration process has been treated in various ways by a number of different authors (2) (3) (4) (5). Most of the authors reviewed make use of the so-called Dupuit assumptions in their discussions of the infiltration process. Dupuit first made his assumptions in the derivation of the flow rate towards a well in the center of a circular island. This study was concluded in 1863; since then the Dupuit assumptions have been applied to areas such as flow nets, the calculation of the aquifer coefficients, the balance of surface runoff and infiltration and the vertical seepage through artificial recharge structures, such as spreading basins, ditches or infiltration pits, and recharge wells. The Dupuit assumptions for unconfined well flow are summarized by Davis and DeWiest in the following manner (6):

(1) The flow is horizontal, or the equipotential surfaces are cylinders coaxial with the well
(2) The velocity is uniform over the depth of flow
(3) The velocity at the free surface may be expressed as

$$v = k \frac{\partial h}{\partial r}$$

where h is the hydraulic head, r is the radius of influence of the well oriented away from the well, k is the hydraulic conductivity expressed as

$$k = Cd^2 \frac{\gamma}{\mu}$$

here C is a shape factor which accounts for stratification, packing, arrangement of grains, size distribution, and porosity. This equation for free surface velocity is used opposed to

$$v = -k \frac{\partial h}{\partial s}$$

where s is the flow path to the well. Other symbols used are the specific weight of the fluid γ and its dynamic viscosity μ, and d' is the average pore size of the porous medium.

This is assumed for recharge wells, but can only be approximated in the case of a spreading basin. Berend, Rebhun and Kahan (1) in their work with dune sand in Israel describe a saturated zone which extends underground beyond the boundaries of the spreading basin. This saturated zone is in the form of a wedge. Flow through the pervious layers beneath the basin was shown to be divided into zones of vertical and horizontal flow, with an intermediate zone in between. In the cases where a semipervious layer was encountered, the flow through this layer was shown to be vertical only. Provided the water table does not rise to the bottom of the semipervious layer, the seepage wedge in the horizontal zone can be evaluated by approximating the Dupuit assumptions for unconfined well flow.

From the above discussion, it can be concluded that the infiltrative capacity of a soil, i.e., its capacity to admit water through the soil, is dependent on the following factors: (1) The percolative capacity of the soil, or the quantity of water which will flow through the soil in a unit time. This excludes the effects of clogging due to surface obstruction or obstruction of the underlying layers. (2) The capacity of the soil to transmit the water laterally, increasing the horizontal area through which water can move vertically. (3) The permeability of any semipervious layers. (4) The effect of the hydraulic gradient (head of water) on the percolative capacity of the semipervious or limiting zone.

In the recharge of ground water aquifers by surface spreading, the primary objective is to obtain the highest possible rate of hydraulic acceptance with a minimum land area required for spreading. Therefore, spreading basins for artificial ground water recharge must be located at sites where high infiltration rates (dependent upon the four above mentioned factors) may be expected. Site selection is then based on the type of recharge method used. This is governed by the topography, geologic and soil conditions, the quantity of water to be recharged, and the ultimate use of this recharge water. In some circumstances other factors become important, such as water quality, climate and land value.

D. Prevention of the Clogging Process

1. General

In the preceding sections, the effect of clogging on the infiltrative capacity of a soil has been ignored. There are, however, a number of factors which are considered potential hindrance to the sustained infiltrative capacity of artificial recharge spreading basins. These factors are: (1) biological activity, (2) suspended load, and (3) soil structure changes.

2. Biological Activity

Amramy (1) in a discussion of clogging of sand inundated with sewage wastewater states that biological clogging of soil pore spaces is caused by microbial growths. Studies conducted by Mitchell and Nevo (8) indicate that clogging is a result of the accumulation of polysaccharide and polyuronide slimes.

The production of polysaccharides and polyuronides is by no means a simple process. However, basically they are produced by bacteria which feed on the sewage. In other words, slimes are a by-product of the degradation of organic matter by bacteria. It has been shown that, in the complete absence of oxygen, no polysaccharide production takes place, and in a highly aerobic condition the polysaccharides are decomposed by fungi. Clogging under anaerobic conditions is also attributed to microbial conditions (9).

Clogging by biological factors is basically a surface phenomenon which involves the formation of an organic mat. It has been shown that periodic resting and loading of the soil will bring about a return, or partial return, of the soil to its original infiltration rate. Therefore, in soil systems operating under sewage spreading, the criteria for maximum infiltrative rates are to: (1) maintain an aerobic system by cyclic period of loading and resting, and by proper pretreatment and (2) reduce the biochemically unstable organic matter in the influent water.

3. Suspended Matter

Clogging by suspended matter is considered the most serious deterrent to the utilization of storm runoff for artificial recharge. The clogging process occurs in one of three ways, or a combination of three ways: (1) formation of a surface layer, (2) filling of the soil interstices near the surface, or (3) penetration of the suspended particles and accumulation at deeper levels.

Clogging is dependent upon many variables, of which the most important are the size distribution of the porous media, the vertical approach velocity of the influent water relative to the gravitational acceleration, or settling velocities of the coarser particles, and the concentration of the suspended material (ppm or mg/l).

Behnke (10) has shown that clogging by suspended matter is a surface sealing process. Berend et al. (1) stated that a sediment layer will be formed on the surface if the settling velocity exceeds the infiltration velocity. If the sediment load is nonuniform in size then initially the mechanism for clogging is gravitational settling. A gravitational layer is formed as coarser particles settle first and the limiting layer builds upward becoming progressively finer, straining still smaller particles from the infiltrating water and therefore reducing the infiltration rate.

Resting of the soil surface, as in the case of biological clogging, has little or no effect on a soil surface clogged by turbidity. However, there are many preventive and corrective measures to be considered.

Pretreatment of the flood waters is the most feasible solution. Flocculation and settling or centrifugal methods of removal as well as filtering have been studied.

Cyclonic solids-liquid separation methods have been studied extensively at Oklahoma State University. Research currently proposed will involve the use of a hydrocyclone developed and patented at Oklahoma State University. The hydrocyclone uses centrifugal separation in which suspended matter is accelerated to several thousand times the acceleration of gravity. Using methods of chemical pretreatment, such as coagulation with alum or some other flocculating aid, the efficiency of the hydrocyclone can be increased to produce an effluent suitable for recharging into the groundwater formation.

The feasibility of the hydrocyclone for suspended solids removal has been demonstrated at the bioenvironmental engineering laboratories at Oklahoma State University by several investigators (11).

4. Soil Structure Changes

The permeability of soil is dependent in part on the soil structure. The hydraulic conductivity of a soil may be reduced as a result of soil structure changes brought about by percolation over extended periods of time. Berend et al. (1) has postulated the following mechanisms of clogging by soil structure changes:

(a) Swelling of clay as a function of ionic strength and dissolved cations composition. This swelling may affect the pore-size distribution through internal changes or by enabling consolidation. Swelling may also result in particles migration, leading to their accumulation and clogging of the interstices somewhere in the profile.

(b) Leaching and disposition of salts. Whereas leaching of cementing agents may weaken the soil aggregates enabling consolidation or particle movement, deposition of salts may result in blocking of the soil pores.

