THE EFFECT OF SILT-LADEN WATER ON INFILTRATION IN ALLUVIAL CHANNELS

by

William Gerald Matlock

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF CIVIL ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

1965

THE UNIVERSITY OF ARIZONA

GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction by William Gerald Matlock

entitled The Effect of Silt-Laden Water on Infiltration in Alluvial Channels

be accepted as fulfilling the dissertation requirement of the degree of Doctor of Philosophy

E. M. Laurson
Dissertation Director

June 19, 1965
Date

After inspection of the dissertation, the following members of the Final Examination Committee concur in its approval and recommend its acceptance:*

Harold C. Schwalen	6-14-65
Don A. Linger	6-14-65
Quentin Mees	6-14-65
John Harshbarger	6-14-65

*This approval and acceptance is contingent on the candidate's adequate performance and defense of this dissertation at the final oral examination. The inclusion of this sheet bound into the library copy of the dissertation is evidence of satisfactory performance at the final examination.

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: William Gerald Mattock

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Professor Emmett M. Laursen who served as dissertation director and to the other members of his graduate study committee for their advice and guidance during the preparation of this dissertation.

The research was conducted as part of a continuing project in water resources research by the Agricultural Engineering Department financed in part by the City of Tucson and Pima County. The project is under the direction of Professor Harold C. Schwalen whose support was much appreciated.

Thanks are also extended to Dr. Charles D. Busch for his help with the manuscript and to Bill Kern and Drew Fiedler for their assistance in constructing the equipment.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont.)

LIST OF TABLES

ABSTRACT

A tilting bed flume study was made to examine the relationships between velocity, suspended sediment and infiltration rate in alluvial channels for velocities from 2 to 5 feet per second and suspended sediment up to 0.6 percent. Preliminary experiments using samples from Rillito Creek near Tucson, Arizona to define limits for the flume study included mechanical analyses of bed sediments, permeability and infiltration tests, and analyses of suspended sediment in flood waters. Flume experiments using bed materials from Rillito Creek were made with constant velocity and variable suspended sediment content, then with constant suspended sediment and variable velocity. Considerable variability was found in the mechanical analyses, permeability and infiltration tests, and suspended sediment content for samples from different locations. The flume studies indicated a direct relationship between velocity and infiltration rate and an inverse relationship between the suspended sediment content and infiltration rate in the ranges tested. Very poor correlation was found between the preliminary permeability and infiltration tests and the flume infiltration rates, but good correlation was obtained for the flume results with the flow losses and natural recharge occurring in the river channels in the Tucson area.

INTRODUCTION

In the arid or semi-arid region of southwestern United States many communities depend on a groundwater reservoir for their entire water supply. All of the more intensely developed groundwater basins are being depleted, i.e., water is being withdrawn at a rate higher than it is being replenished by natural recharge, and water levels are falling each year. Two of the contributing factors in the depletion are the rapidly expanding population of the region and the increased per capita use of water.

In attempting to solve the problems of a diminishing water supply detailed information must be obtained about the hydrology of the groundwater system. The hydraulic characteristics of the aquifers must be known, and a hydrologic budget established for the system. The most difficult factor to evaluate in this budget is the natural recharge to the groundwater aquifer.

Statement of the Problem

The most effective source of recharge in many areas is the intermittant flow which occurs in the stream channels formed in alluvial deposits at the base of the mountains and extending out into the valleys. The clear flow which results from mountain snowmelt in the spring infiltrates rapidly and completely, but the silty flow following intense thunderstorms or more prolonged rainfall penetrates more slowly. As the discharge decreases the silt contained in the flood waters settles out and may ultimately seal the streambed. A later flood event must be of sufficient magnitude to remove this deposit before infiltration can occur.

A well defined relationship between silt content, velocity, and infiltration should permit better prediction of recharge from silty flood flows and lead to methods of optimizing the recharge through control of the water or by channel modification. The results would also be applicable to certain artificial recharge projects.

Purpose of the Investigation

The purpose of the investigation was to determine the relationships between the silt content of the water, velocity of flow, and the infiltration rate of the sand bed in an alluvial channel. Because of the difficulty in conducting experiments in a natural channel and the necessity of waiting for a flood event to occur, a tilting-bed laboratory flume study was proposed. This would make possible a range of changing flow and sediment conditions. Preliminary studies of flood waters, infiltration rates, and the particle size distribution and permeability of river bed sediments were made to establish limits for operating the flume.

Previous Studies

The City of Tucson in Southern Arizona obtains its water supply from a groundwater reservoir. A continuous program of groundwater research has been conducted in the area by the Agricultural Engineering Department of the University of Arizona. Included in the study have been attempts to establish a hydrologic budget with a quantitative evaluation of natural recharge. Studies of recharge in Rillito Creek, north of Tucson, have indicated complete infiltration from any clear flow which occurred in the spring. Meager information is available about the effectiveness of silty flow in recharging the groundwater aquifer although such flow is known to contribute a significant amount of recharge.

Literature Review

General

Very few reports have been previously published on research directly related to the effect of silt-laden water on infiltration in alluvial channels. The problem is not one in sediment transportation or infiltration alone, but includes a little of both areas. These subjects have been extensively reported, abstracted and reviewed in the literature and will not be discussed further here except as they specifically apply to the problem.

The most closely related investigations have been those concerned with artificial recharge. The ditch or furrow method of recharge has many similarities to this investigation, but only a limited amount of quantitative results is available. Natural recharge and transmission or channel loss from rivers are also similar, but projects involved with these phenomena did not include more than a cursory examination of the effects of silt-laden water.

Channel or Transmission Losses

Observations by the Bureau of Reclamation (18)* on the Tule and White Rivers in California showed losses during storm flood flows of 1 acre-foot per mile of channel. Losses on the Kaweah River during high water were 9 acre-feet per mile of channel.

Percolation rates in the San Gabriel River bed measured by the California State Division of Water Resources were reported by Conkling (7) to vary from 1.8 feet per day near the mountains to 9.68 feet per day six miles downstream. The rate gradually decreased to 2 feet per day in the next two miles. The differences appeared to be caused by a calcareous deposit near the

*Numbers in parentheses refer to LIST OF REFERENCES.

mountains which was not found farther downstream because of continual moving of the lighter sands and grading of the bed sediments.

Cornish (8) of the U. S. Weather Bureau studied the significant transmission losses occurring with a rise in the water level in the Canadian River. He was particularly concerned with the accompanying problems in flood routing and the undetermined effect of the deep, sandy river beds and channels on the flow characteristics and stage-discharge relationships. A statistical analysis of 18 flood events showed a mean volume loss of 42 percent in a 173-mile reach near Oklahoma City.

Transmission losses in ephemeral streams in Southern Arizona with coarse textured (54 percent gravel) bed materials were investigated by Keppel and Renard (25) for the Agricultural Research Service. They found an average infiltration rate of 4 to 6 feet per day and losses of 25 acre-feet per mile of channel in a five mile reach.

Preliminary observations by Lee (30) working with the Los Angeles Aqueduct Bureau in 1908 showed that up to 50 percent of flood flows disappeared between gaging stations with part of the loss accounted for by percolation into the porous alluvial material. He further studied three factors: the rate of percolation, area of streambed, and velocity of flow; and stated that the character of the surrounding medium was the only channel condition which noticeably affected percolation.

Peterson (37) reported infiltration rates of 0.37 feet per day were found by the U. S. Geological Survey in the predominately fine sediments of low permeability in San Simon Creek, Arizona.

Sharp and Saxton (45) of the Agricultural Research service selected 57 flood events on 18 perennial rivers in the Great Plains (United States) for an analysis of losses between gaging stations. An average loss of 40 percent occurred in an average channel length of 53 miles with as much as 200 acre-feet per mile or 75 percent of the flood volume being lost.

Turner and others (50) with the U. S. Geological Survey stated that infiltration losses from runoff reaching wash channels are a major source of recharge in Southern Arizona. In fairly coarse stream bed materials flow losses of 75 percent in 15 to 25 miles were common. Seepage measurements indicated infiltration rates of 1.0 to 3.77 feet per day with the lower reaches and consequent finer sediments exhibiting the slower rates. They also felt that the depth to the water table below the stream bed had a very important effect on infiltration rates. Pool tests conducted in the low flow channel where silt had been deposited showed infiltration rates inversely proportional to the silt thickness and in the range of 0.31 to 1.2 feet per day.

Infiltration rates of 0.14 to 2.09 feet per day from flashy flood flows with an average of 1.08 feet per day were reported by Babcock and Cushing (1) of the U. S. Geological Survey in Queen Creek, a typical large desert wash in Southern Arizona. Clear water rates of about 4 feet per day were found. The smaller rates in floods were attributed to the sediment load. Over a two year period 50 percent of the flow was recharged. A summary of channel or transmission loss data is presented in Table I.

TABLE I

SUMMARY OF CHANNEL OR TRANSMISSION LOSS DATA

Investigator	Infiltration Rate (feet per day)	Loss (acre-feet per mile)	Average Loss (percent of flow)
Bureau of Reclamation		1-9	
Conkling	1.8-9.68		
Cornish			42
Keppel and Renard	4-6	25	
Lee			50
Peterson	0.37		
Sharp and Saxton		200	40
Turner and others	1.0-3.77		75
Babcock and Cushing	0.14-2.09		50

Effect of Velocity

Bouwer, Myers, and Rice (6) conducted flume experiments to determine the effect of velocity on canal seepage. With velocities from 0 to 7 feet per second in a flume with resin stabilized sand or gravel as bottom material the velocity had no direct effect. They pointed out, however, that velocity can indirectly influence seepage through its effect on erosion, sedimentation and wetted perimeter.

A recharge system in the Santa Ana River discussed by Crooke and Toups (9) used the natural 15 to 20 feet per mile gradient to keep the velocities at such magnitudes that silt deposits from the natural flows were picked up and redeposited at the lower end of the recharge area.

Eaton (12) stated that by keeping water containing sediment moving and scarifying and washing certain areas, the top gravel layers in a recharge project receive a scrubbing action and high percolation rates can be maintained. The necessary velocities are between 2 and 4 feet per second and must be supplemented by flushing before and after a run.

With slightly silty water Laverty (29) observed that pond velocities as low as 0.05 feet per second were beneficial in maintaining percolation rates.

Lee (30) pointed out that an increase in area of streambed covered by a flood event is usually accompanied by an increase in velocity with consequently less time for percolation from a given volume of water. The net result is a proportionally smaller percolation per unit of discharge although this may be counteracted by scouring of the non-porous lining because of the increased carrying power of the stream.

Schiff (41) and Schiff and others (43) in a study of filter materials prepared from aquifer sands by removing particles smaller than 0.5 mm. reported that filtration rates were up to twice as great for river water flowing over a filter as when ponded on the filter. Filtering through only a few tenths of a foot reduced the suspended load from 20 to 1 ppm. The surface of the filters appeared clean for velocities of 0.5 feet per second, but some of the fine particles were carried beneath the surface.

Sonderegger (46) indicated that the absorption of silty water requires water in motion. He related the known absorption of silt-laden water flowing over debris cones and in river channels to "critical" or scouring velocities. He also stated that the problem resolves into the regulation of the flow of muddy waters to the lowest non-silting or "critical" velocities to provide a feasible but possibly low rate of seepage.

Tibbetts (48) found that in spreading operations water velocities during floods were high enough to scour the gravel beds in river channels clean again if the water was not impounded more than 2 or 3 feet deep above the dams.

Various researchers (27, 29, 32, 33, 34, 35) discussed the use of the ditch or furrow method of artificial recharge for successfully handling waters with a high silt content. The ditches are laid out on a slope such that the flow velocities will maintain in suspension or as rolling bed load the silt and fine material known to retard percolation. At the same time the slope must be less than that at which excessive scour will occur.

Other investigators (1, 26, 50, 56) noted the importance of velocity in maintaining or improving infiltration rates in natural channels by breaking up or removing any accumulated slime or silt which tends to clog the bed. Table II summarizes the published information on the effects of velocity.

Properties of the Bed Sediments

In an investigation of the hydraulic conductivity of sands with size ranges found in alluvial fans Behnke and Schiff (5) reported that the velocity and hydraulic conductivity increased linearly with grain size for the range from 0.1 to 1.0 mm. in uniform sands. The position and thickness of layers of low hydraulic conductivity

TABLE II

SUMMARY OF VELOCITY EFFECT DATA

Investigator	Velocity Range (feet per second)	Water Quality	Effect
Bouwer, Myers, Rice	0-7	clear	none
Crooke and Toups	no data	silty	velocities such that silt deposits were picked up
Eaton	2-4	silty	maintain infiltration rates
Laverty	more than 0.05	slightly silty	increased percolation
Lee	no data	silty	increased velocity scours non-porous channel lining
Schiff	0.5	20 ppm. river water	filtration rates twice as great as ponded water
Sonderegger	"critical"	muddy	maintain low but feasible rate of seepage
Tibbetts	no data	flood	velocities high enough to scour gravel beds clean

significantly influence the velocity, hydraulic gradient, and overall hydraulic conductivity. They indicated that particle rearrangement of the soil-water interface generally acts to reduce conductivity but can be stabilized by a layer of coarse sand. In an earlier model study (4) they pointed out that the fine sand content determines hydraulic conductivity in both stratified and mixed sands.

Ghosh (14) studied filter materials in the laboratory and concluded that head loss was not proportional to depth of bed. He said that with turbid water head loss varies more markedly with depth and with time owing to deposition of turbid matter in the bed. He found the permeability to be independent of flow velocity with clean water, but velocity was a factor with turbid water. For filters with sands of 0.46 mm. mean diameter turbidity was found in water samples taken from the first 3 inches of the bed while for coarse grains (0.77 mm. mean diameter) turbidity was found throughout the bed.

Grover and others (15) reported that a thin sediment layer on the gravel surface of spreading ponds effectively reduced the intake rate until the advantage of deeper water was lost. Kazmann (22, 23, 24) indicated that infiltration may be prevented by deposits of silt in rivers and lakes or by lenses of clay or cemented material existing immediately below the stream or lake bed. He also stated that no continuous deposit was ever formed on the surface of an induced infiltration area in the Ohio River. Muckel (34) observed that water stood for two weeks in a previously porous area with 3 to 4 inches of silt deposited. Debris cones were noted as having high infiltration rates.

Duley (11) noticed that the rapid reduction in intake rate of bare soils as rain fell on the surface was accompanied by the formation of a thin compact layer at the surface of the soil. This structural disturbance was caused partly by the beating action of the raindrops and partly by the sorting action of water flowing over the surface. Fine particles were fitted around the larger ones to form a relatively non-pervious seal. Preliminary work indicated the compact layer was not only of greater weight per unit volume than the underlying material but in many cases also contained a higher percentage of coarse material and less organic matter because some of the finer material and lighter organic matter went into suspension. The sealing was therefore not caused by an increase in fines but, rather, by the compact structure formed by fitting finer particles around larger ones.

