Investigation of factors controlling streambed hydraulic conductivity

by Carl Jon Anderson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
Hydrologists are interested in the relationships between flow in a stream channel and in an adjacent ground-water system when a hydraulic connection exists. Better understanding of this relationship is important in the development of improved design models which describe groundwater-surface water systems such as artificial recharge and irrigation systems. This study addresses this need for more knowledge by undertaking a laboratory flume, investigation to determine how fluid velocity, suspended sediment concentration, and sediment grain size distribution influence channel bottom hydraulic conductivity.

Two mechanisms for infiltration rate reduction, deposition and armoring, were observed for the velocities tested. At velocities below 0.6 ft/s, clogging was caused by a layer (1/8 to 1/2 inch thick) of deposited sediment while at velocities above 1.2 ft/s, clogging was caused by a thin layer of sediment with partially exposed sand grains, termed armoring. Some combination of these two mechanisms was occurring in the intermediate velocity range. The suspended sediment concentration was observed to have little effect on the clogging process while changes in the particle size distribution of the sediment caused changes in the magnitude of clogging. The finer grained, better graded material produced larger reductions in infiltration rates than the coarser, more uniform materials. Additional investigations using different sediment materials, other bed materials, and extended time periods are recommended. Studies, of the biological mechanism of clogging are also recommended to further the knowledge of clogging with the horizontal velocity component.

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Carl Jon Anderson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

May 24 1984
Date

Alfred B Cunningham
Chairperson, Graduate Committee

Approved for the Major Department

May 24, 1984
Date

Fred F Videon
Head, Major Department

Approved for the College of Graduate Studies

June 1, 1984
Date

Henry L Parsons
Graduate Dean

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ABSTRACT

Hydrologists are interested in the relationships between flow in a stream channel and in an adjacent groundwater system when a hydraulic connection exists. Better understanding of this relationship is important in the development of improved design models which describe groundwater-surface water systems such as artificial recharge and irrigation systems. This study addresses this need for more knowledge by undertaking a laboratory flume investigation to determine how fluid velocity, suspended sediment concentration, and sediment grain size distribution influence channel bottom hydraulic conductivity.

Two mechanisms for infiltration rate reduction, deposition and armoring, were observed for the velocities tested. At velocities below 0.6 ft/s, clogging was caused by a layer (1/8 to 1/2 inch thick) of deposited sediment while at velocities above 1.2 ft/s, clogging was caused by a thin layer of sediment with partially exposed sand grains, termed armoring. Some combination of these two mechanisms was occurring in the intermediate velocity range. The suspended sediment concentration was observed to have little effect on the clogging process while changes in the particle size distribution of the sediment caused changes in the magnitude of clogging. The finer grained, better graded material produced larger reductions in infiltration rates than the coarser, more uniform materials. Additional investigations using different sediment materials, other bed materials, and extended time periods are recommended. Studies of the biological mechanism of clogging are also recommended to further the knowledge of clogging with the horizontal velocity component.

INTRODUCTION

For many years, hydrologists have been interested in examining the relationship between flow in a stream channel and flow in an adjacent groundwater system when hydraulic connection exists between the two. The theoretical nature of this relationship is of interest primarily from the standpoint of developing improved models which describe the behavior of coupled groundwater-surface water systems. From an applied outlook, understanding the nature of the exchange process is of fundamental importance to the design and operation of irrigation and artificial recharge systems. At present, the lack of understanding of the physical factors which affect the magnitude of the hydraulic conductivity of channel bottom sediments poses a severe limitation to progress in this subject area. This study addresses this need by undertaking a laboratory flume investigation which will determine how variables such as fluid velocity and suspended sediment concentration influence channel bottom hydraulic conductivity.

In river channels and canals the exchange between surface and groundwater is frequently controlled by the infiltration rate occurring through the top-most layer of channel bottom sediments. If this epidermal layer becomes clogged due to settling out of fine suspended material, a substantial reduction in the infiltration rate (and thus the recharge potential) will result. Clogging can occur in open channels as well as in groundwater recharge systems and spreading basins. In many cases, the most plentiful supplies of surface water available to groundwater recharge systems are associated with high intensity storms and contain significant amounts of suspended sediment. Applied directly to the soil surface, these waters quickly clog the surface and vastly reduce the infiltration rate of the water, resulting in insignificant contributions to the ground water reservoir. An understanding of the processes which govern the formation and hydraulic behavior of clogging deposits is essential for the proper management of natural recharge systems as well as proper design of artificial recharge facilities.