E. Scope and Importance of the Present Investigation

Artificial groundwater recharge is accomplished by three basic methods: injection, spreading, and pit recharge. (In this study direct injection into the aquifer is not considered. Soil deposits accumulate more rapidly during an injection operation due to the large quantities of water passing through a relatively small area.) However, in spreading and pit recharge operations, when untreated waters containing high turbidities are applied directly to the soil surface the soil readily becomes clogged, reducing the infiltration rate to an unacceptable level. Knowing that the permeability of the soil to the groundwater table controls the rate of recharge, research in this area is concerned with preventing clogging of the soil pores in order to increase the infiltration rate, thereby increasing the amount of water that can be added to the groundwater reservoir in a given time or reducing the land area needed for the recharge operation.

Past research at Oklahoma State University has been concerned with developing a management model for predicting the overall effect of legal and economic constraints as well as physical conditions on the ultimate management of the Ogallala groundwater formation in the Oklahoma panhandle (12). This management model was developed as a mathematical representation of the movement of water in the aquifer which results from both natural flow and flow from wells. The model is capable of generating data from known physical parameters that can be related to the economic life of the reservoir. The ultimate goal of the model is to forecast the yearly depletion of the groundwater and correlate this lowering of the water table with its effects on the economy of this area.

Proposed research is now concerned with means of maintaining the economy of this agricultural region which relies heavily on groundwater for irrigation.

Replacing the water removed from the formation is the principal aim of water resources planners. Methods of reclaiming wastewater and storm runoff and artificially recharging this water into the formation are clearly needed.

Research at Oklahoma State University includes studies on suspended solids removal by the hydrocyclone methods of solids-liquid separation discussed earlier in this chapter and subsequent studies on artificial recharge of this treated water.

The proposal for this research includes construction of a sand model, consisting of sands from the Ogallala formation, to investigate the effects of using hydrocyclone treated effluents for recharge water. Studies will include the clogging effects of untreated water and studies on well injection and pit recharge of reclaimed water.

The present investigation is concerned with examining the clogging process which is due to the deposition of fine clay particles. The principal objective of this study is to show the relationship between suspended solids concentration and the rate of infiltration loss under prolonged submergence by a turbid water. It is hoped that the results of this study will be helpful to future studies involving sand models and in suggesting some practical remedial measures (related to particulate removal efficiencies) as to altering the nature of recharge water to maximize the rate of recharge.

CHAPTER II

LITERATURE REVIEW

A. General

Artificial groundwater recharge of underground basins has been studied and practiced for more than a century. Literature pertaining to experience in this field has been summarized by Todd (13) and by McMichael and McKee (2). This chapter is a review of some of the pertinent research done by various investigators studying the effects of the clogging phenomenon on the infiltrative capacity of recharge basins.

B. Effects of Biological Clogging

The use of engineered soil systems for the disposal of liquid waste water has experienced periods of popularity for centuries. However, the major application of recharging groundwater up to 1949 was for the prevention of salt water intrusion.

In 1949 the University of California began experiments on the spreading of wastewater effluent at Lodi, California. These experiments concluded that: (1) a bacteriologically safe water can be produced by percolation through at least four feet of soil, (2) a water of satisfactory chemical quality can be produced from the effluent, and (3) in order to obtain good infiltration rates highly treated wastewater must be used (4). This study was the first major investigation which led to more intensive work in Southern California, dealing with biological activity in a recharge basin.

In January of 1962, research work was authorized by the California State Water Pollution Control Board for the investigation of a sewage spreading operation at Whittier Narrows (2). The principal objective of this study was to determine the effects of intermittent percolation of a highly treated activated-sludge system effluent through a soil system on the quality of groundwater. Also, the main objective of the investigation was to study the fate of mineral, organic and biological matter in a wastewater and investigate the processes associated with the removal of these various wastewater constituents.

The Whittier Narrows study consisted of three main parts. The first step was to drill 25 wells near the test basin to monitor the quality of the groundwater at various depths. The next portion of the study was the construction and operation of the test spreading basins to investigate the effects of percolation through the soil. Thirdly, soil columns were constructed in the laboratory to study the degradation of linear alkylate sulfonates (LAS) and alkyl benzene sulfonates (ABS) in order to make a comparison in the degradability of the new LAS compound.

In this section the main concern is with the second phase of the Whittier Narrows project, the operation of the recharge basin.

Over a period of two years, 193,515 acre feet of Colorado River water, 33,640 acre feet of local water and 28,373 acre feet of reclaimed water was spread on the basin at Whittier Narrows. The reclaimed water, as can be seen, accounted to only 11.0 percent of the total, or a dilution of more than eight to one.

The bed was loaded 5 days a week with 2.0 feet of sewage effluent. This water percolated into the soil in less than 10 hours; in the remaining time before reloading, the bed was subject to aeration. The average infiltration rate decreased in the first five months, beginning with a rate of 1.45 feet per day and decreasing to a rate of 0.59 feet per day, then increased to a high of 5.20 feet per day, decreasing slightly in winter months but increasing in warmer months. This marked rise to 5.20 feet per day infiltration rate gives much credibility to the conclusion that spreading of a highly treated activated sludge system effluent did not clog the basin surface but to the contrary improved the infiltrative capacity considerably. This exceptionally high hydraulic acceptance was not investigated thoroughly as to the process behind such a spectacular rise in rate but was assumed to be due to biological growths in the soil of the basin surface which forced the soil structure to heave and open and to remain open during cycles of drying and aeration (2).

Improvement in hydraulic acceptance at Whittier Narrows was also correlated with the application of a six-inch layer of pea gravel. It was concluded that the pea gravel brought about turbulent flow conditions which caused the colloidal solids of the effluent to flocculate and were oxidized on the surface of the pea gravel, thereby preventing the colloids from reaching the basin surface (2).

It was concluded at Whittier Narrows that if the objectives of groundwater recharge by surface spreading of wastewater effluents were to be attained then a highly aerobic environment must be maintained in the spreading basin by intermittent or cyclic loading and resting in a way that optimizes the reaeration of the soil (2). The objectives of groundwater recharging by surface spreading of a wastewater effluent are to obtain the highest infiltrative rates possible to minimize the required land area and the achievement of an optimum degree of tertiary treatment of the sewage effluent in order that the percolated water will be suitable for beneficial use.

The Whittier Narrows test basin and water reclamation operation is a unique pilot plant operated very efficiently by making use of a highly treated activated sludge effluent. The main concern of the study was to determine the travel of pollution (bacteria and viruses) through the soil system and determine the degradation of organic compounds by the active soil mantel.

In dealing with flood waters containing high concentrations of organics or sewage effluents, a high degree of treatment is not feasible due to the large quantities of water involved. Therefore, a closer examination of the clogging process must be made.

Allison (14) conducted permeability tests under sterile conditions to obtain quantitative evidence pertaining to the exact effect of microorganisms on permeability of soils subjected to prolonged submergence. Citing earlier work, it was pointed out that permeability tests in which the water was treated with toxic chemicals were not conclusive evidence that soil clogging was due mainly to microbial sealing.

Tests by Allison were conducted using soils from the San Joaquin Valley, California, where surplus water resulting from high stream flow was to be stored underground for future use as irrigation water.

Using a sterile water, as in earlier investigations, Allison also used a sterile soil sample because the soil also has an active zone in which organic matter and bacteria coexist. The results indicated that the sterile soil and water exhibited a high constant permeability over time, whereas, the control systems which had soil of higher organic content clogged to unacceptable levels and sealed more rapidly.