Sonderegger (46) emphasized that permeability is a combination of elements: the mechanical, chemical, and mineral composition of the bed material and the percent and composition (mechanical, chemical, mineral) of the bed load, silt, and colloids. Sharp and Saxton (45) mentioned the gross and non-capillary pore space of the bed sediments as factors influencing the rate of transmission loss. In a gravelly, sand channel loss rates of tens of feet per day occurred; in finer soils they were only a few feet per day and in clay and heavy clay as low as fractions of an inch per day. They estimated the total available storage capacity of dry valley soils to be approximately 3 inches per foot of depth.

Jopling (20) studied sediment sorting processes in a laboratory flume. He found that the structure of stratification responded to hydrodynamic and rheological sorting processes even under uniform sediment transport conditions. The structure was affected not only by fluctuations of velocity but also by "dispersive pressure" and the selective transportation and deposition due to differential settling velocities. Bed layers tended to be repetitive. He suggested that the variability in bedding characteristics in natural deposits is higher than that occurring in the laboratory.

Treatment to Alleviate Clogging

Many investigators have suggested methods to alleviate or overcome clogging of porous bed materials by sediment laden water. Most of this work has been in connection with artificial recharge projects. Periodic cleaning and removal of silt deposits is recommended for recharge basins and induced infiltration beds. (2, 17, 27, 30, 32, 33) In stream bed areas cultivation or "scarifying" a few inches is sufficient to increase percolation rates markedly until more silt is deposited. (12, 17, 29, 32)

Mitchelson and Muckel (32) stated that plants will puncture any film of silt or other deposit which tends to seal the surface. Thomas (47) reports that there has been no evidence of silting up in several years of spreading operations in a highly absorptive oak brush area near Bountiful, Utah. Schiff (40) suggests the use of a soil conditioner to provide high infiltration rates. Todd (49) proposes that rapid sand filtration to eliminate fine material may be economically justified. Karr (21) indicates the possible use of a water jetting action for cleaning induced infiltration beds.

Schiff and Johnson (42) used overlying filter materials to cause deposition of fine material with depth rather than in a compact layer. With river water and a filter 0.2 feet deep, coarse sand (0.5 to 1.6 mm.) was twice as effective as 1/8-inch or 1/4-inch pea gravel in maintaining infiltration rates. Raking the filter beds to a depth of 1/2-inch caused deposited fines to be carried away. Cleaning by suction or scraping was also discussed.

Sediment in the Water

Artificial recharge projects have been concerned with the effect of silty water on infiltration rates, and although the problem is frequently discussed very little factual data appears in the literature. Some investigators (27, 31, 36, 40, 41, 51) favor diversion of flow heavily laden with silt from recharge works without placing limits on what constitutes heavily laden flow. Limits of permissible silt content reported by others (2, 32, 33, 38, 46) vary from 300 to 10,000 ppm with a usual high of 3000 ppm.

The ASCE Hydrology Handbook (18) indicates variations in rate of percolation on ten spreading grounds from 12.0 feet per day to 1.4 feet per day following silty storm flows. Mitchelson and Muckel (32) stated that the percolation rate decreased appreciably with the application of silty water on the Upper Santa Ana River. Whetstone (52) points out that silt in filtering out narrows the "necks" in the percolation tubes and reduces the total voids by lodging in the interstices of the existing larger-grain structures. Kazmann (22, 23) noted the importance of water movement perpendicular to the infiltration direction in keeping the fine materials removed in induced infiltration areas.

Robinson and Rohwer (39) listed the amount of sediment in the water as a factor affecting the seepage rate from irrigation channels but in experiments used only water with little or no sediment. Sharp and Saxton (45) said the content and nature of the sediment in the stream flow would affect transmission losses. They also stated that floodwaters with high sediment content, particularly clayey materials, may rapidly clog soil pores and reduce infiltration rates. Eaton (12) reported that flood flows contain sufficient fine suspended matter with colloidal content so that a depth of deposit of from 1/16 to 1/8-inch is sufficient to reduce the percolation rates or practically to seal the surface. Karr (21) noted that turbulence carries suspended material but subsiding movement permits deposition and in a limited way seals the bed.

Schiff (41) and Schiff and others (43) emphasized that sediments in flood waters reduce recharge rates and recommended that heavily laden flows not be used. Schiff and Johnson (42) used waters with up to 1840 ppm suspended solids in an artificial recharge experiment. They observed an increase in the concentration of fines smaller than 0.1 mm. in the first 0.01 feet of the bed. A visible deposit formed with most particles smaller than 0.002 mm. In a report of previous work Schiff (40) said that fine textured material was found between sand layers down to about 4 or 5 inches following the application of silty water.

Curry and Beasley (10) conducted experiments on the flow of colloidal suspensions through porous media using distilled water, granular carborundum as the media, and bentonite to form the suspensions. Three specific problems studied were the effect of head, concentration, and electrokinetic properties as related to the sealing of the media. Among their conclusions were the following:

1. Mechanical filtering is the main removal process,
2. The degree of sealing increases with decreasing particle size, increases with the hydraulic gradient, and increases with the concentration,
3. The shape of the particles had some effect,
4. The calculated zeta-potential correlated with the degree of sealing.

Summary

The notable lack of consistancy of quantitative results in the literature was pointed out previously. However, the review has been of definite value. A range of infiltration rates to be expected in alluvial channels has been suggested. The effect of velocity in maintaining fine sediments in suspension and scouring the bed is noted although the range of effective velocities is somewhat speculative.

The phenomena occurring at the surface of and within the bed sediments are discussed. Particle rearrangement and the deposition of fine material with depth are indicated as factors affecting infiltration. Treatments to alleviate clogging proposed in the literature are mainly mechanical processes with limited applicability to natural channels. A range of sediment content is defined, and the effects of particle size and shape, concentration, and gradient on the degree of sealing are reported.

STREAMBED INFILTRATION

The problem of determining streambed infiltration in alluvial channels is extremely complex with a large number of variables. The major factors which control the infiltration rate are the channel and its past history, the flood flows, the inter-relationships between the channel and the floods, and their overall relationship to the infiltration process. Each of the major factors also contains many variables. The discussion applies specifically to the channels in the Tucson area but should be applicable to similar channels in other areas.

Channel Characteristics

In effective recharge sections the average channel varies in width from 30 to 100 feet and has a uniform coarse, sandy bottom. At sections where the channel is wider than 100 feet, whether naturally or artificially created, there is a tendency for more than one channel to form with silt bars deposited between the channels and with native growth on the deposits. Figure 1 shows a section of Rillito Creek with optimum conditions for recharge. Figure 2 shows a section where the channel was constructed 400 feet wide four years previously for flood control purposes. The multiple channel formation is evident with two major

Figure 1 Rillito Creek Channel
Optimum Recharge Conditions

Figure 2 Rillito Creek--Multiple Channel Formation

channels and various cross-overs between them. The growth is not yet well established at this section.

The bed sediments have a uniform appearance to depths of 10 feet or more. Actual maximum depths of the coarse sand are not known, but during bridge construction at two locations the coarse material was found to be continuous to depths of 30 feet. No evidence of fine material layering is seen in the bed, but occasionally a layer 1/16-inch or more in thickness is found on the surface following a flood.

Examination of the channel banks or areas of thick silt deposits does show layering with alternate coarse and fine beds as shown in Figure 3, a photograph of the bank. Frequently thick silt layers deposited in man-made pits by one flood are covered by coarser materials in a later flood, but no evidence has been found that this happens under natural conditions in the bed of the main stream channel. Closer examination of the layers shows that the coarse sand layers contain very little silt and that the fine material layers have almost no coarse particles.

Flood Flows

Flood flows in this area are of two types. The spring flow which results from mountain snowmelt is a fairly uniform flow beginning with warming temperatures and continuing until the snow is gone, sometimes for a period of several months. The daily flow is cyclical when

Figure 3 Rillito Creek Bank Layering

nightime temperatures are below freezing in the mountains. The pattern of flow may be radically altered for either of two reasons: a cold spell with freezing temperatures lasting all day which stops the flow at its source, or a general rain causing increased flow from a larger area as well as more rapid melting of the snow cover.

The average wetted channel area varies, of course, with the daily discharge from the mountains but may remain fairly constant for a period of several days when there are only minor changes in the flow pattern. Because of infiltration losses there is a point of no flow which oscillates over a mile or more of the channel according to the daily flow cycle.

The sediment content of this Spring flow is very low at the base of the mountains with almost no settleable solids but a characteristic brownish color of organic origin. As the flow travels down the channel some suspended load is picked up.

The second type of flood results from summer thunderstorm rainfall or from area-wide winter rains of long duration. The thunderstorm caused floods are sudden, intense and short lived. The rise time may be very rapid (on the order of minutes) giving false credence to the expression of a "wall of water" moving down a dry channel. The flow may endure for several hours or a day or two, often stopping almost as suddenly as it started. The flow from the more general winter rains may also rise quite suddenly and is usually of longer duration, continuing for several days depending on the magnitude and extent of the rainfall. Figure 4 is a hydrograph for typical summer and winter floods.

With a change in flood discharge there will be a corresponding change in wetted channel area. The channel area increases with flow until the banks are reached. In some sections where the banks are not high or well defined a further increase in wetted area may occur as flow increases and spreads out in the flood plain area.

The sediment content of the flood waters will depend on the source of the runoff. Thunderstorm rainfall in the mountain areas will produce more sediment in the runoff than occurs from snowmelt. Rainfall on desert areas will produce a heavy silt load. Runoff from the Tucson urban area might be expected to be low in silt content because of the paved and grassed areas but actually is generally high in silt content because of the large amount of construction activity and consequently increased erosion opportunity. Also the unpaved streets and wind-blown dust provide additional sources of fine material.

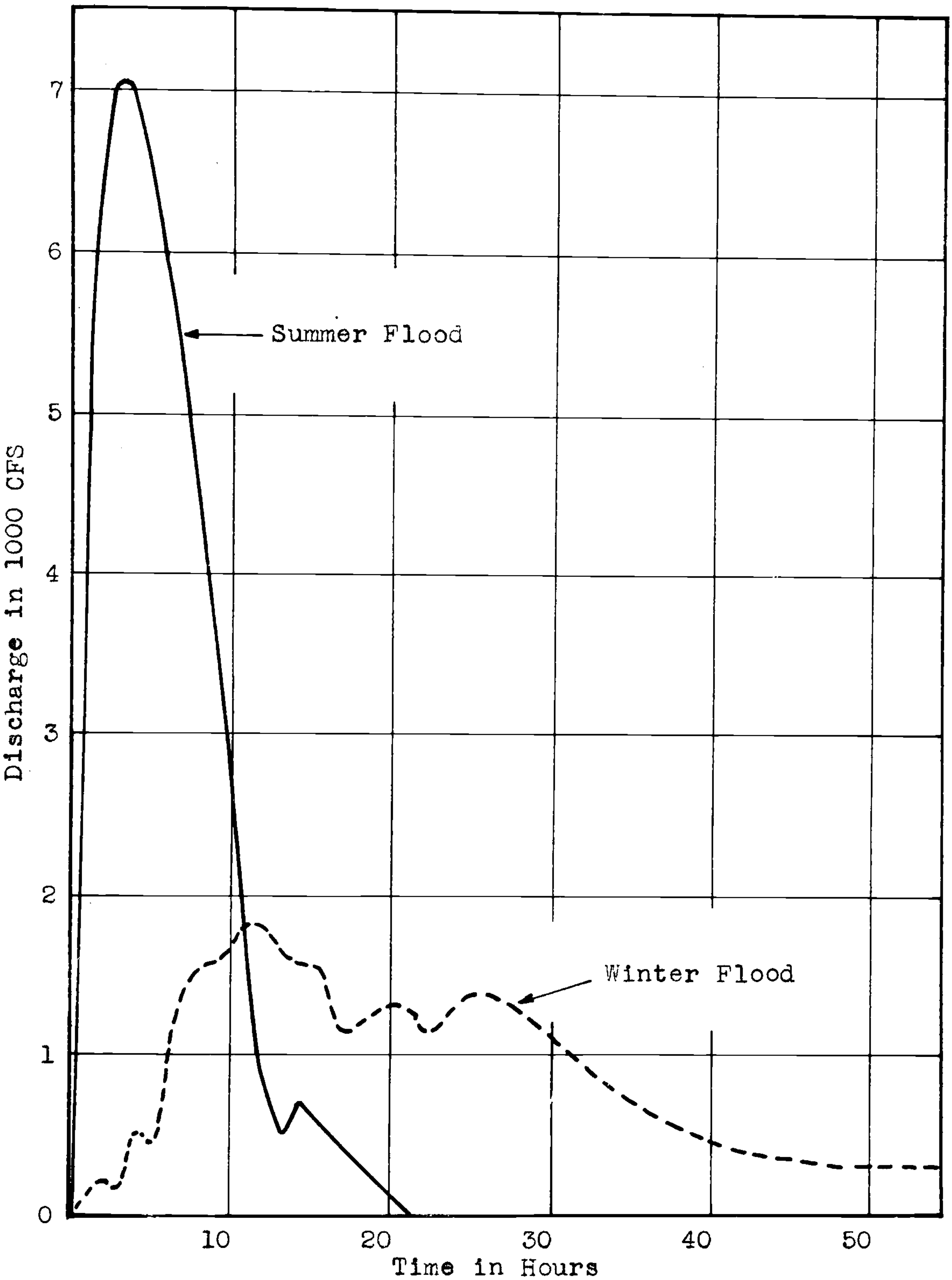


Figure 4 Typical Hydrographs of Flood Flows

Flood - Channel Relations

With flow in the channel three conditions of sediment transport are possible: 1) equilibrium when the sediment load equals the flow capacity for transport, 2) deposition when velocity is lower than that required to maintain the existing concentration of moving material, and 3) scour when velocity exceeds that required for the existing concentration. In addition to the considerations above of total sediment load, a concentration gradient must exist with depth to keep any particular size particle in suspension. For very fine sediment the gradient is nearly uniform from the water surface to the bed. Because the suspended material is always falling even in a rising volume of water, some of the suspended particles will reach the bed where they will become a part of the active bed load. The same particles will later be picked up by the flow as others fall, maintaining a constant interchange between the bed and the flow. (28)

With very low flow velocities bed movement will be negligible. As velocity increases, the formation of ripples, and then of dunes, is evident with a uniform pattern in uniform channel sections. Further increases in velocity will produce plane-bed conditions.