Berend (1) proposed that suspended matter, biological activity, and soil structure deterioration are all factors which can significantly contribute to the clogging and the reduction in the infiltration rate through channel bottom sediments. The deposition of suspended matter on the soil surface constitutes the clogging process due to inert suspended matter. Clogging caused by biological activity is characterized by growth of microscopic organisms between the grains of the soil surface. Chemical and physical changes on the soil surface can also cause clogging to occur. Although these factors can all be involved in the clogging of channel bottoms, clogging due to inert deposits of sediment was the factor isolated and investigated in this study.

There is no doubt that channel bottom deposits can cause reduction in hydraulic conductivity. Behnke (2) observed clogging of coarse textured soils in recharge basins at sediment concentrations as low as 50 mg/l. Rice (3) reported serious soil clogging with infiltration of secondary sewage effluent if it contained more than 10 mg/l suspended organic solids. McNeil and Ahnell (4), in an investigation of salmon spawning beds, reported a reduction in streambed infiltration due to accumulation of suspended solids in gravel pores. In laboratory experiments carried out at Montana State University, head losses of up to 1 meter were reported due to clogging in a vertical infiltration column containing 0.1 mm glass spheres.

The study of clogging in vertical static columns has led to a few important results which are also applicable to the case of clogging with a horizontal flow velocity herein considered. In a study of clogging in a vertical static column, Hall (6) proposed two mechanisms for sediment removal in sand filters: gravitational settling and interstitial straining. The gravitation settling mechanism depends on the deposition of the suspended sediment particles on the surface in the porous medium. Interstitial straining is dependent upon suspended particles being strained from the flowing water at points of contact in the solid matrix of the porous medium. The initial clogging mechanism for a non-uniform sized suspended material is gravitational settling. The larger particles settle at a faster rate and are deposited on the surface of the porous medium first. Then, successively smaller particles settle out reducing the pore size on the surface. The finer particles are then strained through the interstices of these graded layers of material and constitute the interstitial straining mechanism of clogging. Although Hall was referring to sand filters, these mechanisms are applicable to any porous medium in which clogging is occurring.

In another study of clogging in a static column, Benke (2) proposed that three of the more important variables in the clogging process are the size distribution of the particles in the water relative to the pore size distribution of the porous medium, the vertical approach velocity of the incoming water relative to the gravitational acceleration (settling velocities) of the coarser particles in suspension, and the concentration (ppm) of the material in suspension. Since the experiment designed for this study involved a horizontal flow velocity, the vertical approach velocity of the incoming water relative to the gravitational acceleration of the coarser particles in suspension will not be a variable needing consideration. Therefore, variations in the clogging process will be a result of the size distribution of the particles in suspension, the horizontal approach velocity of the incoming water, and the concentration (ppm) of the material in suspension.

To date, infiltration reduction caused by suspended sediment deposits (the major independent variable being suspended concentration of inflow water) has been studied and quantified only for the case of vertical seepage through infiltration basins (1, 2). The similar sediment process occurring in flow systems with a horizontal velocity component parallel to the channel bed has not been investigated experimentally. In a study done with a horizontal flow velocity, Bouwer (5) found that a horizontal flow velocity with no suspended sediment present did not affect seepage in a flume with sand and gravel as a bottom material. Therefore, this project will address the gap in the present knowledge by experimentally analyzing how horizontal velocity as well as suspended sediment concentration affect channel bottom hydraulic conductivity.

Statement of Objectives

This study was intended to experimentally investigate the effects of variations in horizontal flow velocity, suspended sediment concentration, and suspended sediment grain size distribution on the hydraulic conductivity of channel bottom sediments. Accordingly, the objectives of this study are:

1. To determine parameters which control the clogging of a porous medium.
2. To determine the effects of horizontal velocity on the clogging process.
3. To explain the mechanisms of clogging with a horizontal velocity component.
4. To suggest topics of study for further research in this area.