These tests were conducted under conditions of prolonged submergence without resting. There was no evidence of soil aggregate breakdown due entirely to physical causes. It was concluded that the reduced permeability was due entirely to microbial sealing because of clogging by-products of growth, such as cells, slimes, or polysaccharides.

Thomas et al. (9) conducted tests to investigate soil chemical changes under sewage spreading operations. Lysimeters were filled with Ottawa (silica) sand and intermittently spread with a treated sewage from an experimental septic tank.

It was noted that the total organic matter present appeared to contribute greatly to the clogging, because it was observed that the recovery of the infiltration rate was related to a decreased concentration of total organic matter in the soil.

Although this study did not specifically characterize the soil clogging mechanism, some probable steps within the mechanism were indicated. The infiltration rate loss exhibited three phases. The first phase occurs under aerobic conditions and exhibits a slow reduction. In the second phase a rapid reduction of the infiltration rate takes place under anaerobic conditions. The second phase occurs as the porosity is reduced by the accumulation of organic and inorganic residues in the soil which causes air diffusion into the soil to fall below the biological requirement, and the environment becomes anaerobic. Phase three exhibits a gradual decline in infiltration rate under anaerobic conditions. It was observed in these tests that the impedance in each of the three phases of hydraulic behavior occurred in the 0 to 1 centimeter soil layer where 87 percent of the total impedance took place.

Thomas concluded that the concentration of total organic matter, polyuronide, and polysaccharide increased in the first phase of operation, and the accumulation rate was slower during phase II. Polyuronide concentration was shown to be approximately 10 percent of the total organic matter in both phase I and II, but polysaccharide concentration decreased from 10 percent in phase I to about 4 percent in phase II. It was concluded that polyuronide was directly associated with the accumulation of resistant organic matter, but the polysaccharide was not (9).

Nevo and Mitchell (18) conducted studies in the laboratory using lysimeters which consisted of glass columns 45 centimeters long and 5 centimeters of the soil in the lysimeters. It was concluded from the tests that periodic resting of infiltration basins would effectively unclog the sand beds because during flooding polysaccharide is produced while degradation is prohibited, the result being a new accumulation of polysaccharide and resulting sand clogging.

C. Effects of Clogging by Sediment Load

Behnke (10) conducted laboratory studies using sand columns 85 centimeters long through which a turbid water was passed under a constant head. The turbid water was obtained by mixing floodplain surface deposits with distilled water. Different soil types were used in the turbid water mixes; some contained predominantly clay fractions, while others contained sand and silt in abundance. Concentrations were patterned after actual sediment concentrations in streams flowing from the Sierra Nevada into the San Joaquin Valley. These concentrations generally range from 50 to 250 parts per million, although some streams exceed 250 parts per million, but 250 was considered a reasonable upper limit.

It was concluded from these studies that clogging by sediment load is complex and is dependent on many variables such as size distribution of the particles in the turbid mix relative to the pore size distribution of the porous media, the approach velocity of the in-coming water relative to the settling velocities of the coarser particles in suspension, and the concentration of the suspended matter. Clogging was observed to be a surface sealing process, noting that clogging took place with concentrations as low as 50 parts per million. For suspended matter of nonuniform size, clogging is due to gravitational settling (10).

Much work in the area of artificial recharge has been done in the High Plains of Texas where natural recharge is greatly exceeded by pumpage from irrigation wells; the USGS has estimated the natural recharge to be only 10 percent of the current annual withdrawals (15).

W. L. Broadhurst, Chief Hydrologist at the High Plains Underground Water Conservation District, has headed studies in recharge of water that collects in the many depressions called playa lakes that dot the plains (15). These depressions, some as large as a mile in diameter and 50 feet deep, have relatively impermeable bottoms and consequently hold water until it eventually evaporates. It is the object of the high plains investigation to find a suitable method of recharging this water into the underground formation.

It was found that sediment in the playa lake water was the main deterrent to recharging through wells. Two studies at Texas Technological College were cited which dealt with the clogging of recharge wells. The first study concluded that fine material does not filter out of the water to form a cake on the face of the well, but rather it moves into the water bearing formation. Recharge tests showed a loss in permeability over a two-year period to be about 15 percent (15).

The second study cited concerned the use of a flocculant which was applied to the lakes from a crop dusting airplane. Results from this indicated that much of the suspended matter could be removed at a moderate cost (about two dollars per acre-foot) (15).

Hauser and Lotspeich (16), also, were involved in recharge work in the Texas High Plains. Polyelectrolyte polymers (cationic) were examined to determine concentrations, relative to turbidities, for optimum removal. The water to be recharged was then settled and filtered through a gravel bed to remove large trash, but no sand filters were used due to the difficulty of field operation. Flocculant and alum concentrations were determined by jar tests and were found to vary from 1 to 4 parts per million for the cationic polymer and 0 to 20 parts per million for the alum.

Results of these tests showed that turbidity in the playa lake water was reduced to less than 10 percent of that found in the raw water. However, it was pointed out that sufficient sediment remained to clog the recharge wells (16).

Schiff and Johnson (17) conducted studies to investigate filter materials that would cause sedimentation through a depth of the filter rather than sealing the surface. Filter materials, each 0.2 foot in depth, were placed over the aquifer. These filter materials consisted of sand ranging in size from 0.5 to 1.6 millimeters, one-eighth inch pea gravel, and one-fourth inch pea gravel. After each run the filter material was removed along with 0.2 inch layer of the filter material and replaced by new material of the same specifications.

Results of the tests showed that the coarse sand had the greatest effect on maintaining a high infiltration rate. Later in the basin operation, the one-eighth inch pea gravel had significant influence in maintaining the infiltration rate, but the one-fourth inch pea gravel layer had no significant effect on improving the infiltration rate. It was generally concluded that total infiltration through the aquifer material was doubled when a coarse sand filter was used as compared to the aquifer material with no filter at all (17).

D. Other Factors Affecting the Reduction of the Infiltration Rate

Nevo and Mitchell state in their investigation of biological clogging by polysaccharide that observations on the effect of temperature on production and degradation of polysaccharide indicate that sudden changes in permeability due to water temperature changes can be predicted. If the water temperature was below 20 degrees centigrade, the rate of clogging would be expected to be high. Moderate clogging occurs between 20 and 30 degrees centigrade and little or no clogging should occur at 37 degrees centigrade or higher (18).

The effect of entrapped air on the movement of water through soil has been studied extensively in the last thirty years.

Pillsbury and Appleman (19), in their work with soil binding by entrapped air, have shown that some of the air can be removed by displacement by the percolating water as the soil is wet. But the remaining nondisplaceable trapped air can only be removed by being dissolved into the percolating waters. Naturally, the air content of the water entering the soil has an effect on the rate at which entrapped air is dissolved. The most important factors in removal of entrapped air is the amount of water per unit volume of trapped air and the capacity of the water to dissolve air.

Christiansen (20) also reporting on the effect of entrapped air on soil permeability states that when a soil is wetted the permeability decreases and then increases sharply for a period of time. Then a second decrease in permeability is noted which is not correlated with air binding but rather with the growth of soil flora.

CHAPTER III

MATERIALS AND METHODS

The apparatus and experimental procedure used in the laboratory portion of this study were relatively simple and straightforward.