The channel state is a function of its history, and any reach in a stream may exhibit the three conditions of sediment transport during a single flood. Sediment moving as bed load will keep the fine materials moving and retard sealing. Deposition or scour will change the permeability; the deposit of very fine material may seal the bed. Contractions or expansions in the channel will produce deposition or scour under uniform flow conditions. Meandering and undercutting of banks will change the relative sediment load as will side channel inflow and the loss of flood volume by infiltration.

The clear inflow in the spring tends to be in non-equilibrium with the desert channel and will pick up silt from bed and banks to reach its transporting capacity. Since the inflow is clear the continued flow of water would clean the surface layers of the channel.

The silty flood flows may be in equilibrium with the channel if the silt content is moderate. A very silty flow will likely not be in equilibrium which simply means that there must be an adjustment between the flow and the channel. For any drainage basin there is probably an "average" flood in both size and sediment characteristics with which the "average" channel is in equilibrium--again remembering that the channel condition depends on its past history.

Infiltration

Infiltration is defined as the process of water entry into soil and infiltration rate as the rate, commonly in feet per day, at which a soil will absorb water impounded at a shallow depth on the surface with adequate precautions taken regarding border or fringe effects. (19) Infiltration rate is herein applied to water in motion. Infiltration is essentially a surface phenomenon.

Infiltration rate is a function of many factors most of which are variable at a given location and particularly under the dynamic conditions existing with silty flood waters flowing in an alluvial channel. Part of the water flowing across a permeable bed will infiltrate. With clear water and a stable bed material the infiltration rate will be governed primarily by the hydraulic gradient and the permeability of the bed. (3) With silty water the same two factors will control the infiltration rate but permeability may vary in the zone of bed action. Because fine materials must be in the bed, permeability changes will result in changes in the infiltration rate. Temperature will also be a factor principally because of its effect on water viscosity.

As water infiltrates the volume of flood waters decreases. If the same sediment load is carried an increase in concentration results which is possible if the capacity of the flow is not exceeded. If, on the other hand, the flow is already carrying its limiting capacity of sediment the decrease in water will mean a portion of the sediment load must be dropped.

The hypothesis is made that a relationship between velocity of flow, suspended sediment, and infiltration rate can be defined that will permit more accurate prediction of the natural recharge from flood flows. Low flow velocity with high sediment content will lead to a rapid reduction in bed permeability and ultimate sealing. The final limit for infiltration rate will be provided by layers of fine material either on the surface or at some depth within the channel as a result of previous floods.

PRELIMINARY EXPERIMENTS

Several experiments were conducted prior to the flume studies to obtain more detailed information about an ephemeral stream with a sandy channel. The knowledge gained was used to provide a reference framework for the flume operation and also to give some indication of the effect of silt content on infiltration with ponded water. The section of Rillito Creek shown in Figure 5 was used for obtaining samples and making tests.

Sediment Characteristics

Two series of sand samples were taken from Rillito Creek for analysis of particle size distribution using a set of nested 8-inch sieves and a mechanical shaker. All samples were given a 20-minute shaking period. The first samples were taken from the top of the bed following a long period of no flow in the river. Silt bars were deposited randomly in the channel, and there was considerable variation in the characteristics of the bed even at a single cross-section. At one section a heavy silt layer was deposited across the entire channel. During periods when the river bed is dry it is used for many purposes which disturb the surface layer. Consequently many sections of the river

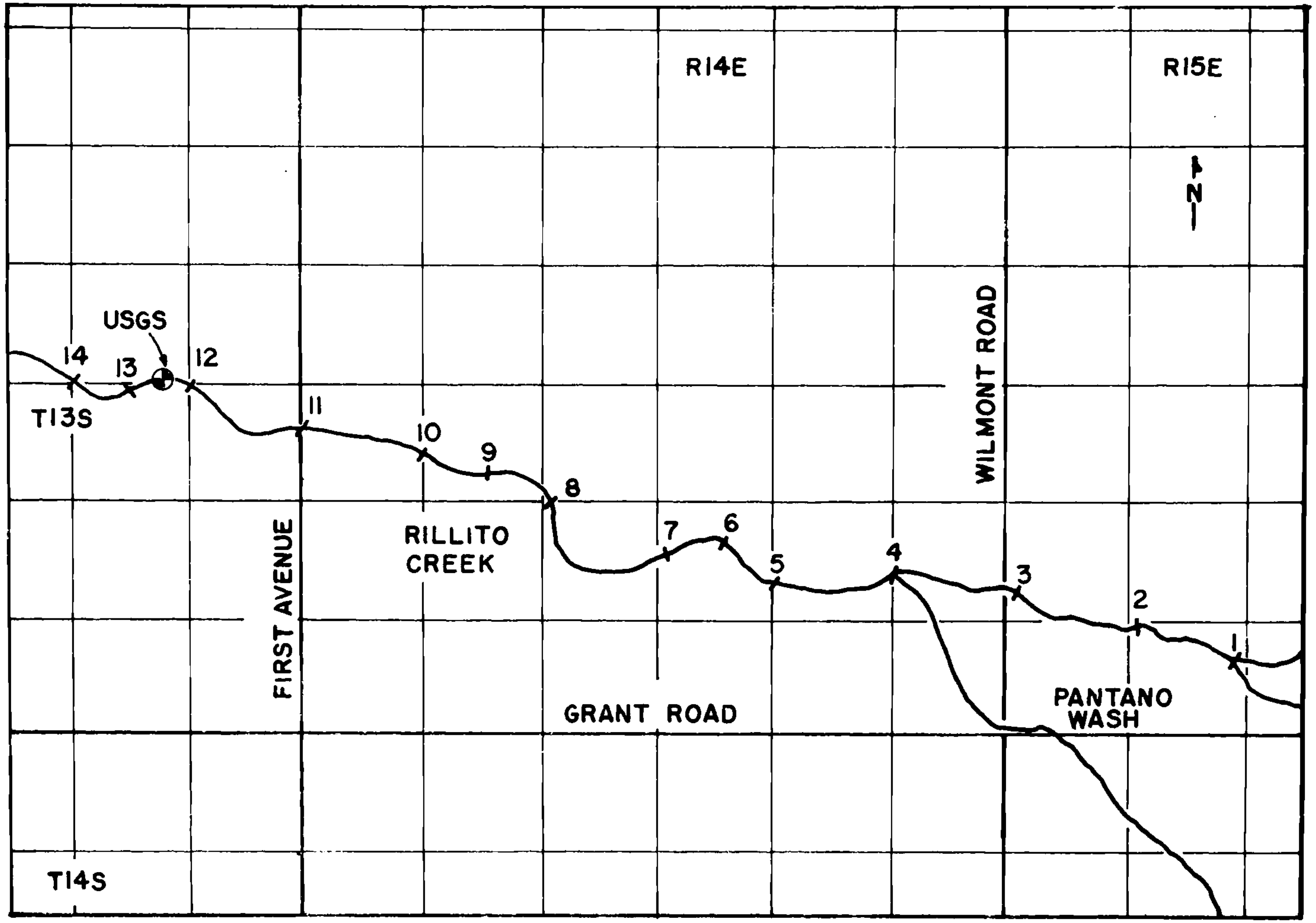


Figure 5 Section of Rillito Creek Showing
Numbered Locations of Sampling or Tests

did not exhibit the bed conditions which exist during or following a large flood.

The results of the mechanical analysis of the first series of samples are shown in the envelope curves of Figure 6A. The extreme variability of the bed materials is indicated with an approximate ratio of 4 between maximum and minimum particle size which may be present at any given concentration.

The second series of samples was taken from the top and at a depth of 6 inches below the dry river bed following a typical flood. Samples were not taken from areas of heavy silt deposits but, rather, from those areas where infiltration was possible.

The results of the analyses of these samples are shown in Figure 6B. The same variability for the sediments at the top of the bed is shown as in the preceding series, but the samples from 6 inches below the surface are more uniform. The content of particles smaller than 0.1 mm. is seen to be near 1 percent in all cases. The comparison of average sediments for the two sample series shown in Figure 7 indicates a variation of no greater than 10 percent between the samples which is probably less than the variation in sediment characteristics at any one location.

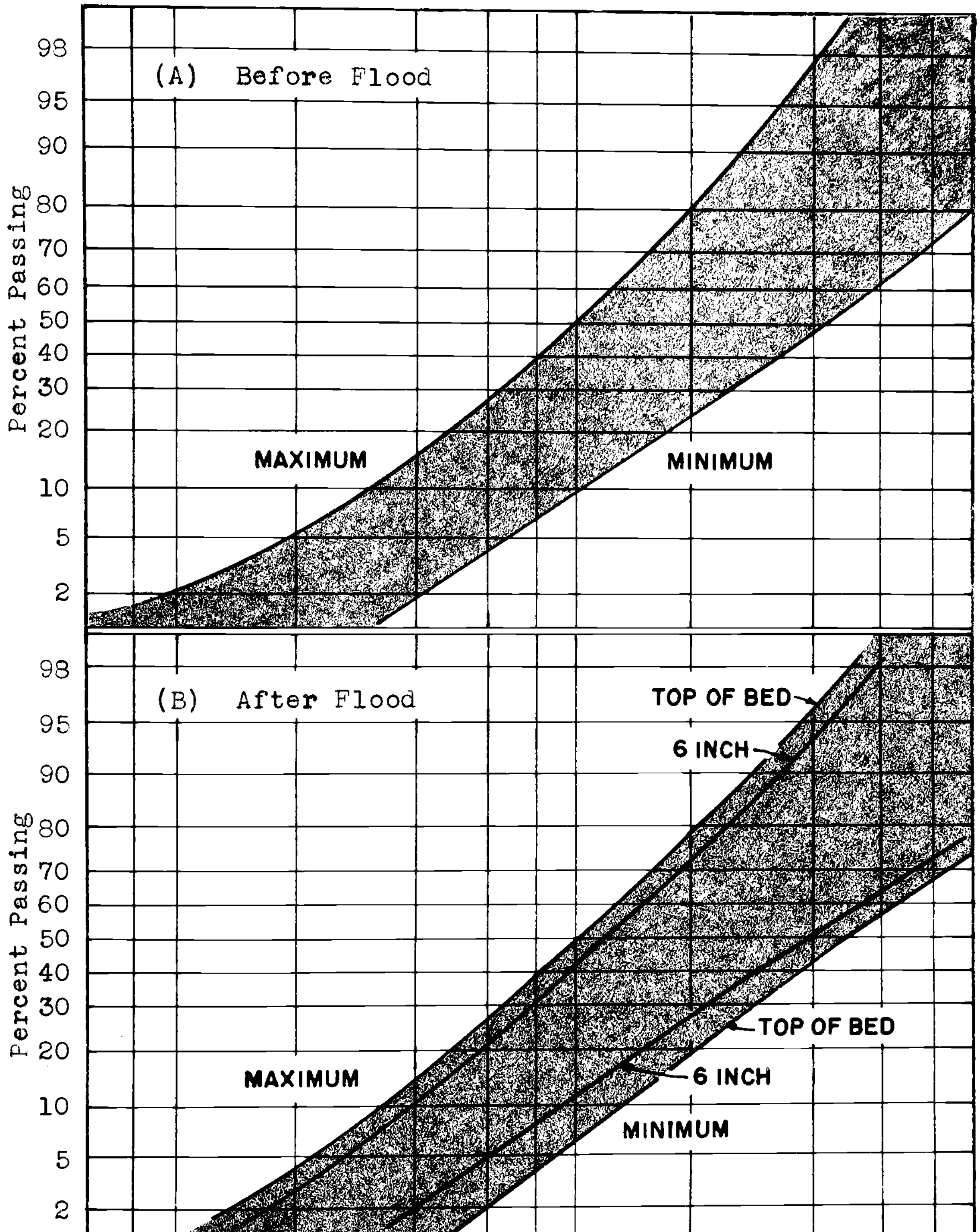


Figure 6 Analysis of Rillito Creek Bed Sediments

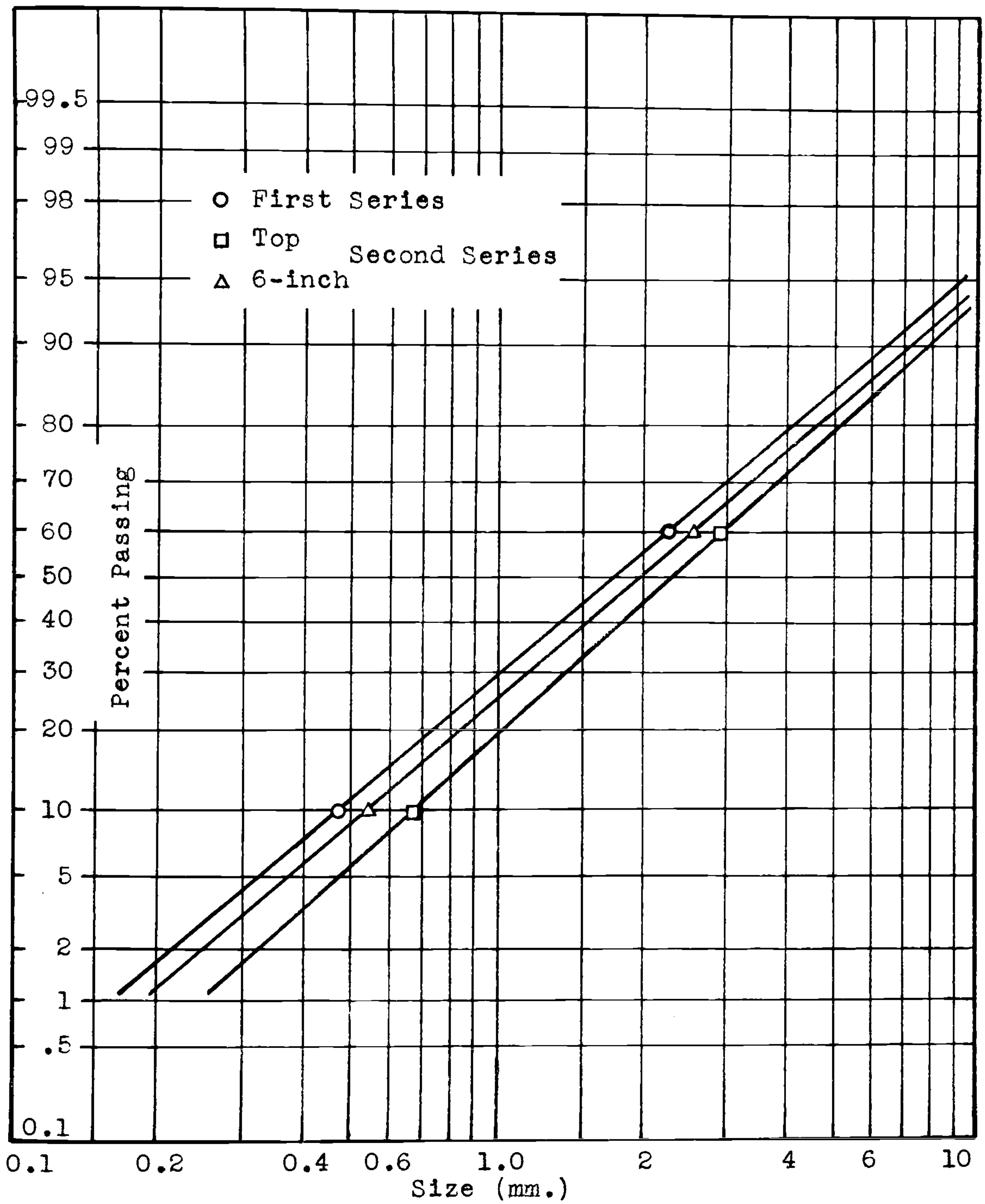


Figure 7 Comparison of Average Sediment Characteristics--Rillito Creek

Suspended Sediment

Samples of flood water were taken from Rillito Creek during a flash type flood and also a flow of relatively clear water from melting snow for measurement of the suspended sediment content. Wide-mouth quart jars were held just below the water surface until they were filled. In all cases the flow depth was less than 1 foot at the sampling locations.