EXPERIMENTAL DESIGN

The laboratory investigation involved the use of a 25 foot recirculating flume which was modified for this experiment by installation of a drop chamber and return flow pipe (see Figure 1). When filled with sand, the drop chamber allowed the vertical infiltration process through the channel bottom to be monitored. The variable position vertical riser located in the return flow system controlled the hydraulic gradient available to move water through the sand bed. The hydraulic head was measured at three vertical positions in the sand layer and one location below the sand layer using piezometer tubes. Measurement of volumetric flow rate leaving the drop chamber along with hydraulic head allowed the computation of hydraulic conductivity for the top-most layer of channel bottom sediments. By varying channel velocity, suspended sediment concentration, and the grain size distribution of the suspended sediment the corresponding effect on sediment hydraulic conductivity was assessed.

At the beginning of each experimental run, the flume was filled with clean tap water and the water was recirculated through the flume. The desired channel velocity

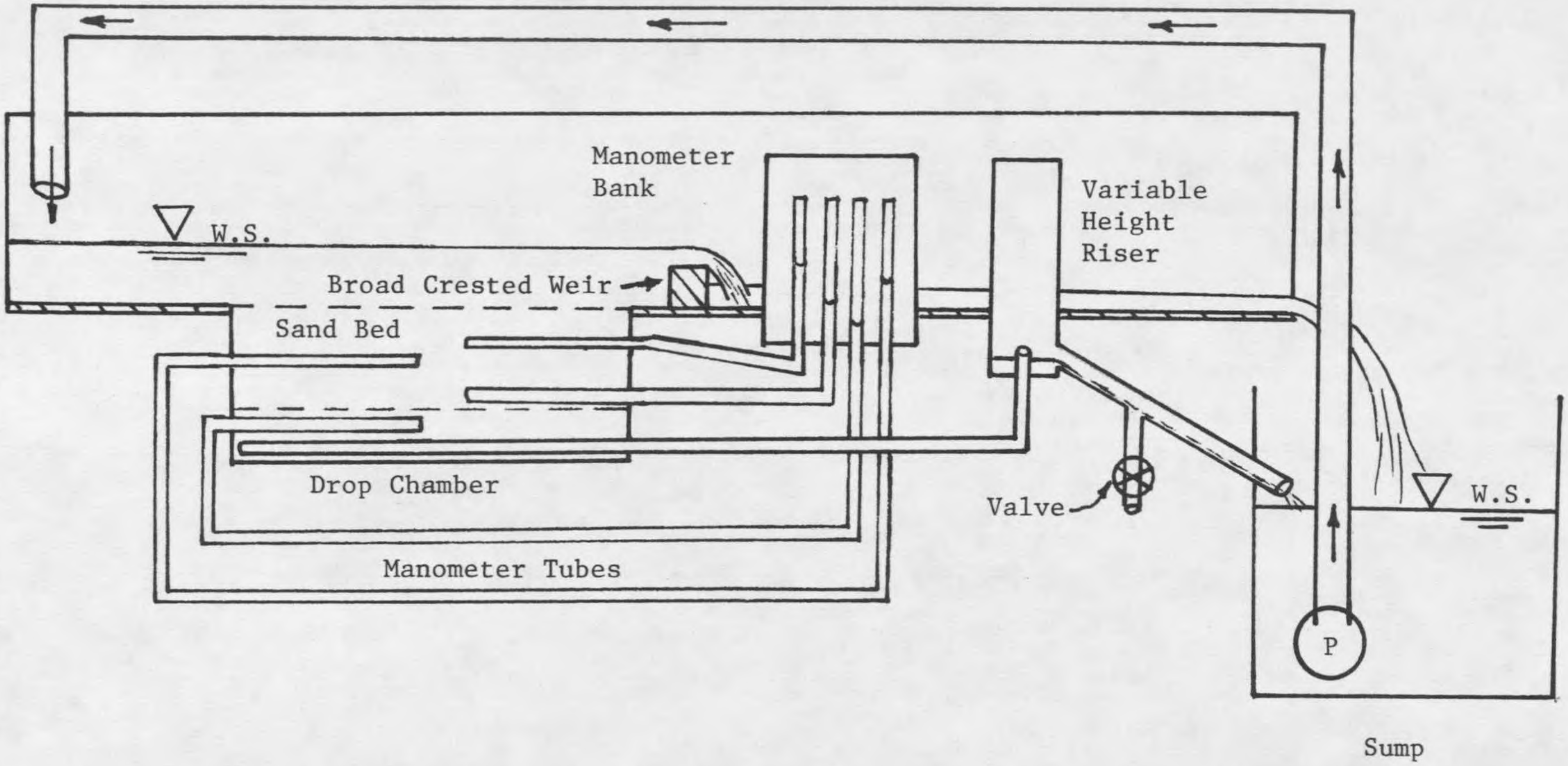

Figure 1. Diagram of the experimental apparatus.