The apparatus consisted of an ordinary constant head permeameter obtained from the soils testing laboratory at Oklahoma State University. It is illustrated in Figure 1, where h is the head of water above the evaporating dish in centimeters and L is the length of the soil column in centimeters. Figure 1 and the experimental procedure are after Means and Parcher (21). A large pyrex battery jar was used to contain the turbid water mix which was conveyed to the constant head permeameter by siphoning. The turbid water mix was constantly stirred throughout each experimental run, by means of an electric motor driven stirrer, to maintain the clay particles in suspension.

The turbid waters were obtained by mixing Permian red clay with tap water. Permian red bed clay is a clay of medium plasticity which is obtained from Permian terrestrial and shallow marine (estuary) deposits of Oklahoma. It has a high iron oxide content which gives it its distinctive red color. Its size distribution was determined by Marks and Haliburton (22) and is as follows:

Less than 10 micron -- 38.0%
Less than 5 micron -- 32.0%
Less than 1 micron -- 26.0%

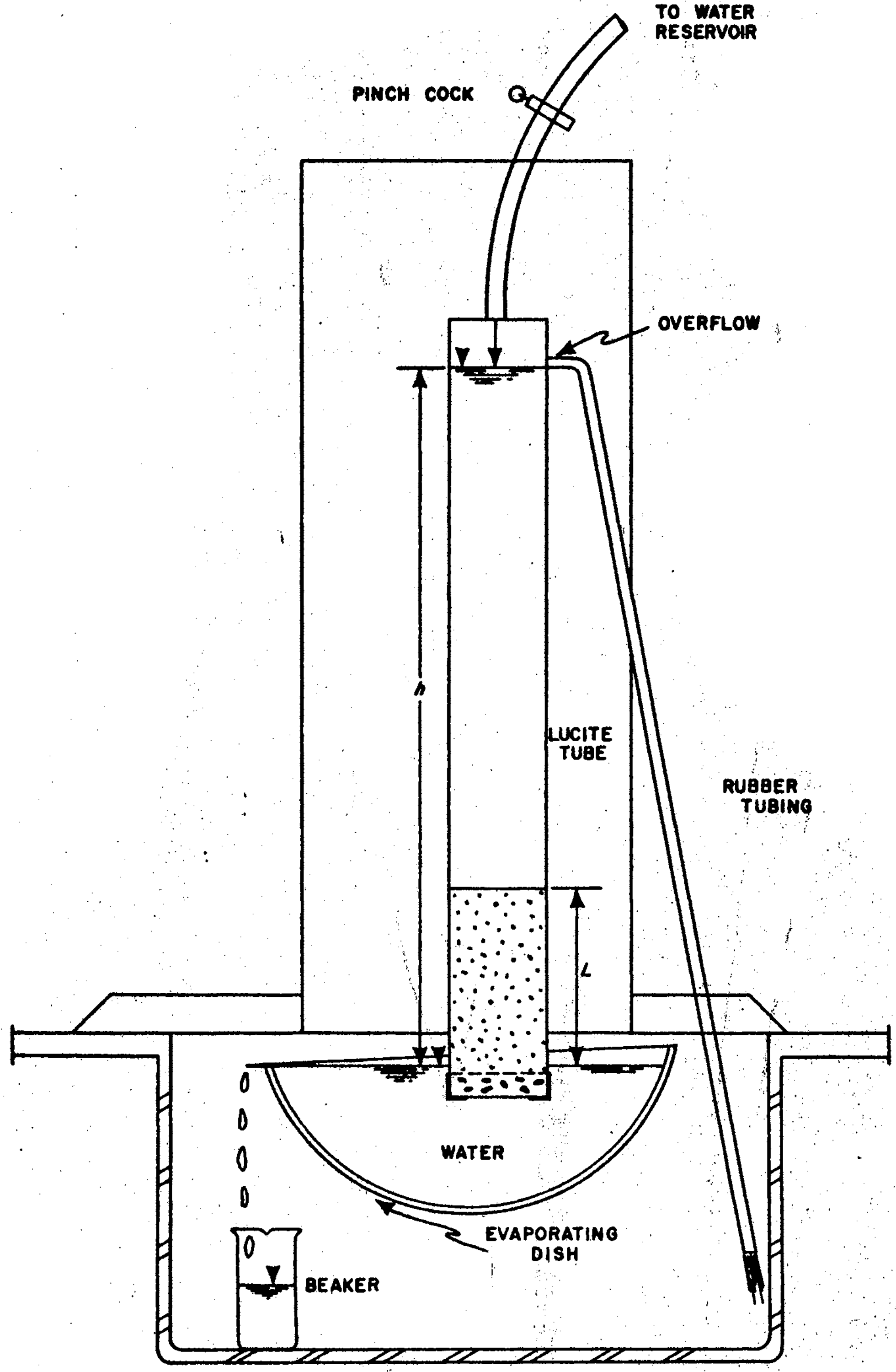

Figure 1. Diagram of a Permeameter.

This clay was chosen because of its presence in surface waters throughout central Oklahoma.

The clay suspension was first mixed at concentrations of 10,000 mg/l by adding 10 grams of oven dried clay to one liter of distilled water. This was done to expedite the mixing of needed concentrations for the various runs. Concentrations of 316 mg/l, 143 mg/l and 70 mg/l were percolated through the porous media. These concentrations were chosen on the basis of literature review and sampling of the Cimarron River near Perkins, Oklahoma. Behnke (10) in studies on recharging waters containing suspended solids considered concentrations ranging from 43 parts per million to 203 parts per million. Sampling of the Cimarron River was conducted in August 1971 when low flow conditions existed. The suspended solids concentration on this date was found to be 75 mg/l. This value is not entirely due to mineral matter, but it does indicate the relative concentrations that would be involved in excess storm runoff. Sediment concentrations of many rivers at flood stage would easily exceed 316 mg/l, therefore this was considered a reasonable upper limit.

The porous media consisted of Ottawa (silica) sand having an effective diameter of 0.12 millimeters and a uniformity coefficient of 1.5. The sand was placed in the plastic permeameter cylinder with the sand column being 20 centimeters long and having a surface area of 19.63 square centimeters. Initial permeability through the sand column, using clear water, was 6.9×10^{-2} centimeters per second.

Measurements of the reduction in infiltration rate were taken in the following manner: a 600 ml beaker was placed beneath the outfall from the evaporating dish as shown in Figure 1. Readings were taken for up to 26 hours in the 70 mg/l turbid water mix but readings at 16 hours were conclusive for the 143 and 316 mg/l concentrations. Each reading was taken for a duration of 120 seconds and the flow recorded in cubic centimeters.

Permeability was calculated from Darcy's Law

$$K = \frac{QL}{hAt}$$

and was recorded in centimeters per second. In Darcy's equation K is a function of the flow Q, the length of the soil sample L, the hydraulic head h, the sample area A, and the sampling time t.

The concentration of the turbid water was verified using the standard test for solids. A sample of 50 ml was taken from the pyrex battery jar and was filtered through a 0.45 micron membrane filter. The filter was weighed prior to filtering and after filtering and oven dried to determine the amount of solids deposited. Temperature was considered constant throughout the experimental runs.

Using this experimental procedure and design it was possible to measure the reduction in infiltration rate resulting from clogging of the sand column by various concentrations of turbid water.