Analysis of the flash flood samples shown in Table III was made by weighing, evaporating to dryness and reweighing. Dissolved solids of about 250 ppm were thus included. Concentrations of suspended material in flood flow varied from about 0.1 percent to 1.1 percent with the concentration generally increasing downstream. Mechanical analysis of the dry material obtained showed that 96 percent was finer than 0.1 mm. and that about 10 percent of the coarser material was organic.

The turbidity of the clear water flow was measured with a Jackson Candle Turbidity Meter with the results shown in Table IV. Again the turbidity increased downstream as the clean water coming out of the mountains picked up fine material from the river bed. The decreasing sediment concentration at the last two stations was consistent with the diminishing flow which ended just down the river from the last sampling point. Later observations

TABLE III

ANALYSIS OF SILT SAMPLES FROM FLOOD WATERS			
Location	Concentration (percent)	Location	Concentration (percent)
1	0.1	8	0.5
2	0.08	10	0.5
3	0.1	11	0.9
5	0.1	12	1.0
7	0.3	14	1.1

TABLE IV

TURBIDITY OF SPRING FLOW--RILLITO CREEK			
Location	Turbidity (ppm)	Location	Turbidity (ppm)
1	25	10	75
5	25	11	130
6	40	12	145
8	80	USGS	130
9	80	13	120

showed that turbidity decreased with time for periods when the daily flow was changing only slightly as the river bed was gradually cleaned.

Permeability Tests

Laboratory permeability tests were conducted with the river bed samples that had been analyzed for particle size distribution in the constant head, discharging permeameter shown in Figure 8. The standard procedure for permeability tests is to direct the flow from bottom to top of the sample to reduce problems of air entrainment. This procedure was not followed so that silt added to the water above the sample would settle in a manner closely resembling the settling of silt in a pond.

The samples were thoroughly mixed, poured into the permeameter and then tamped to more nearly duplicate natural packing. Ordinary tests were run long enough to obtain a relatively constant permeability which usually occurred within a period of a few hours. Silt (particles finer than 0.074 mm.) was added to the water supplied to some of the samples after their flow rates had stabilized to simulate the application of silty water in a natural channel. The silt was added in increments from the top of the permeameter and settled down through the water above the sample.

The results of permeability tests made on river channel sediments emphasize the wide variations in these

Figure 8 Constant Head, Discharging Permeameter

Figure 9 Preferred Permeability Paths

materials. Permeabilities ranged from about 20 gallons per day per square foot (gpd/ft^2) to about 18,000 gpd/ft^2. (see Table V) The samples were disturbed samples as a result of having been sieved and repacked, and a wide range of values was anticipated. In most cases the permeabilities obtained were in accordance with the particle size analysis, i. e., the coarser and/or more uniform materials were more permeable than the finer and/or less uniform sediments. The method of placing and packing the samples in the permeameter probably caused some discrepancies. Neglecting the two very low permeabilities of thick silt deposits an average value of 6300 gpd/ft^2 was obtained.

The addition of silt to the water flowing through the permeameter provided some interesting and somewhat unexpected results. The silt settling on top of the sample formed a thin layer, but some silt could also be seen moving into the material at the sides of the permeameter. As silt addition continued the layer generally increased in thickness, but not uniformly. In certain areas the layer was not as thick or in some cases practically non-existent. (see Figure 9) The total flow passing through these preferred permeability paths had sufficient velocity to carry the silt particles farther down into the sample. Layers of as much as 1/2-inch average thickness were still affected.

TABLE V

PERMEABILITY OF RILLITO CREEK BED SEDIMENTS		
Location	Permeability (gpd/ft^2) Top	6-inch Depth
1	17000	8000
2	5600	8600
3	4200	2300
4	80	20
5	120	520
7	2100	1200
10	2200	7200
11	1600	4800
12	4600	4500
14	15000	18000

Adding silt and allowing it to settle in a 1/2-inch layer before discharge was started was also not effective in completely sealing the bed. Settling for more than 48 hours did not remove all turbidity, but turbidity was quickly eliminated after flow started (about 15 minutes). Preferred permeability paths still developed in the silt layer.

Stirring the top few inches of the sample and allowing it to settle through water formed a graded layer on top of the sample. However, this layer also did not seal the bed but showed the existence of preferred permeability paths. Since the phenomenon of preferred paths has not been observed in river bed silt deposits this phenomenon apparently does not occur in the presence of a horizontal velocity component.

Figure 10 shows the change in relative permeability with time when silty water was applied to one sample. A rapid reduction took place at first as the settling material covered most of the permeable area, then there was a decrease in the rate of reduction as silt penetrated the bed through the preferred permeability paths. Lower permeability material did not decrease as rapidly in relative permeability because fine material was being deposited within the sample from the beginning of the test and preferred permeability paths were slower in developing.

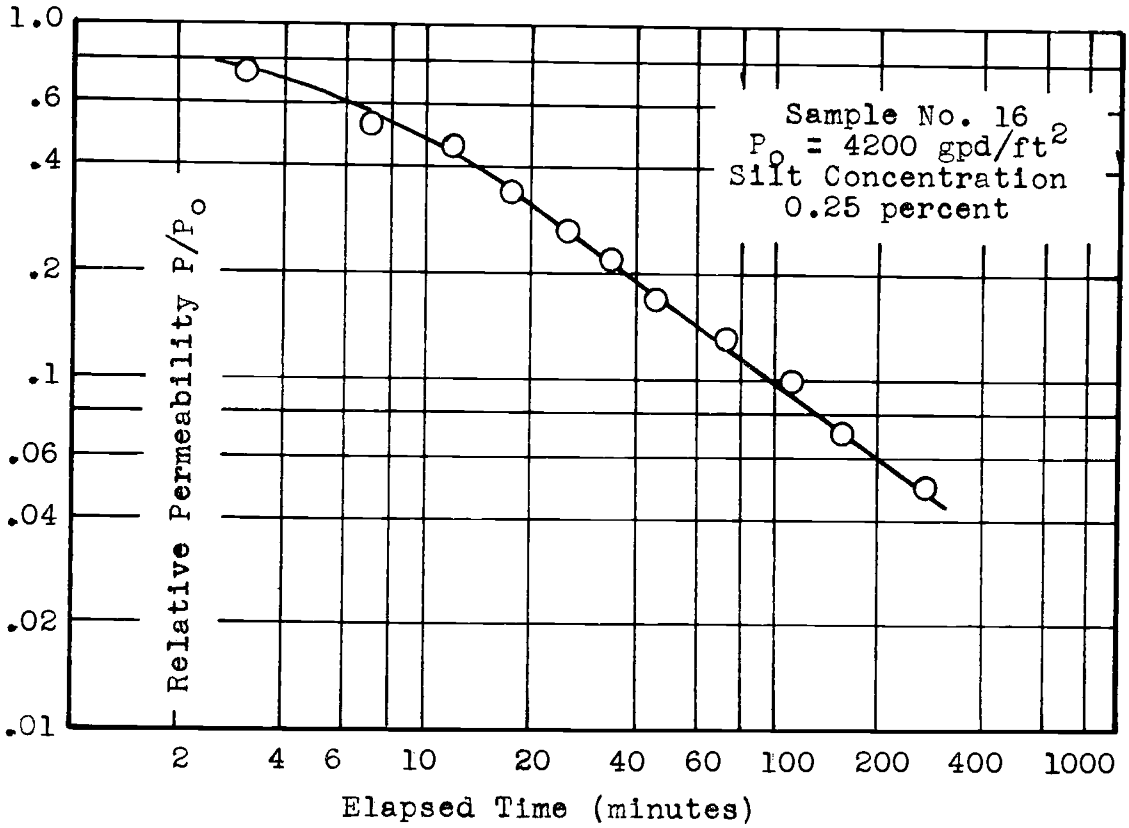


Figure 10 Effect of Silty Water on Permeability

Two permeability tests were also run with synthetic samples made by starting with uniform, coarse material and adding increments of increasingly finer material. More uniform bed structure resulted although sealing was still not complete. Preferred permeability paths did not develop, and the graded crust formed in one instance was very much like those observed frequently in the natural channel, formed as the flow diminished. Permeability was reduced to less than 0.002 of the original value.

Infiltration Tests

Two types of infiltration tests were made at selected river bed locations: the first series in the dry river bed used cylinder infiltrometers and buffer ponds (see Figure 11) according to the procedures outlined by the U. S. Department of Agriculture (16); the second was made when the river was flowing, eliminating the need for buffer ponds. The results of the first series are shown in Table VI, and Figure 12 is a curve of accumulated infiltration and infiltration rate vs. time for one test. Examination of this summary data shows that the initial infiltration rate may be extremely high--on the order of hundreds of feet per day, but this decreases rapidly with time to a value of less than 20 feet per day. There is a wide variation in the infiltration characteristics of the river channel even at one location. A silt layer of 1/16 to 1/8-inch thickness

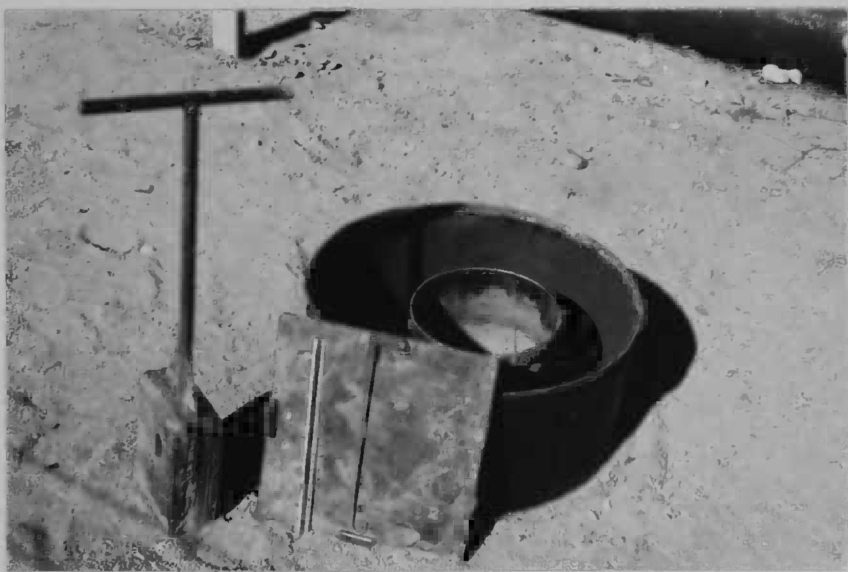


Figure 11 Infiltration Equipment

TABLE VI

INFILTRATION TESTS--RILLITO CREEK (DRY)			
Location	Infiltration Rate (ft/day)		Remarks
	1 minute	1 day	
7	103	13.6	sandy stream bed
12	512	18.7	sandy stream bed
12	104	10.2	1/16 to 1/8-inch silt layer
12	0	--	3 to 4-inch silt layer

TABLE VII

INFILTRATION TESTS--RILLITO CREEK (FLOWING)		
Location	Permeability (gpd/ft^2)	Remarks
1	6200	Bed material saturated to depth greater than penetration of intake cylinder makes these tests comparable to falling head permeameter tests.
2	2900	
3	3600	
5	1300	
8	1400	
9	2100	
11	1000	
12	200	
14	200	

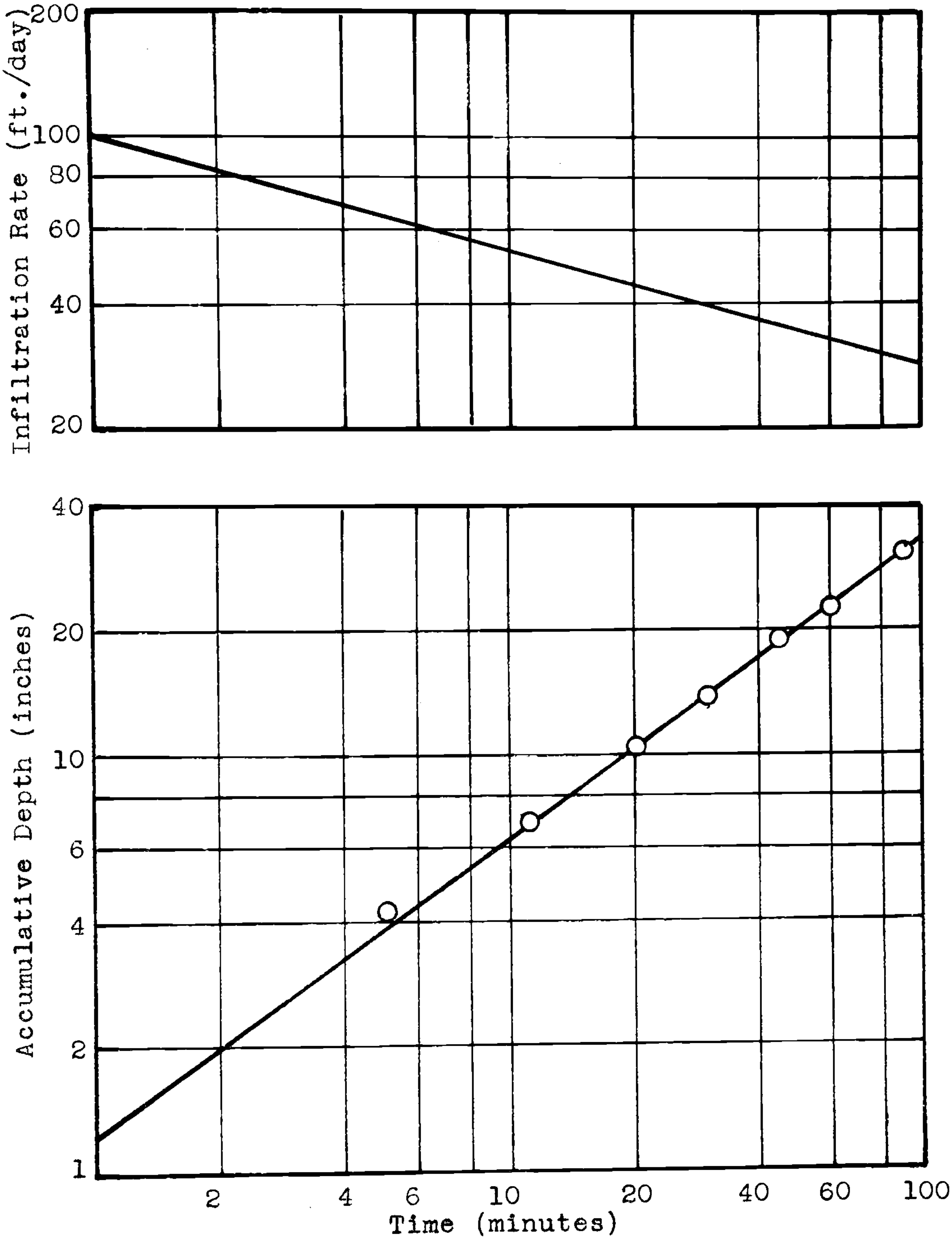


Figure 12 Infiltration Test Results
Rillito Creek at Alvernon Road

reduced infiltration rate by 80 percent while a 3 to 4-inch thick silt layer had no measureable infiltration in a four hour period.