was established by varying either the flow rate, the channel slope, or the height of the portable broad crested weir located immediately downstream from the sand bed (Figure 1). The average channel velocity was determined from the depth of flow, the channel width, and a gravimetric measurement of the flow through the channel. At this time the hydraulic conductivity of the sand bed was established at approximately the same value for each experimental trial. This was accomplished by repacking the sand bed, if necessary, until the desired conductivity was achieved. Fine sediment was next added to the circulating water so as to produce the desired suspended sediment concentration.

Once the experiment was under way, measurements were taken at specified time intervals in order to monitor the change in hydraulic conductivity of the sand bed. Infiltration rates and piezometer tube readings were taken at these time intervals. In addition, the suspended sediment concentration was monitored to insure consistency. If the concentration had significantly dropped, more sediment was added to maintain the initial concentration. Each experimental trial was monitored for at least 24 hours since it was found that the infiltration rate did not vary significantly after that time interval.

Experimental trials were performed using three different sediment types including materials obtained directly from river channel deposits. Basic experimental relationships between horizontal flow velocity and suspended sediment concentration and the reduction in the infiltration rate of the porous medium were developed using a red silt loam. These trials were performed over a wide range of horizontal velocities and four suspended sediment concentrations. Once these relationships were developed, two sediment materials from the Salt River flood plain were tested to determine whether the grain size distribution affected the clogging mechanism.

Apparatus

A schematic drawing of the laboratory experimental apparatus is shown in Figure 1. The 25 foot recirculating flume had a capacity of 0.12 cfs and circulated the sediment laden water over the surface of the sand bed. A mixer located in the downstream sump insured that the sediment remained in suspension, and a submersible pump delivered the water from the sump to the upstream end of the flume. Sediment laden water entering the upstream end of the flume first passed through a series of turbulence dissipating screens, then flowed over the sand bed to the sump at the downstream end of the flume. Water infiltrating through the sand bed was collected in a perforated pipe in the bottom of the drop chamber and discharged through a tube at the downstream end. This tube carried the infiltrated water into a variable height riser which was open to the atmosphere. The riser could be raised or lowered to insure a constant head difference across the sand bed at different channel depths. The vertical discharge of water inside the riser created a free-surface reservoir for which the surface elevation could be easily controlled. A clear plastic pipe was used to return water from the riser to the downstream sump. A valve and tee in this return pipe allowed the flow of infiltrated water to be diverted and gravimetrically measured.

A more detailed look at the drop chamber (Figure 2) shows that approximately 5-1/2 inches of sand were placed on top of a fine screen. This screen was included to prevent the migration of the sand particles out of the sand bed. Below the screen was a supporting structure of rocks with a perforated pipe running close to the bottom of the box to collect the water which infiltrated through the sand bed. Also shown in Figure 2 are the bed dimensions along with the four manometer tube locations. These manometer tubes were installed to measure the piezometric head at different levels in the drop chamber.

To simulate conditions in a natural streambed, sand, with a uniform size distribution, was used as the porous medium. The sand used was from a local sand and gravel distributor and sieved through a #16 screen to remove