With the results from these soil clogging tests, insight can be gained in the degree of treatment that must be achieved by the cyclonic method of solids-liquid separation discussed in the introductory chapter of this paper.

CHAPTER IV

RESULTS

The results of permeability tests involving percolation of a turbid water through a porous media are shown in Figures 2 and 3. The results are also shown in tabular form in Tables I, II, and III.

Figure 2 is a graphical representation of the flow (Q) in cubic centimeters plotted against elapsed time in hours. The flow accumulated for a 120 second interval at times during the experiment is plotted rather than permeability. This was done in this manner because all samples were collected for the same time interval, thus the flow and permeability will exhibit the same characteristic curve. Also, there is more interest in the accumulated flow that can be infiltrated into a soil under conditions of clogging.

It was observed that settling of the suspended matter occurred in the tube above the sand sample. This settling would simulate actual conditions in the field during recharge operations. It was also noted that the clay particles infiltrate into the sand column as well as depositing a limiting surface layer. In the water containing higher concentrations of suspended matter (316 mg/l), the clay particles did not infiltrate the porous media as deeply as did the clay particles in the waters containing lower concentrations of turbidity. Also from Figure 2 it can be seen that with the higher concentration of turbid water (316 mg/l) the initial permeability of sand (6.9×10^{-2} cm/sec)

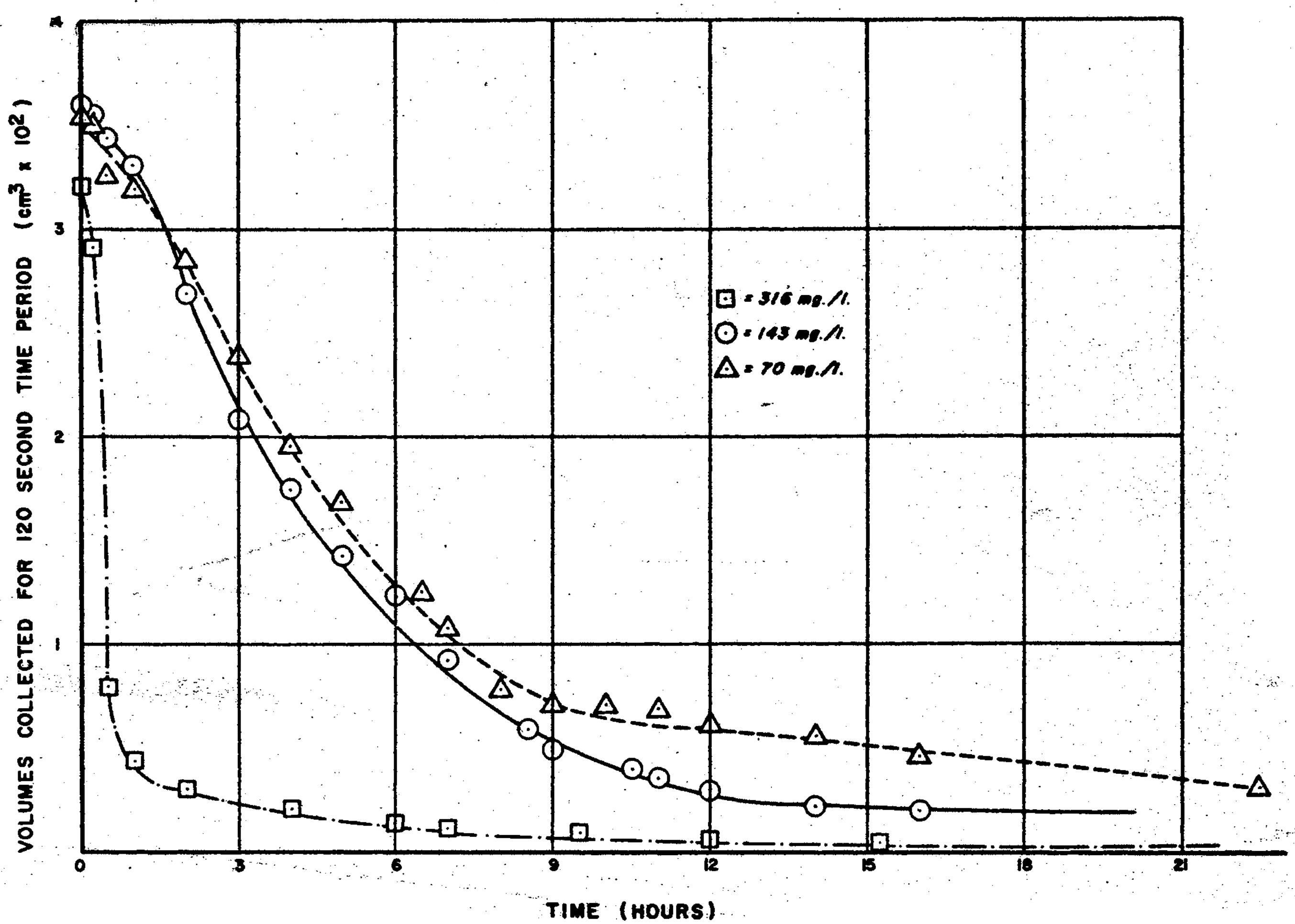

Figure 2. Volumes Collected for 120 Second Time Period Versus Elapsed Time.