The second series of tests made when the river was running are effectively insitu permeability tests with a falling head because the bed was saturated below the depth of cylinder penetration. The results of these tests are given in Table VII and show that the permeability of the bed generally decreases with distance from the mountain source of the stream.

TILTING BED FLUME EXPERIMENTS

The principal equipment for the laboratory studies was the 100-foot long, tilting-bed flume seen in Figure 13. A two-point support system was used to facilitate changes in slope with the upper end fixed and adjustments made with the lower support. The water supply was from a recirculating system with a sump tank for storage of the water between runs. A 5000-gallon per minute, engine-driven pump was used with variable discharge obtained by changing the engine speed. One side of the flow channel was constructed of 1/4-inch plexiglass for observing the action at the interface between the sand bed and the flowing water. The perforated bottom plate, provided for infiltration, was covered with galvanized screen to prevent sand entry into the infiltration channel. Sediment was added or removed as necessary in the sump at the lower end of the flume. Details of the flume construction are shown in Figure 14.

Instrumentation

Total discharge was measured with a flow meter installed in the 12-inch supply pipe line. Stations were established at 10-foot intervals along the flume for observations of water surface elevation and depth. Average velocity was computed from discharge-area relationships.

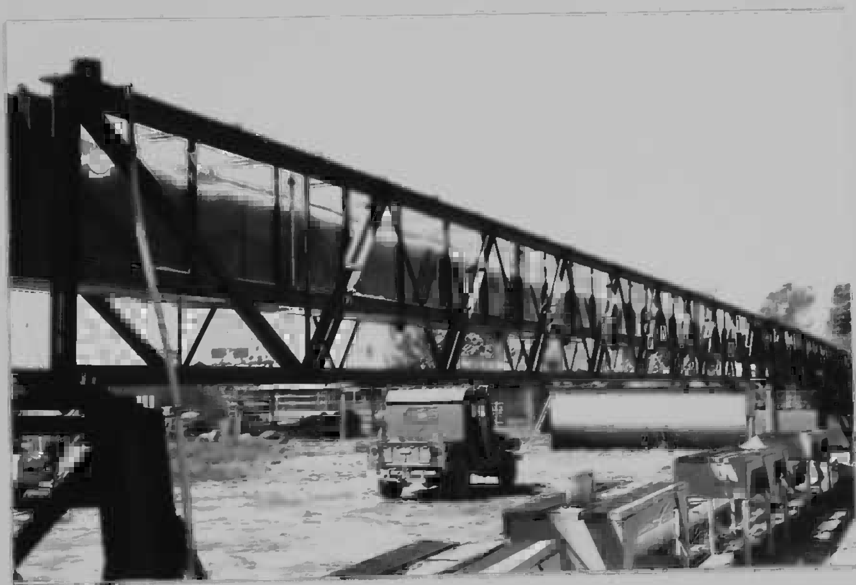


Figure 13 100-foot Tilting Bed Flume

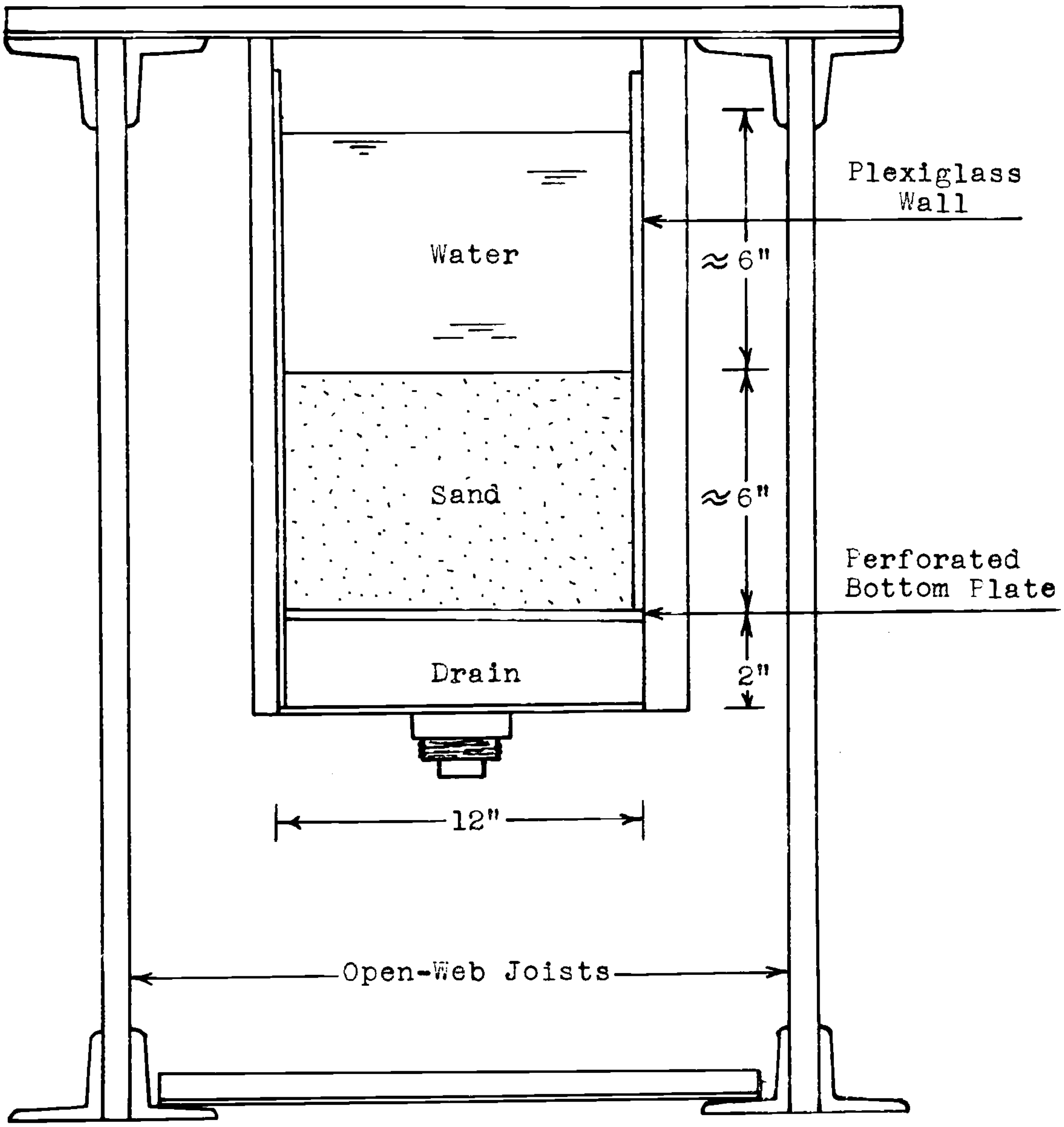


Figure 14 Cross-section of Flume

Depth of flow was measured on the plexiglass channel wall by visual averaging of fluctuations. The slope of the bed was determined by differential leveling and indicated by a pointer and scale on the end of the flume. Water temperature was measured with a thermometer several times during each run.

The relative concentration of suspended sediment was determined by withdrawing samples from the flume with a siphon tube adjusted to the flow velocity. The samples were then filtered to separate the sediment. The ratio of sediment weight to sample weight expressed as a percent was called the suspended sediment index.

Infiltration rates were computed from volumetric measurements. The sediment content of the infiltrate was examined as above for suspended sediment and with a Jackson Candle Turbidity Meter. Piezometers in the sand bed were used to indicate saturated or unsaturated flow in the bed.

Design of Experiments

The operating procedure and measuring techniques were designed to control the flow conditions in the flume for the duration of the test. The tilting bed permitted rapid establishment of the desired conditions. To confirm the establishment of the imposed conditions repeated measurements over a period of time and at successive stations were necessary.

Selection of the channel dimensions, pipe sizes, and pumping equipment defined the flow limits of from 2 to about 5 feet per second with a depth of 6 inches. Choosing and placing the river bed materials in the channel provided the starting point for bed permeability. Controlled variables in the test procedure were the suspended sediment index which was varied from about 0.02 percent to 0.6 percent and the discharge-slope relationship which controlled velocity and depth of flow.

Test runs were made according to two different procedures: 1) tests were started with high velocity and a given suspended sediment index. After making a series of measurements and observations velocity was reduced by decreasing the discharge rate while maintaining the same depth of flow by decreasing the slope. Velocity reduction was then continued in steps to the lowest velocity; 2) tests were made at a constant velocity varying the suspended sediment index from a minimum to the maximum 0.6 percent.

In addition to the measurements made and described in the paragraph on instrumentation, frequent examination was made through the plexiglass side wall of the action occurring at the interface between bed and flow and of the penetration of silt into the bed. Bed profile was also noted. Following some of the tests more detailed examination of the bed was made. Algae growth in the bed was controlled by adding copper sulfate to the water at a rate of about 1 part per million.

Results of Flume Studies

Infiltration Rate

A correlation is seen between the infiltration rate and velocity with different suspended sediment index conditions, but because of difficulty in maintaining uniform bed material characteristics for each test the combined effects were not altogether consistant. Figure 15 shows the relationship between velocity and infiltration rate obtained for different values of the suspended sediment index taken from different tests. Inconsistancies were caused by the inability to return the bed materials to the same conditions for each change in velocity. A clearer picture of the relationships was obtained by running the flume at different velocities without changing the suspended sediment index, and then running at constant velocity with a variable suspended sediment index and plotting the results separately.

Velocity

Infiltration rate increased with the velocity in the range from 2 to 5 feet per second. Figure 16 shows the relationship between infiltration rate and velocity for all tests disregarding the suspended sediment index, bed

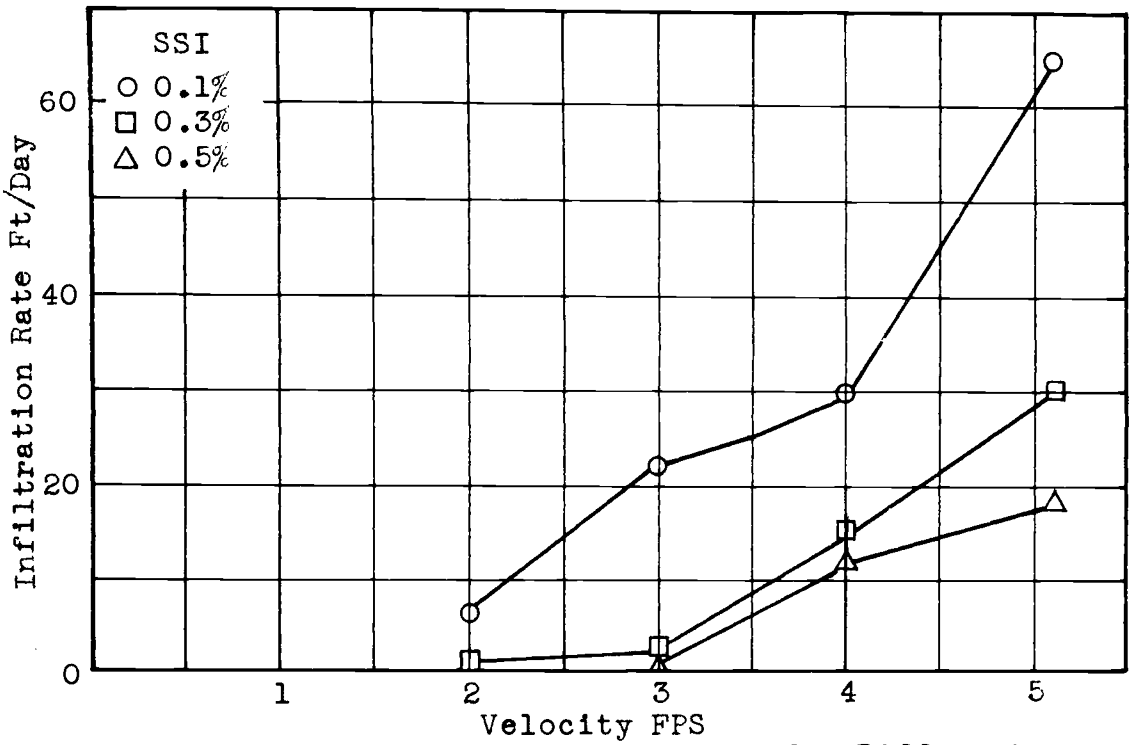


Figure 15 Infiltration Rate vs. Velocity for Different Values of Suspended Sediment Index