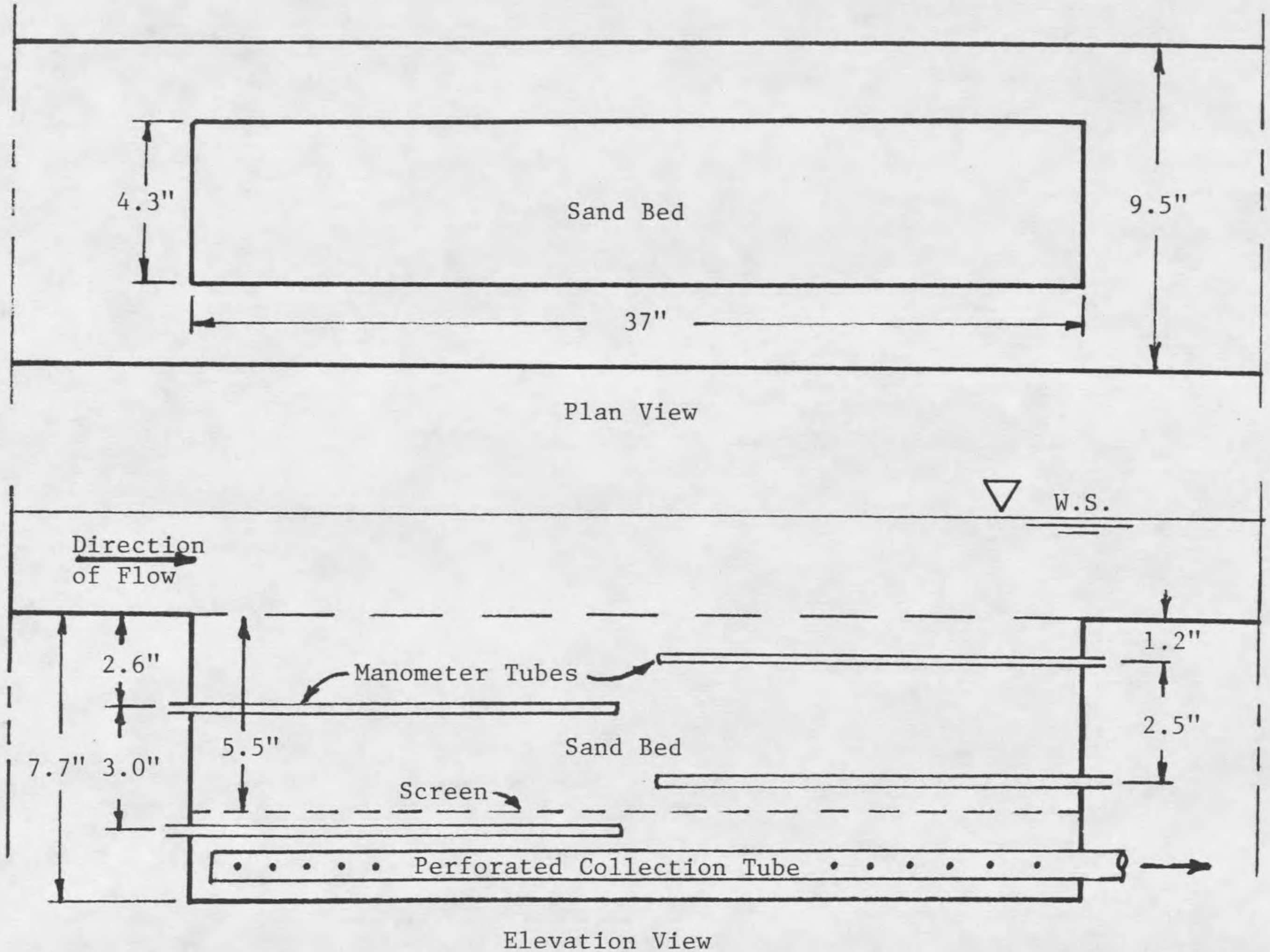

Figure 2. Details of the drop chamber.

larger diameter material. A grain size distribution for the sand used in the experiment is shown in Figure 3. The sand was placed in the drop chamber while moist to prevent segregation of different particle sizes and to insure cohesion during the packing process.

Initial Hydraulic Conductivity

To begin each experimental trial, the sump was filled with 80 gallons of tap water and this water was circulated through the system for 4 to 6 hours. This procedure allowed the water to warm to the ambient room temperature and the infiltration rate through the sand to stabilize. The clear water infiltration rate was measured at intervals over an extended period of time. The results of these measurements are shown in Figure 4 as a curve of infiltration rate versus time. This curve shows that the infiltration rate asympotically approached a value of approximately 14.6 inches per hour (in/hr). To minimize the time between experimental runs, initial infiltration rates between 7.3 in/hr and 10.9 in/hr were achieved before the experiment proceeded. The quasi-steady infiltration rate was not achieved for every trial but each trial was started with an infiltration rate within the stated range to provide for consistency between trials.