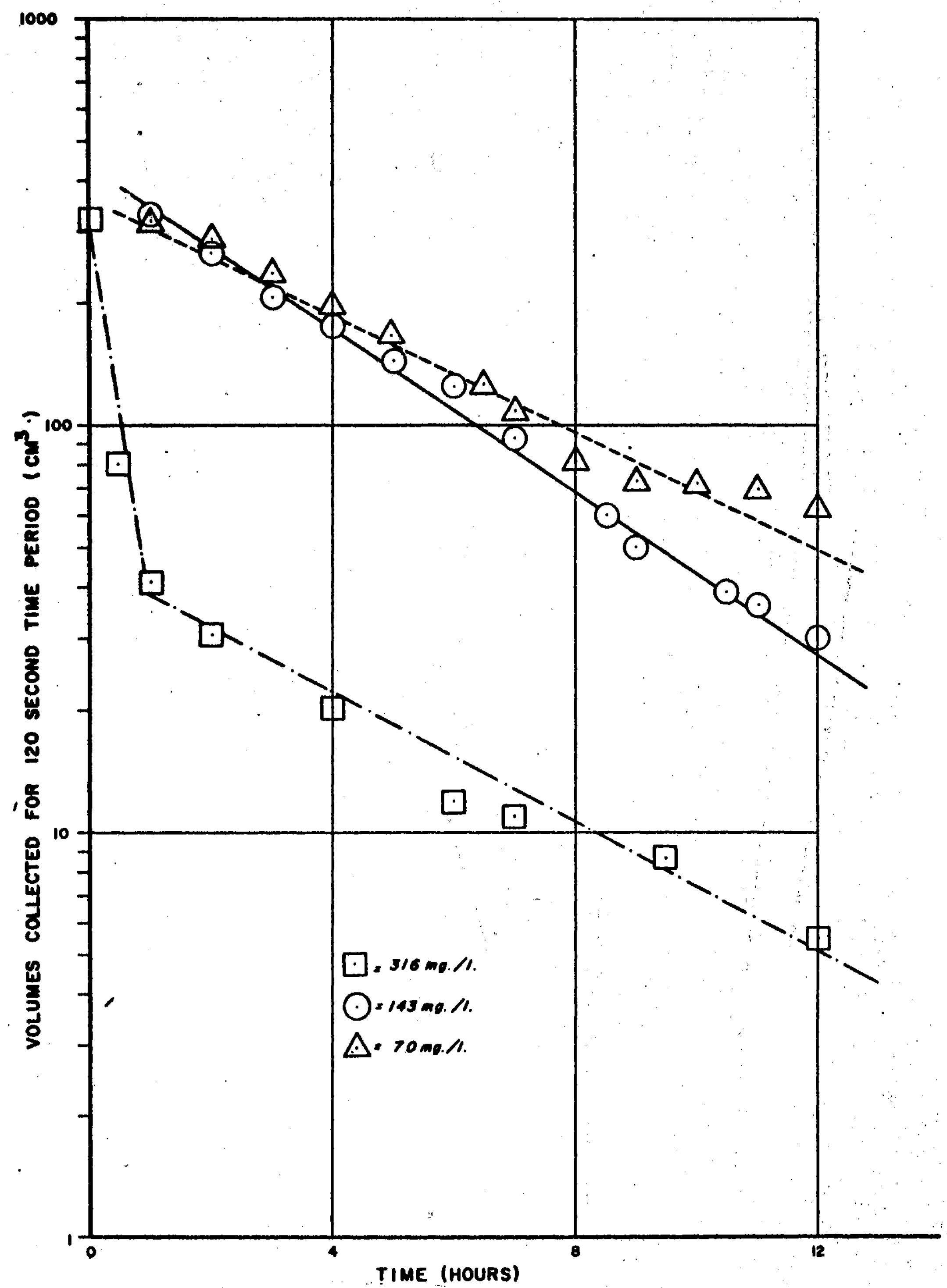

Figure 3. Log-Volumes Collected for 120 Second Time Period Versus Elapsed Time.

TABLE I

FLOW AND PERMEABILITY DATA
70 MG/L RUN

Time Sec.	Head h cm	$\frac{h}{L}$	Flow Rate cm^3	Permeability K cm/sec	Elapsed Time
120	44	2.2	353	6.8×10^{-2}	0
120	44	2.2	350	6.75×10^{-2}	15 min
120	44	2.2	333	6.4×10^{-2}	30 min
120	44	2.2	319	6.2×10^{-2}	1 hr
120	44	2.2	285	5.5×10^{-2}	2 hr
120	44	2.2	239	4.6×10^{-2}	3 hr
120	44	2.2	197	3.8×10^{-2}	4 hr
120	44	2.2	168	3.2×10^{-2}	5 hr
120	44	2.2	125	2.4×10^{-2}	6½ hr
120	44	2.2	108	2.1×10^{-2}	7 hr
120	44	2.2	81	1.6×10^{-2}	8 hr
120	44	2.2	72	1.4×10^{-2}	9 hr
120	44	2.2	72	1.4×10^{-2}	10 hr
120	44	2.2	69	1.3×10^{-2}	11 hr
120	44	2.2	62	1.2×10^{-2}	12 hr
120	44	2.2	54	1.0×10^{-2}	14 hr
120	44	2.2	46	0.88×10^{-2}	16 hr

TABLE II

FLOW AND PERMEABILITY DATA
143 MG/L RUN

Time Sec	Head h cm	$\frac{h}{L}$	Flow Rate cm^3	Permeability K cm/sec	Elapsed Time
120	44	2.2	365	7.0×10^{-2}	0
120	44	2.2	358	6.9×10^{-2}	15 min
120	44	2.2	344	6.6×10^{-2}	30 min
120	44	2.2	330	6.4×10^{-2}	1 hr
120	44	2.2	269	5.2×10^{-2}	2 hr
120	44	2.2	208	4.0×10^{-2}	3 hr
120	44	2.2	175	3.4×10^{-2}	4 hr
120	44	2.2	142	2.7×10^{-2}	5 hr
120	44	2.2	124	2.4×10^{-2}	6 hr
120	44	2.2	93	1.8×10^{-2}	7 hr
120	44	2.2	60	1.2×10^{-2}	8½ hr
120	44	2.2	50	0.96×10^{-2}	9 hr
120	44	2.2	39	0.75×10^{-2}	10½ hr
120	44	2.2	36	0.69×10^{-2}	11 hr
120	44	2.2	30	0.67×10^{-2}	12 hr
120	44	2.2	23	0.44×10^{-2}	14 hr
120	44	2.2	20	0.38×10^{-2}	16 hr

TABLE III

FLOW RATE AND PERMEABILITY DATA
316 MG/L RUN

Time Sec	Head h cm	$\frac{h}{L}$	Flow Rate cm^3	Permeability K cm/sec	Elapsed Time
120	44	2.2	321	6.2×10^{-2}	0
120	44	2.2	291	5.6×10^{-2}	15 min
120	44	2.2	80	1.5×10^{-2}	30 min
120	44	2.2	43	0.8×10^{-2}	1 hr
120	44	2.2	31	0.59×10^{-2}	2 hr
120	44	2.2	21	0.40×10^{-2}	4 hr
120	44	2.2	12	0.23×10^{-2}	6 hr
120	44	2.2	11	0.21×10^{-2}	7 hr
120	44	2.2	8.7	0.16×10^{-2}	9½ hr
120	44	2.2	5.5	0.10×20^{-2}	12 hr
120	44	2.2	3.9	0.07×10^{-2}	15¼ hr
120	44	2.2	2.6	0.05×10^{-2}	26 hr

was not realized. Figure 2 also shows that the higher concentration turbidity clogged the soil markedly faster than the lower concentrations. But as can be seen in Figure 3 the clogging procedure is completely different in the higher concentration run (316 mg/l), at least in the first hour of the experimental run. This is an interesting phenomenon and will be discussed further in the next chapter.

The initial permeability of the sand using clear water was determined to be 6.9 x 10^{-2} cm/sec. In the case of the 70 mg/l suspended solids experimental run, the initial permeability was found to be 6.8 x 10^{-2} cm/sec. The variation of 0.1 x 10^{-2} cm/sec below the initial permeability value for this run is small and is due only to some experimental error and not to the relative concentration of turbidity.

In the 143 mg/l run, the initial permeability was 7.0 x 10^{-2} cm/sec. This small variation is also considered insignificant and not due to the relative turbidity concentration.

The initial permeability in the 316 mg/l run was significantly lower than the initial permeability using clear water. It can be assumed that this difference is due to the relatively high concentration of suspended solids. The permeability for the 316 mg/l run was 6.2 x 10^{-2} cm/sec.

In an attempt to make a further comparison of the relative rates of clogging due to the three different concentrations of suspended solids, the percentage that the permeability was reduced in each case was considered for a given elapsed time. The 70 mg/l run showed a reduction in permeability of 82 percent in a 12-hour period. The 316 mg/l run showed a reduction in permeability of 98 percent in a

12-hour period. This gave some indication of the total reduction in infiltration rate for a given time period.

Figure 4 is a plot of the total volume of flow accumulated at various time intervals for each experimental run. This figure shows how clogging is related to solids concentrations and the relative amounts of water that can be infiltrated through the soil in a given time. Both the 143 mg/l curve and the 70 mg/l curve follow the same path closely until later in the run when the 143 mg/l run begins to exhibit a smaller accumulated flow. The 316 mg/l curve is drastically different from the other two showing a marked decrease in total accumulated volume. This difference is attributed to gravitational settling of the suspended matter.