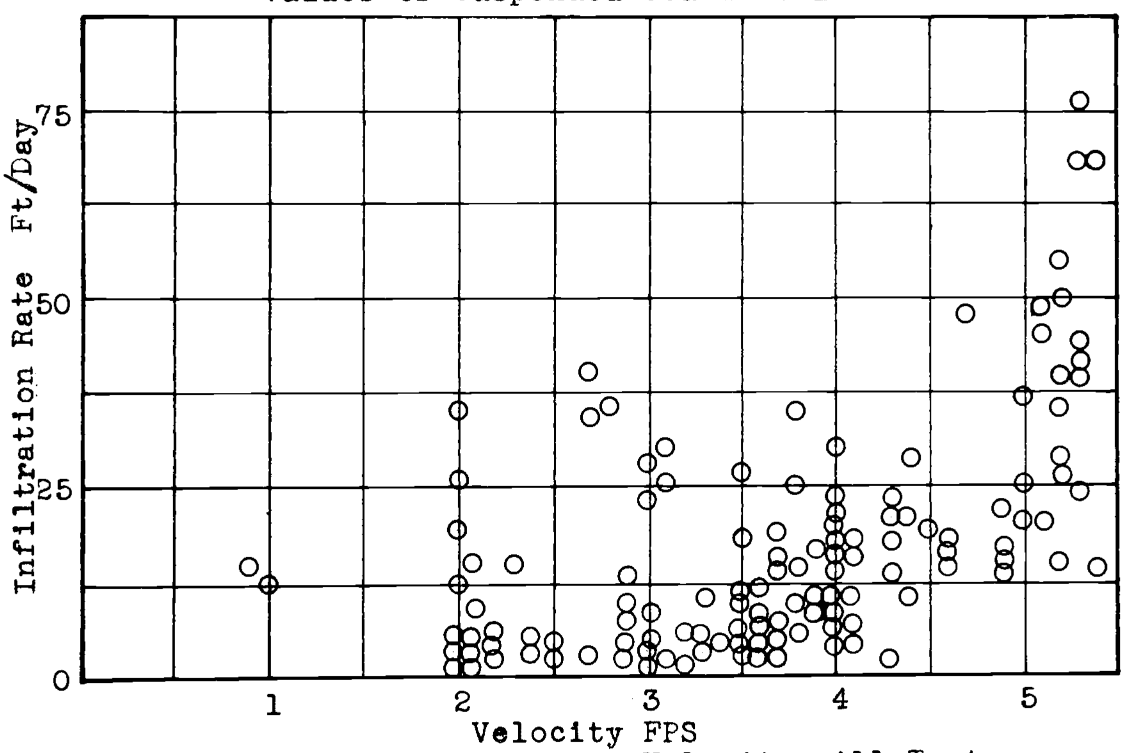


Figure 16 Infiltration Rate vs. Velocity--All Tests

material conditions, and temperature. Although considerably scattered these points do show a trend toward higher infiltration rates for increased velocity.

Figure 17 shows the results of starting a run at high velocity and decreasing the velocity in steps without artificially changing the sediment load. A significant change in total load occurred as velocity decreased, but the change in the suspended sediment index was minor. A temporary increase in infiltration rate occurred with a decrease in velocity from 5 to 4 feet per second as a result of more, higher dunes and more turbulent flow as the bed was adjusting to the new flow conditions.

Figure 18 shows the result of an attempt to reverse the run shown in Figure 17, i.e., to start at low velocity and increase the velocity in steps and increase the infiltration rate. This attempt failed for two reasons. The high infiltration rate at 1 foot per second was the result of a long period of bed drying and no visible bed movement after flow started at this velocity. Immediately on increasing to 2 feet per second the infiltration rate decreased rapidly as bed movement started and repacking of the surface layer occurred. A trend toward higher infiltration rates is seen for velocities of 3 to 4 feet per second, but this was short lived because of the limitations of the equipment used. With decreasing flume velocities

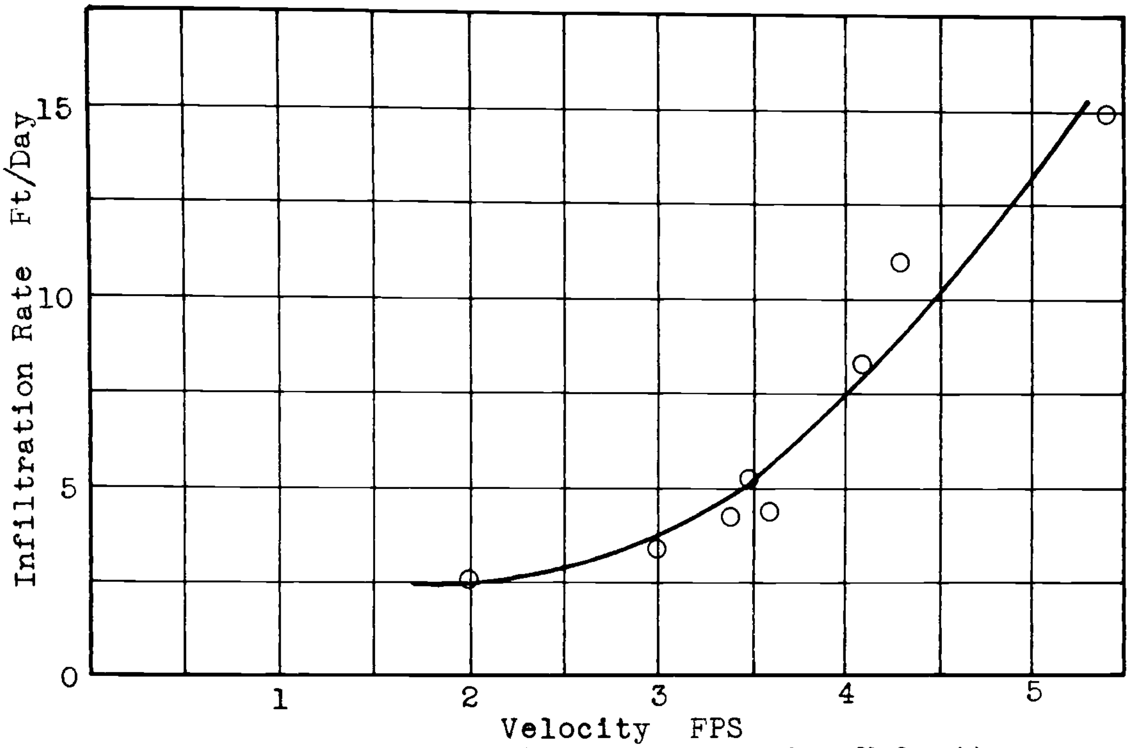


Figure 17 Infiltration Rate vs. Decreasing Velocity
Suspended Sediment Index 0.3 Percent

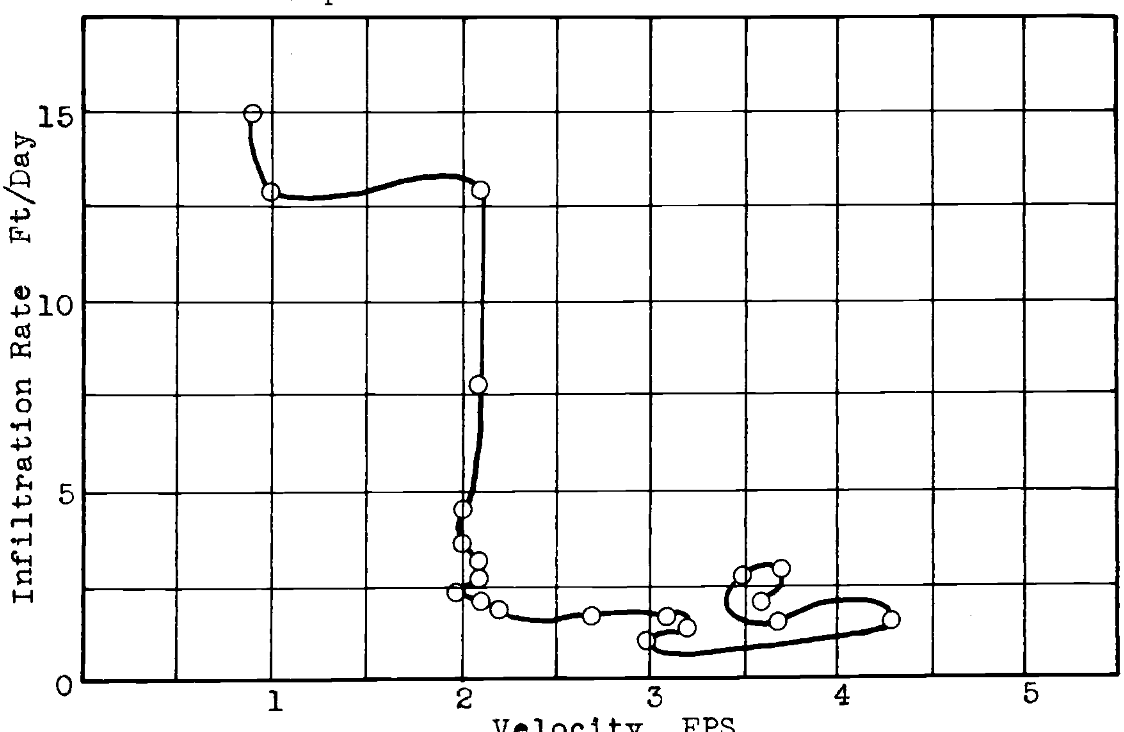


Figure 18 Infiltration Rate vs. Increasing Velocity
Suspended Sediment Index 0.2 Percent

the total amount of bed material in the flume decreased because the velocities in the return pipeline permitted more material to be deposited there. When the velocity was increased this process was reversed and the material from the pipe line was carried back into the flume. This material was deposited on top of the previously formed bed layer and prevented the increased flow velocity from effectively coming in contact with the restricting layer. Similar action can take place in the natural stream on rising and falling stages.

Suspended Sediment Index

A given flow regime will carry a constant sediment load. Adding fine materials to the flow changes the relationship between suspended and bed load. When the suspended load is not in equilibrium with the bed load or bed materials, changes in the loads or bed characteristics will take place to produce this equilibrium.

The fine materials used in the study to produce changes in the suspended sediment index were obtained from natural deposits along Rillito Creek. The characteristics of the materials are shown in Figure 19 where it can be noted that more than 90 percent is finer than 0.1 mm. which compares favorably with the previous results of mechanical analyses of flood carried sediment. The suspended sediment index was not increased to more than 0.6 percent because

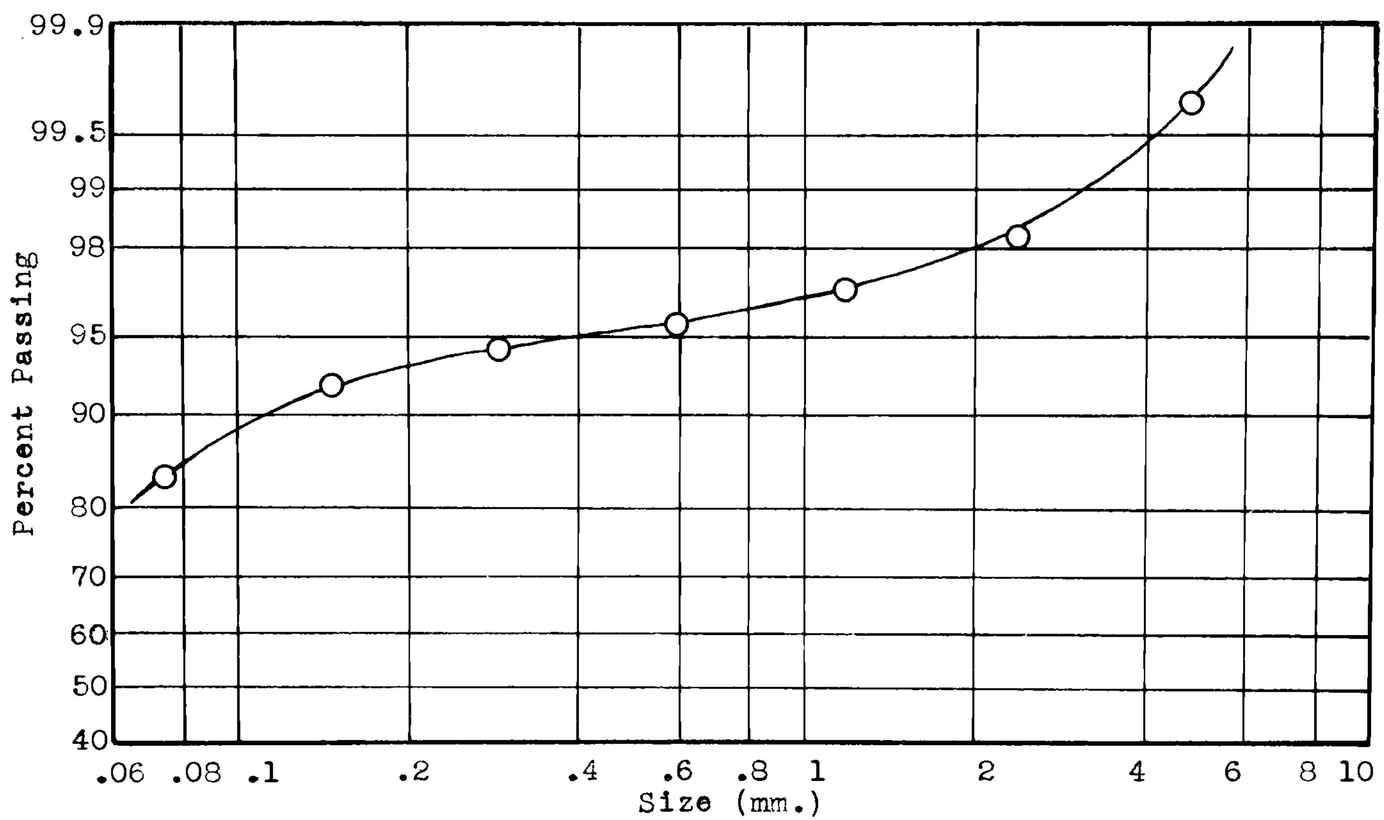


Figure 19 Characteristics of Fine Material Added to Increase Suspended Sediment Index

of problems in maintaining a higher index and because the desired relationships were well defined within this range.

Figure 20 shows the inverse relationship between infiltration rate and suspended sediment index for constant velocity. These curves indicate the rapid decrease in infiltration rates occurring with increasing suspended sediment.

Again emphasis is placed on the fact that correlation between the relationship for different velocities is not ideal because of the different bed characteristics existing at the beginning of each test. The tests were all started with a minimum suspended sediment index which was then increased in steps to a maximum of about 0.6 percent. Between tests the bed was raked, turned and flushed with clean water in an attempt to return its characteristics to the original conditions.