The infiltration rate versus time curve is seen to increase with time. This increase suggests that biological

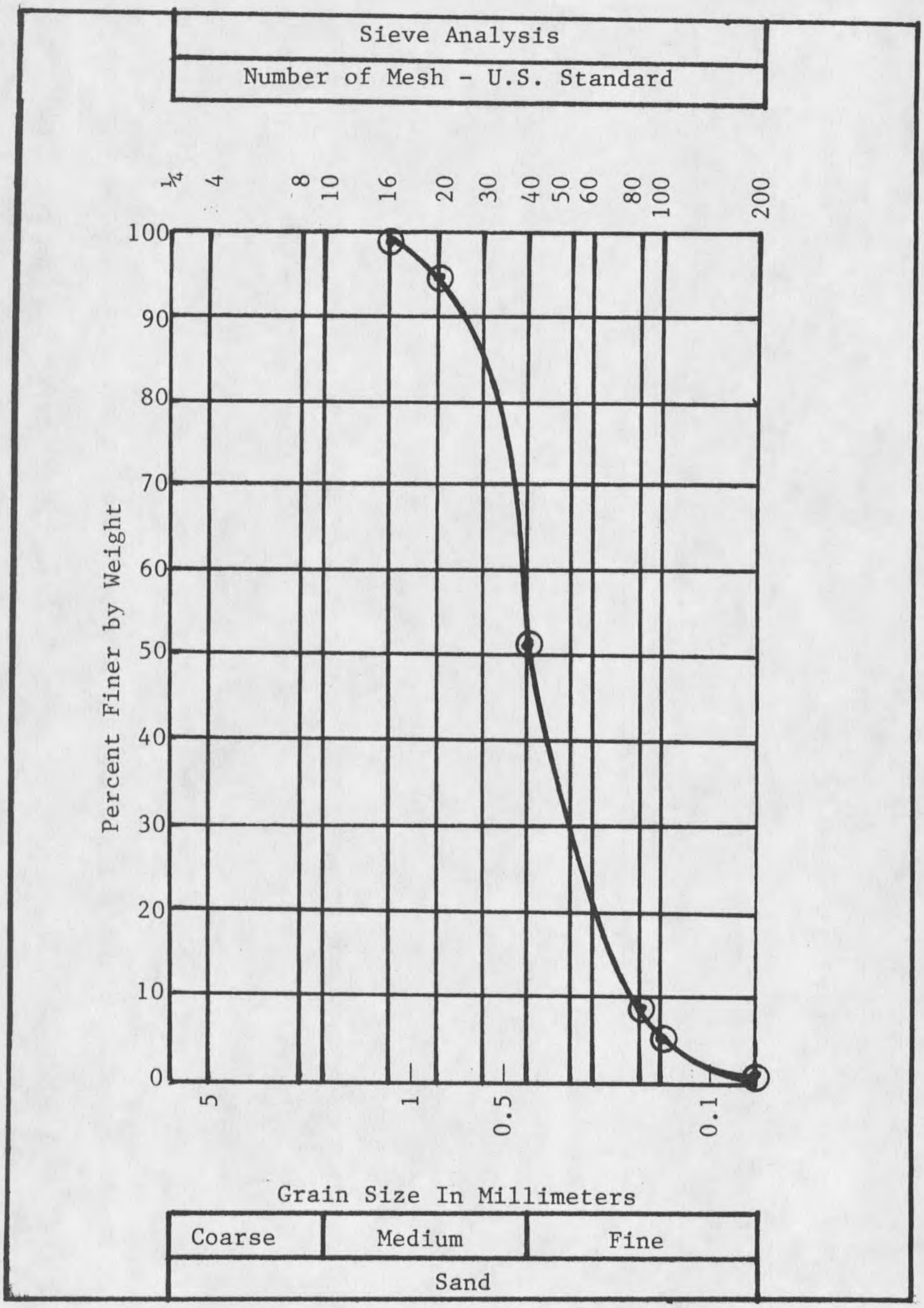

Figure 3. Gradation curve for the bed sand.