Figure 5 is a plot of the permeability for the three solids concentrations at selected time periods. This graph shows that at a high concentration of suspended solids the soil readily reaches a low infiltration rate and that at some elapsed time infiltration for any concentration would reach a fairly constant, low rate.

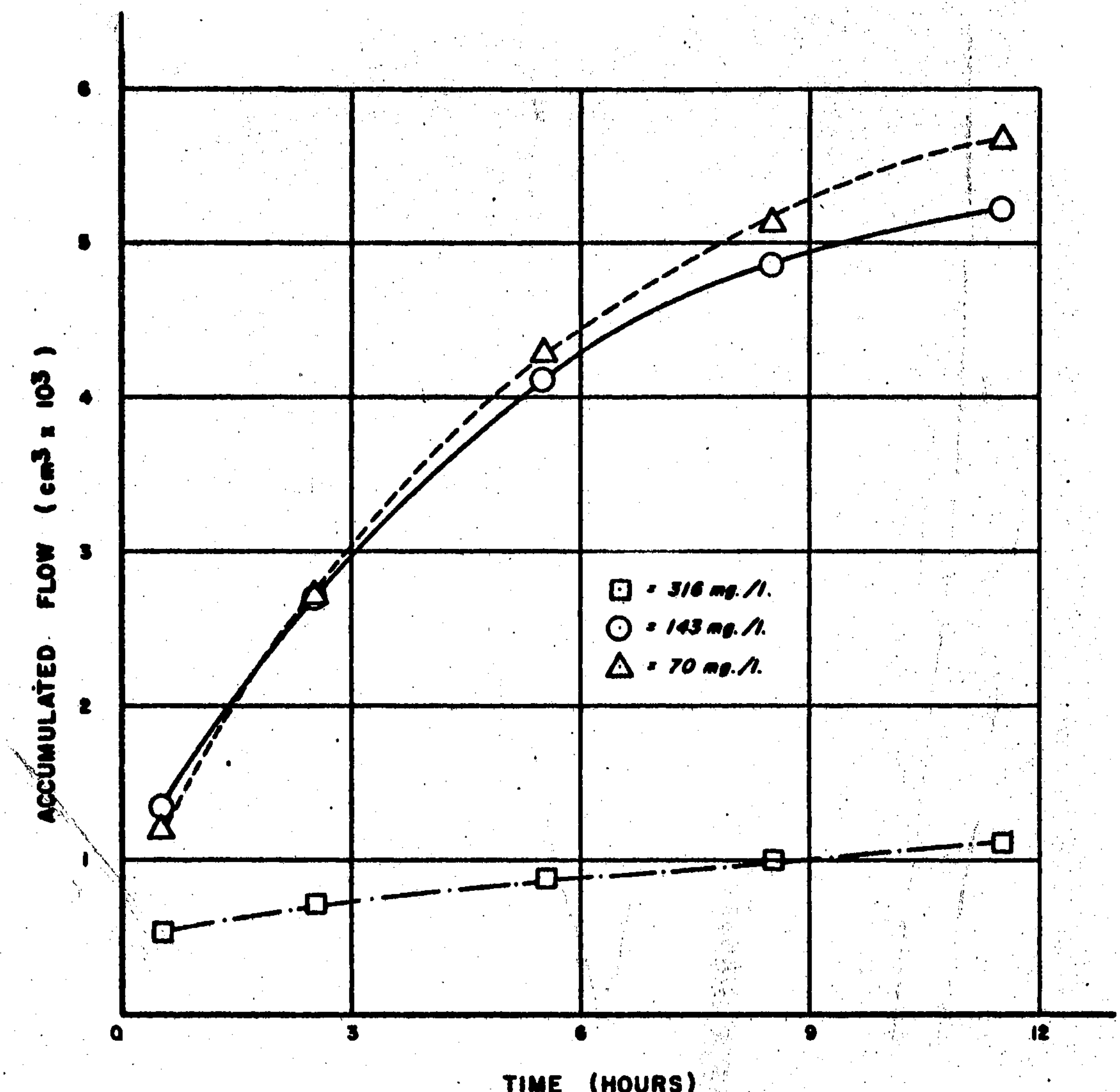

Figure 4. Accumulated Flows Versus Elapsed Time.

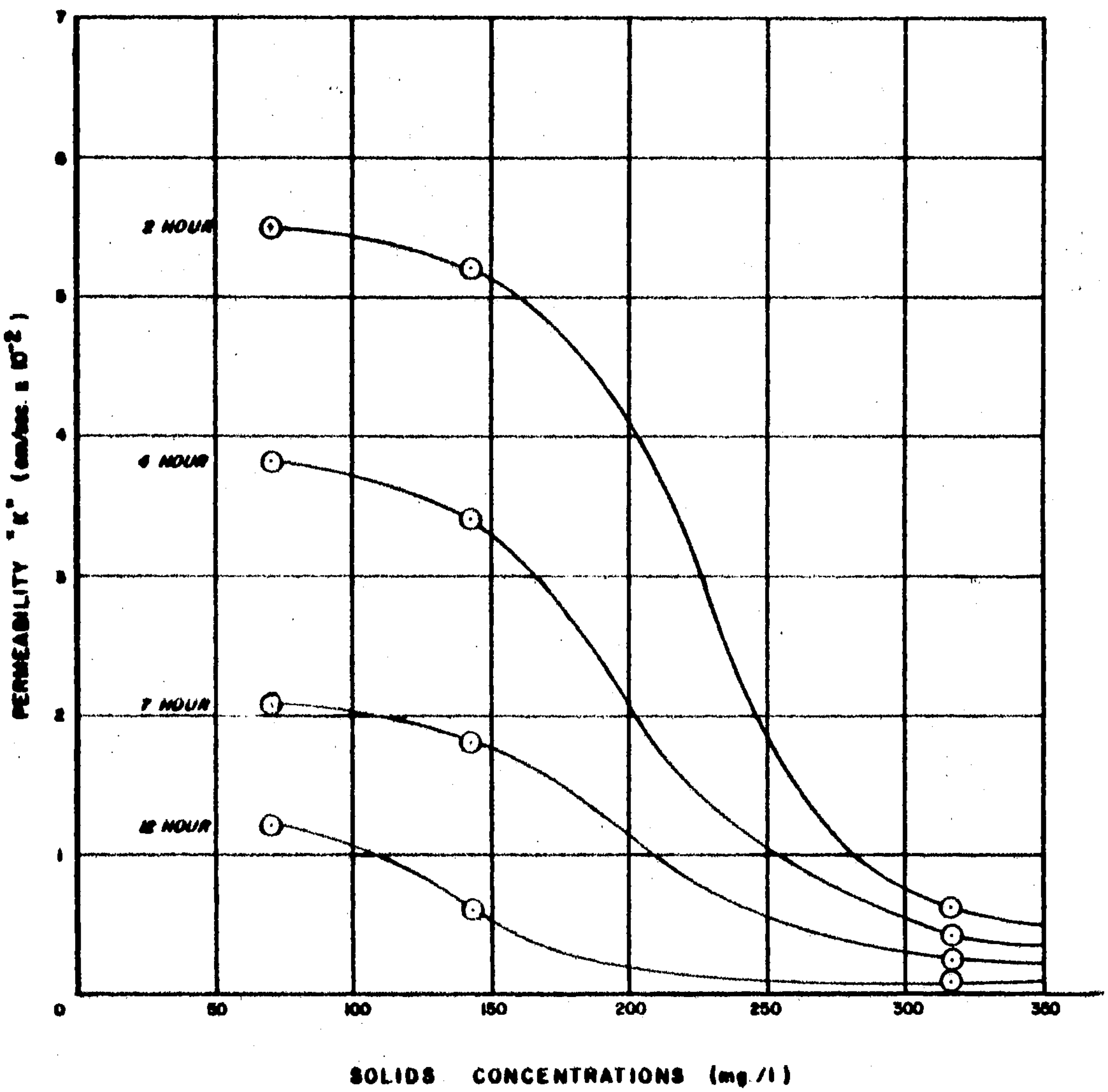

Figure 5. Permeability Versus Solids Concentrations for Selected Elapsed Times of 2, 4, 7, and 12 Hours.