Bed Material

The bed material used in the flume was obtained from Rillito Creek and had the characteristics shown in Figure 21 before and after the flume tests. The mechanical analysis of original characteristics was made before placing the material in the flume and subsequent removal of fine material by flow over and through the bed. Thus the particle size distribution of the bed material did not change appreciably over the period of the tests.

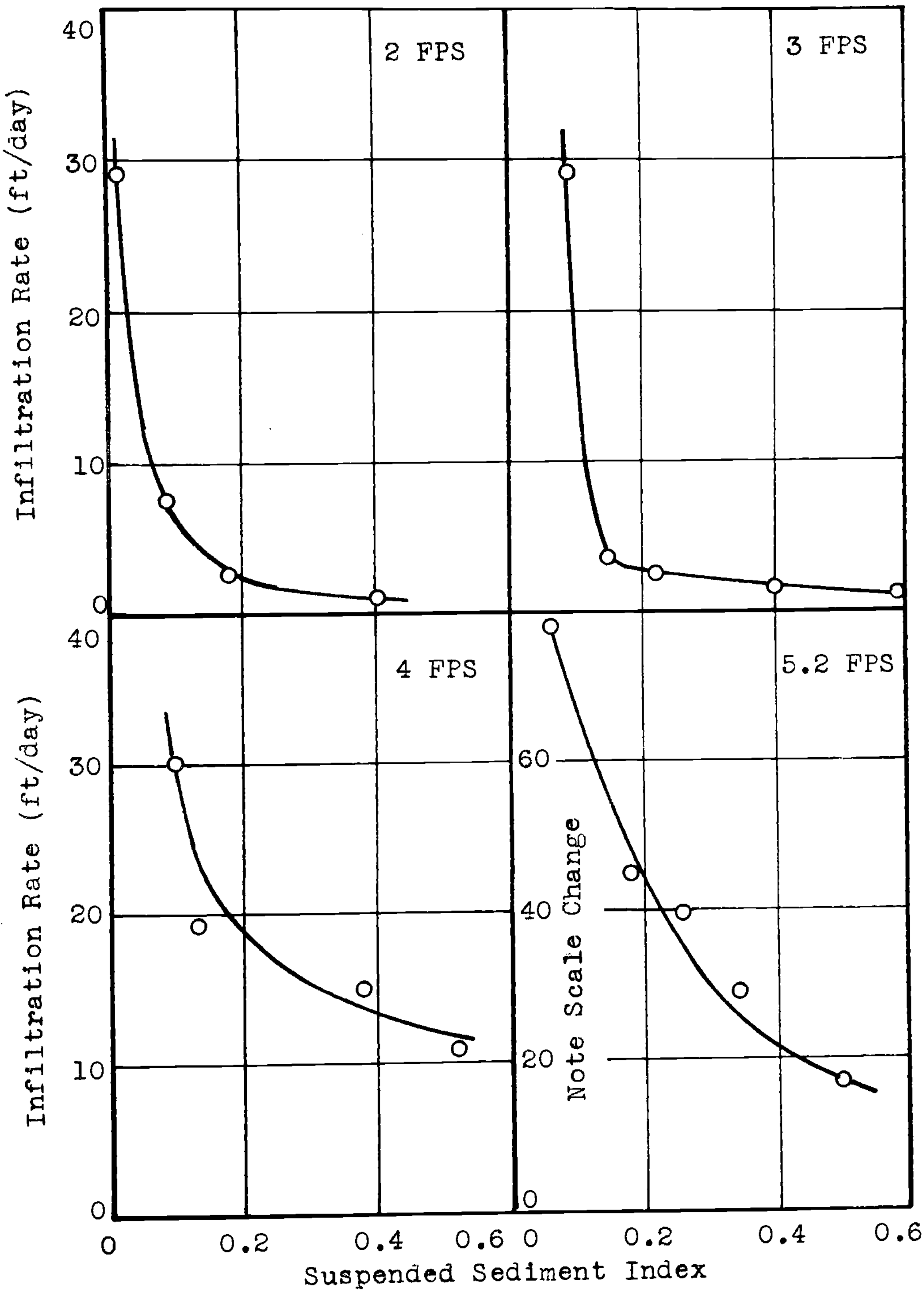


Figure 20 Infiltration Rate vs. Suspended Sediment Index

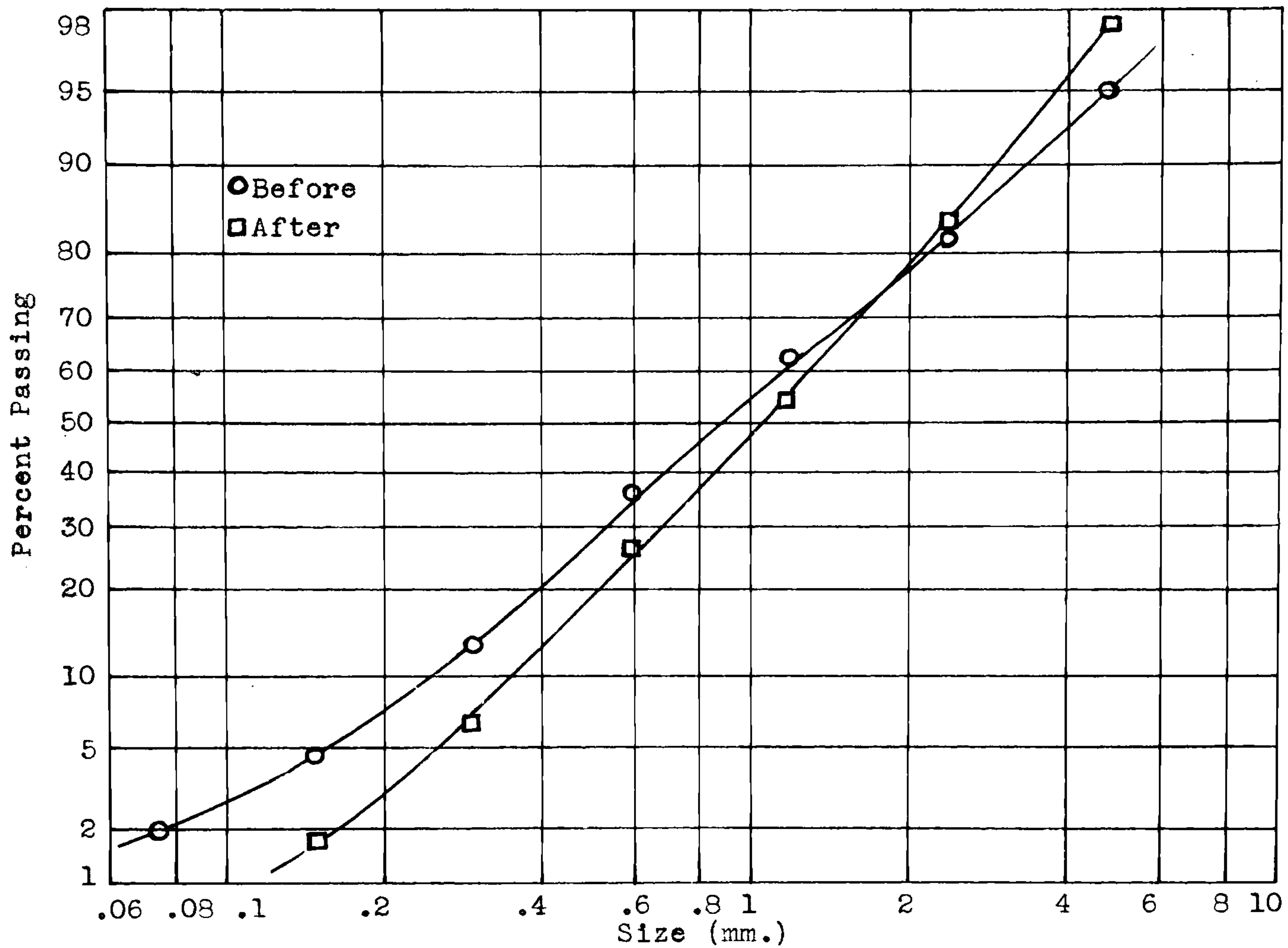


Figure 21 Bed Material Characteristics

Laboratory permeability of the same two samples used for size analysis was markedly different with 500 gpd/ft^2 before and 8500 gpd/ft^2 after the tests. There were changes in the bed characteristics during the individual tests, and as previously indicated the effect of these changes was reduced between runs.

All of the bed surface conditions observed in the flume have also been seen at one time or another in Rillito Creek. Plane-bed conditions occurred occasionally at the flume entrance but did not occur continuously over any other section of the channel. With the two-dimensional flow of the flume, plane-bed conditions did not seem to be as effective as dune action in maintaining fine material in suspension.

There was a continuous sorting and rearranging of the sediment particles at the surface of the bed for all tests except those at 2 feet per second or less. The sorting and rearrangement process formed a packed layer that restricted infiltration. The most stable packing seemed to form when the larger particles did not move readily and finer particles were fitted around them.

Continuous silt layers were not deposited on the bed surface for velocities of 3 feet per second or greater when the flume was running. When the flume was stopped after running with a high suspended sediment index a fine layer was deposited on the surface of the bed. (see Figure 22) This layer was not picked up by flow of the same velocity after the flume was shut off for a few hours. A hysteresis effect was noted on several occasions when a higher velocity was required to pick up a silt layer than had deposited it. A similar layer has been observed frequently in the Rillito Creek channel on a relatively coarse bed.

At 2 feet per second and suspended sediment index of 0.02 percent, dune movement was evident. As the index was increased a fine layer was immediately deposited. With further increases to 0.4 percent the fine layer covered the dunes and dune movement stopped. Only the larger grains were visible through this layer shown in Figure 23. Silt addition was not continued beyond this point because the carrying capacity of the flow was obviously being exceeded which would only result in a gradual increase in the thickness of the silt layer.

The dune structure in the flume was quite variable with, in general, lower and longer dunes at 2 and 3 feet per second than at 4 and 5 feet per second. At the higher velocities changes in flow regimes produced extremely high dunes and turbulent flow as seen in Figure 24. However, the dunes would move over a layer of fine silt without disturbing it. (see Figure 25)

Figure 22 Silt Layer Deposited When Flow Stopped

Figure 23 Silt Layer Deposited at 2 FPS

Figure 24 High Dunes and Turbulent Flow

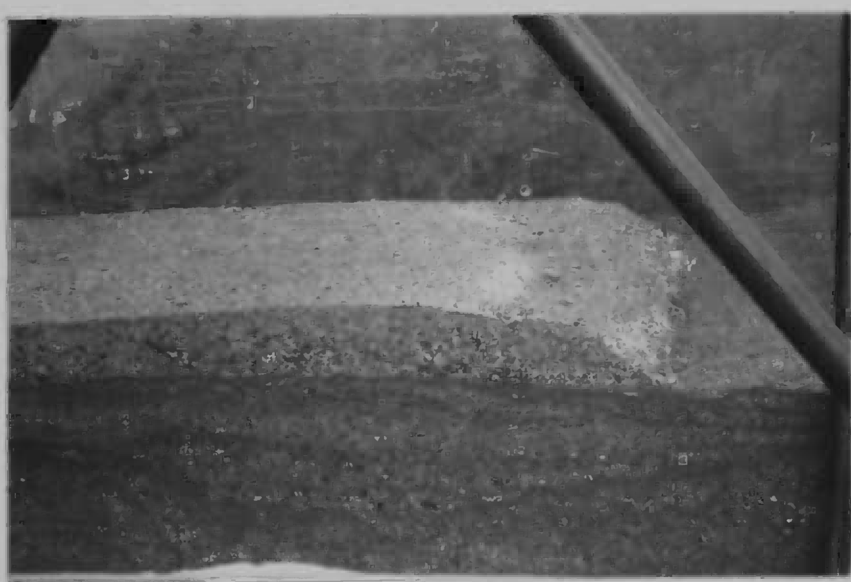


Figure 25 Dune Moving Over a Fine Layer

A fine layer formed below the surface at the elevation of maximum dune scour at velocities of 3 feet per second or greater. Figure 26 shows the sequence of processes involved in the formation of this layer. As bed load was carried over the end of the dune the coarser material settled first with a graded layer over it. Fine material from above the larger grains could be seen drifting down through the interstices of the larger grains to form a fine layer underneath. The more uniformly graded material under the zone of dune action prevented the fine materials from penetrating more deeply into the bed. The water in the interstices of the large grains appeared relatively clear even for the higher values of suspended sediment index. As the tail of the dune approached, the fine material on top was picked up and carried away. Then the coarser grains moved as rolling bed load, but the fine layer underneath was not moved. Occasionally one of the larger grains was not moved and gradually settled into the compact layer. The entire process was repetitive as dune followed dune down the flow channel. Although the layer was quite evident at the plexiglass wall (see Figure 27) it could not be seen in the bed when it was examined after a run. The disturbance of the bed by digging was enough to destroy the layer showing that its thickness was very small.