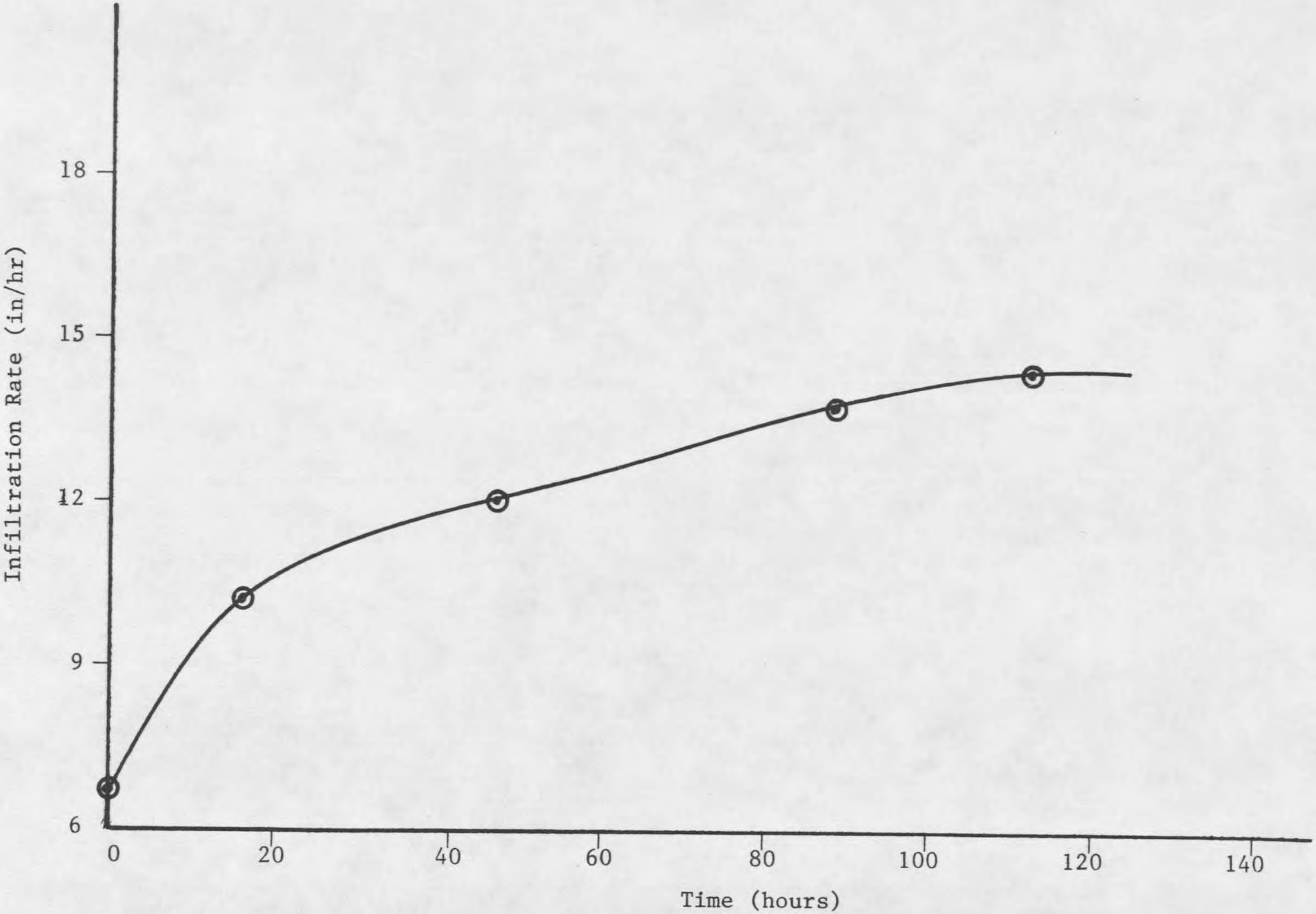

Figure 4. Extended time plot of the infiltration rate for the case with no suspended sediment present.

activity and soil structure deterioration were insignificant in relation to this infiltration rate increase with time. If biological activity or soil structure deterioration were taking place, the infiltration rate would be expected to decrease with time.

Sediment Types

Three sediment materials were used to investigate whether the sediment particle size distribution affected the clogging process. The sediment materials included a red silt loam taken from the Bozeman area and two silt deposits taken from the Salt River flood plain near Phoenix, Arizona. Since two materials were both classified as silty soils according to the U.S. Department of Agriculture Soil Conservation Service soil classification triangle, the soils were labeled silt A and silt B for this study. The hydrometer analysis (particle size distribution) shown in Figure 5 indicated that each material had a significantly different size distribution. The red silt loam had the largest percentage of fine particles and the best gradation while silt A and silt B had successively smaller percentages of fine particles and more uniform grain size distributions.

In addition to differences in grain size, the degree of gradation was different for the three sediment materials. The red silt loam had the flattest grain size dis-