CHAPTER V

DISCUSSION

The general objective of this study has been to investigate the effects of clogging which is due to the deposition of fine clay particles. More specifically the objectives were to obtain results that would be helpful in future studies involving particulate removal and recharging methods. This chapter contains an analysis and discussion of the results reported in the preceding chapter.

The flow-time curve (Figure 2) can be divided into three sections. The first portion is not as steep in slope as the second portion. This is because sufficient material has not been deposited on the surface to form a limiting layer. The second portion of the curve is characterized by a steep slope and therefore rapid clogging because the surface layer is continuous in the horizontal direction and finer particles are being strained from the infiltrating water by the newly deposited layer. The third part of the curve is characterized by a milder slope and little additional clogging because the impedance of the surface layer is nearly constant; the rate of flow through the column has reached such a low level that little material is being deposited to the surface of the existing layer and the thickness of the layer is essentially constant. Behnke (10) noted the same characteristic curve for the flow-time relationship and gave an explanation for each portion of the curve. The first part of the curve is controlled by the texture of the porous media and the concentration and grain size distribution of the suspended clay particles in the water. The second part of the curve is controlled by the continuous horizontal layer and the pore size distribution of this graded layer which affects the straining efficiency of the layer. The third section of the curve is controlled by the stability of the pores in the limiting layer and also to some extent on the additional thickness of the layer.

In Figure 3, as mentioned in the previous chapter, the higher concentrations of suspended solids exhibits a semilogarithmic plot unlike the lower concentration clay suspension. The steepness in slope is a direct correlation to the clogging rate. The 143 mg/l concentration run has only a slightly faster clogging rate than the 70 mg/l concentration run. The 316 mg/l run, on the contrary, is greatly different exhibiting two parts on the semilogarithmic plot. The explanation for this drastic drop in the infiltration rate in the first hour of operation for the 316 mg/l run can be explained by considering the gravitational settling in the head of water above the sand column. In a high concentration suspension, considerable settling by gravitational acceleration takes place. This gravitational settling produces a graded layer on the surface of the porous media. The pores in the graded depositional layer become progressively smaller, and the upward grading of the deposited layer produces, in effect, a filter.

The 316 mg/l suspended solid concentration by-passed the first part of the flow-time curve because a dispositional layer was formed rapidly and grading began sooner than in the case of the lower concentration suspensions.

It is noted that in Figure 3 the second portion of the 316 mg/l plot is approximately parallel to the 70 mg/l plot indicating that after the graded dispositional layer is formed the rate of clogging is relatively the same for varying concentrations of suspended solids even though the accumulated infiltration or accumulated flow is considerably less.

It was pointed out before that with the higher turbidity water, less suspended matter passed into the porous media, and it did not penetrate as deep. This is due to the dispositional graded layer formed on the surface of the porous media.

Imbertson (23) stated in recharge work involving suspended solids concentrations ranging from 50 to 100 parts per million that the dispositional layer could be removed from the spreading basin surface by scraping, but that 3 to 4 inches of the porous media was removed in the process.

Skodje (24) in an article on artificial recharge by the use of gravity shafts stated that clogging occurs in the upper few inches of the porous media and that periodic replacement of the upper level of sand would be feasible to restore shaft permeability (provided the permeability of sand in a shaft does not exceed the permeability of the aquifer so that sediment will be trapped in the shaft and will not enter the aquifer). The permeability of the shaft would be restricted to the permeability of the aquifer.

Sand models for the investigation of clogging by suspended solids in a pit recharge operation are planned at Oklahoma State University. These models are to be constructed using two cylindrical tanks, one of larger diameter than the other. The smaller diameter tank is to be filled with the aquifer material and placed inside the larger tank. Holes placed in the sides of the smaller tank will allow water in the area between the two tanks to flow into and out of the aquifer material. To simulate a pit recharge operation, a small pit would be dug in the center of the aquifer model and filled periodically with the recharge water. Time for infiltration of this water into the soil would then be noted. The recharge water is to be the effluent from the hydrocyclone previously discussed.

There will be difficulty in correlating sand model data to the data obtained from the soil column tests. This difficulty would be due to the nature of each apparatus and the flow patterns encountered. The soil columns would restrict flow to the vertical direction because of the boundary conditions imposed by the sides of the tubes. In the sand models, both vertical and horizontal flow would occur as noted in the discussion on the infiltration process.

There are no physical correlations that can be made between the sand model and the soil columns in terms of dimensional similitude.

The only comparison that can be made is that the soil column tests show that a high degree of treatment, in regard to solids removal, is necessary in order that a turbid water can be made suitable for a recharge operation.

The effect of suspended solids on the sustained infiltration rate in a recharge operation can be shown with the proposed sand model. Studies to determine the economic and physical feasibility of removing particulate matter from excess storm runoff, by such methods as hydrocyclonic removal, must now be undertaken.

Considering the results of this investigation and previous work done in this field, conclusions can now be drawn and suggestions for future studies made.

CHAPTER VI

CONCLUSIONS

From the results of this investigation, the following conclusions can be made:

(1) Clogging of a soil during infiltration by water containing suspended clay particles is basically a surface sealing process.

(2) After a horizontally continuous surface layer is formed, clogging progresses at approximately the same rate for varying concentrations of suspended matter. Although clogging and infiltration loss may progress at the same rate, the accumulated infiltration is, of course, much lower.

(3) Clay particles were observed to penetrate deep into the sand column, but it can be concluded that this deep penetration has no effect on the overall infiltration rate.

(4) Low concentrations of suspended matter will eventually reduce the infiltration rate, but the rate will never completely reach zero. Total removal of particulate matter would need to be approximated in order to solve the problem of clogging by suspended solids.

SUGGESTIONS FOR FUTURE STUDY

Based on this investigation, the following suggestions are made for future study involving artificial recharge of excess surface runoff:

(1) Study the degree of treatment necessary to make recharge of a turbid water economically feasible.

(2) Investigate the use of coagulating aids and dosages for optimum chemical precipitation of particulate matter.

(3) Study design criteria for replaceable sand and gravel filters to be used in conjunction with an infiltration basin.

(4) Investigate the effects of dissolved solids, contained in recharge water, on aquifer characteristics.

(5) Further investigate clogging by suspended matter using sand models to simulate field conditions and aquifer characteristics.

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