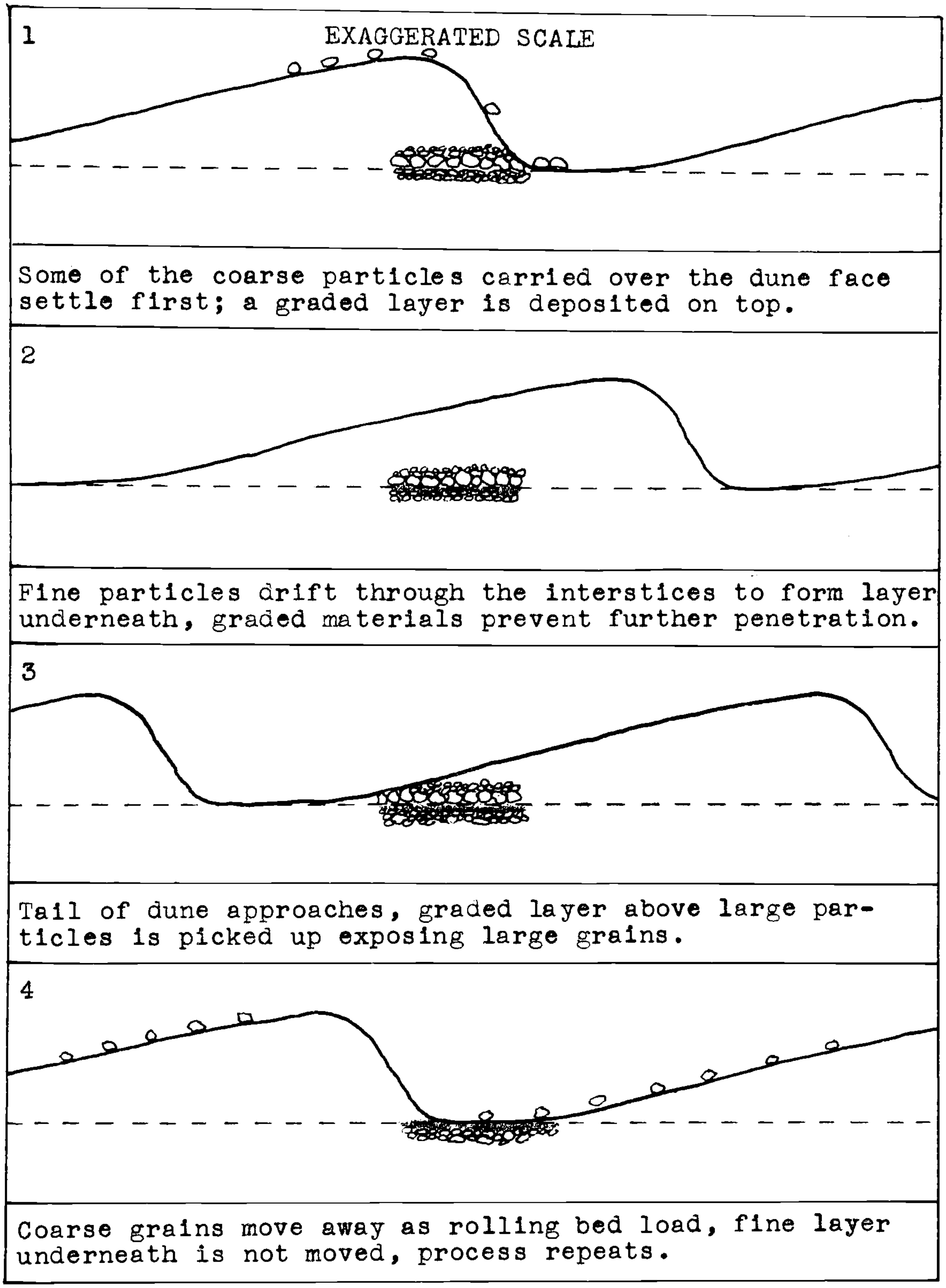


Figure 26 Sequence of Fine Layer Formation in Bed

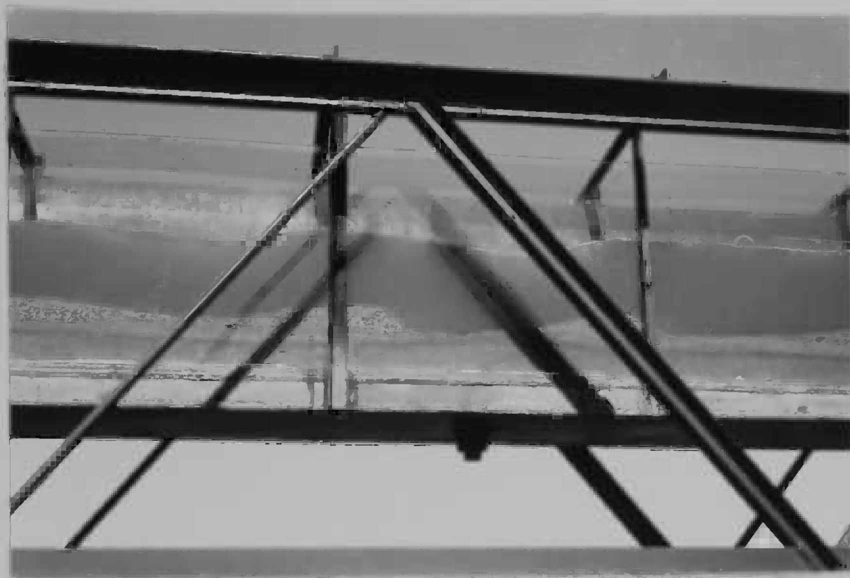


Figure 27 Continuous Fine Layer in Bed

Figure 28 Layering Within Dune Structure

Other layering patterns were seen in the dunes themselves similar to those noted by Jopling (20) and shown in Figure 28. Raking the bed when there was flow in the channel with high suspended sediment index produced some unusual layering patterns. Compaction of the bed always followed flow in the channel; shoveling and turning the bed increased its volume by a third. Flow in the bed was unsaturated for all tests although saturation probably existed above the fine layer formed under the dunes.

Time

With each change in velocity or suspended sediment index a period of time was required to reach an equilibrium between the bed and the sediment load. Figure 29 shows the change in infiltration rate with time at a flow velocity of 3 feet per second for two changes in the suspended sediment index. Similar results were obtained for velocities of 4 and 5 feet per second. At 2 feet per second the sediment transporting capacity of the flow was so low that a change in suspended sediment index from 0.02 to 0.07 percent caused a dramatic decrease in infiltration rate; a layer started to form on the surface; but no equilibrium was attained. Further increase in the suspended sediment index only caused an increase in the thickness of the layer.

Intermittant flow in the channel always resulted in increased infiltration rates when there was no silt

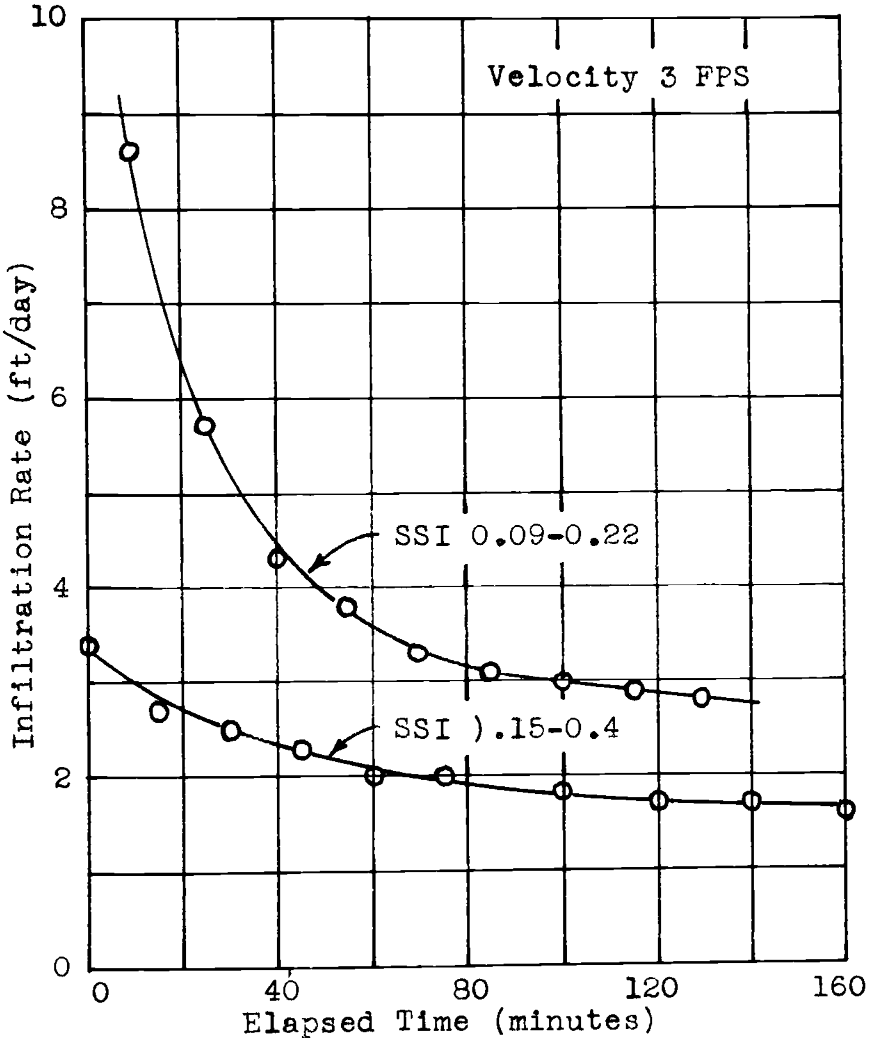


Figure 29 Infiltration Rate vs. Time for Changes in Suspended Sediment Index

layer on the surface. The increase was greatest immediately after flow started and no longer in evidence after about 90 minutes. With a silt layer on the surface of the bed there was no significant increase in infiltration rate when flow was started after having been shut off for several hours.

Temperature

Temperatures varied from 62°F to 90°F during the test period and by a maximum of 16° during one test. All measured infiltration rates were adjusted to a temperature of 68°F by a correction factor of viscosity at measured temperature/viscosity at 68°. Other effects of temperature such as those on fall velocity and dune formation cannot at this time be isolated.

Infiltrate

The sediment content of the infiltrated water usually was related to the suspended sediment index and varied from less than 25 ppm to about 1000 ppm or 0.1 percent except following a disturbance of the bed. Because fine material could pass through the screen over the perforated bottom plate, the drain channel always had some sediment in it. When flow was started, the infiltrate would be noticeably silty, but this soon cleared to about 100 ppm of turbidity. Following turning or raking of the bed material the sediment content of the infiltrate was very high, clearing after 20 or 30 minutes. Because of these characteristics no detailed analyses of the sediment content or turbidity of the infiltrate were made.

Errors

Two possible sources of errors exist in an investigation of this type. First and probably least serious are the instruments used for direct measurement or computations based on measurements. Included in this category are the stopwatches, flow meters, graduated cylinders, calibrated pails, scales, etc., where the error did not likely exceed five percent of any single measured quantity.

Second and more important are the errors that might result from the procedure used in operating the flume and in making the observations of non-measureable phenomena which depend on the operator's judgement. The inability to adequately describe the bed conditions limits the repeatability of the results. Procedures used in the investigation were designed to duplicate the happenings of a natural channel, and as operator experience increased a closer similarity was achieved. Flume studies are based on averages, and the data obtained must be so considered; the relative values of the results are more important than absolute values.

CORRELATION WITH FIELD DATA

In attempting to correlate the flume results with the flow losses in natural channels in the Tucson area the lack of data on floods is immediately apparent. Missing are their dimensions--length, width, depth, and their sediment content. By estimating some of these quantities, however, a degree of correlation can be obtained.

Flow Losses Between Gaging Stations

Figure 30 shows the location of the U. S. Geological Survey gaging stations in the Tucson area. The mileage figures are the length of the channel between stations or confluences of streams. Analyses were made of flow losses between Continental and Tucson; between Tucson, Rillito Creek and Cortaro; and between Vail and Rillito Creek.

For the 26.4 mile reach in the Santa Cruz River between Continental and Tucson all average daily flows larger than 10 cubic feet per second (cfs) at Continental were tabulated with the flow at Tucson for the same day for the 10-year period October 1953 to September 1963. When flow at Continental exceeded that at Tucson the difference was plotted against the discharge at Continental in Figure 31 with lines representing 100, 50, and 25 percent loss. The largest relative loss occurred with an average daily

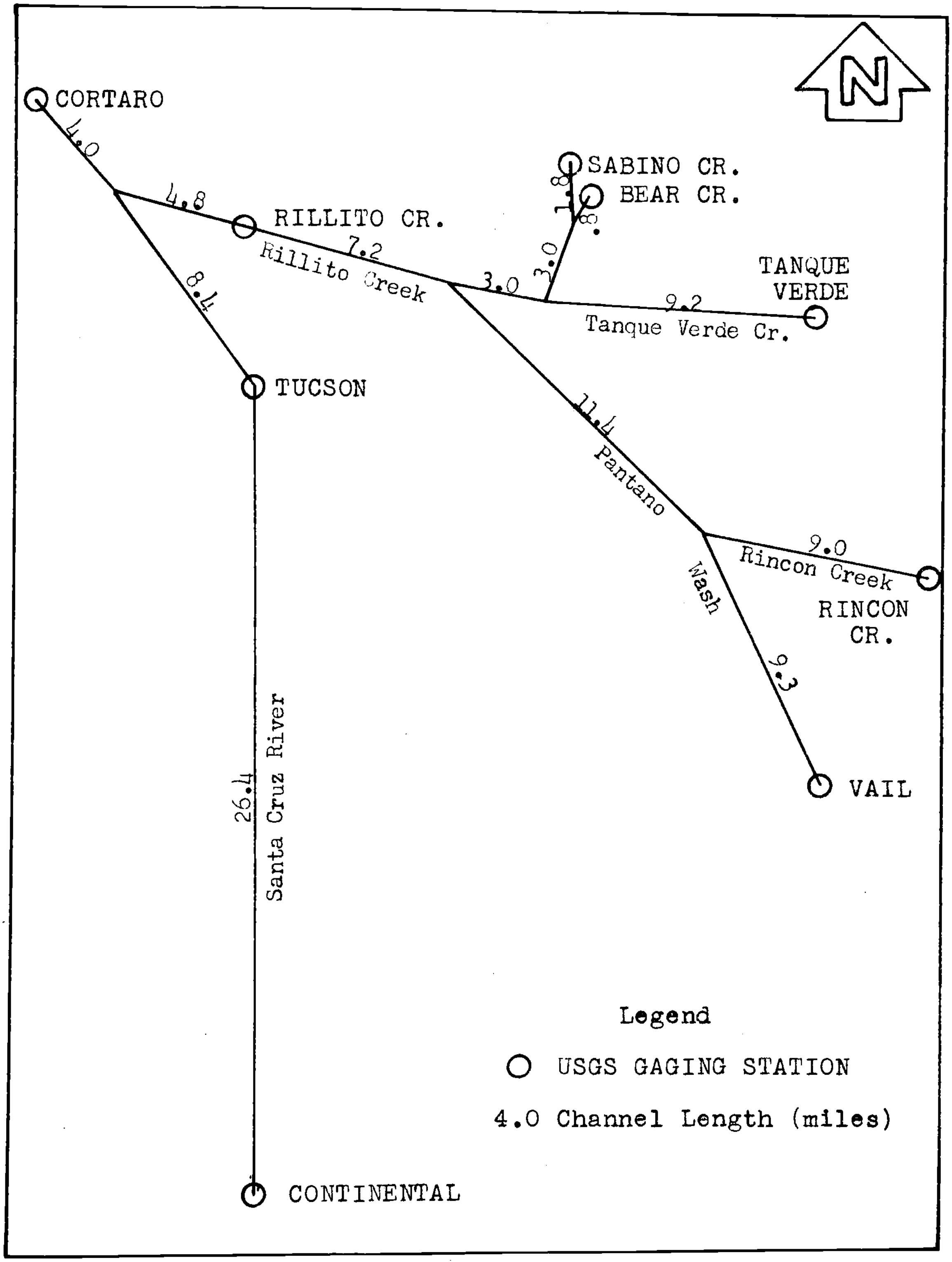


Figure 30 Tucson Area Drainage

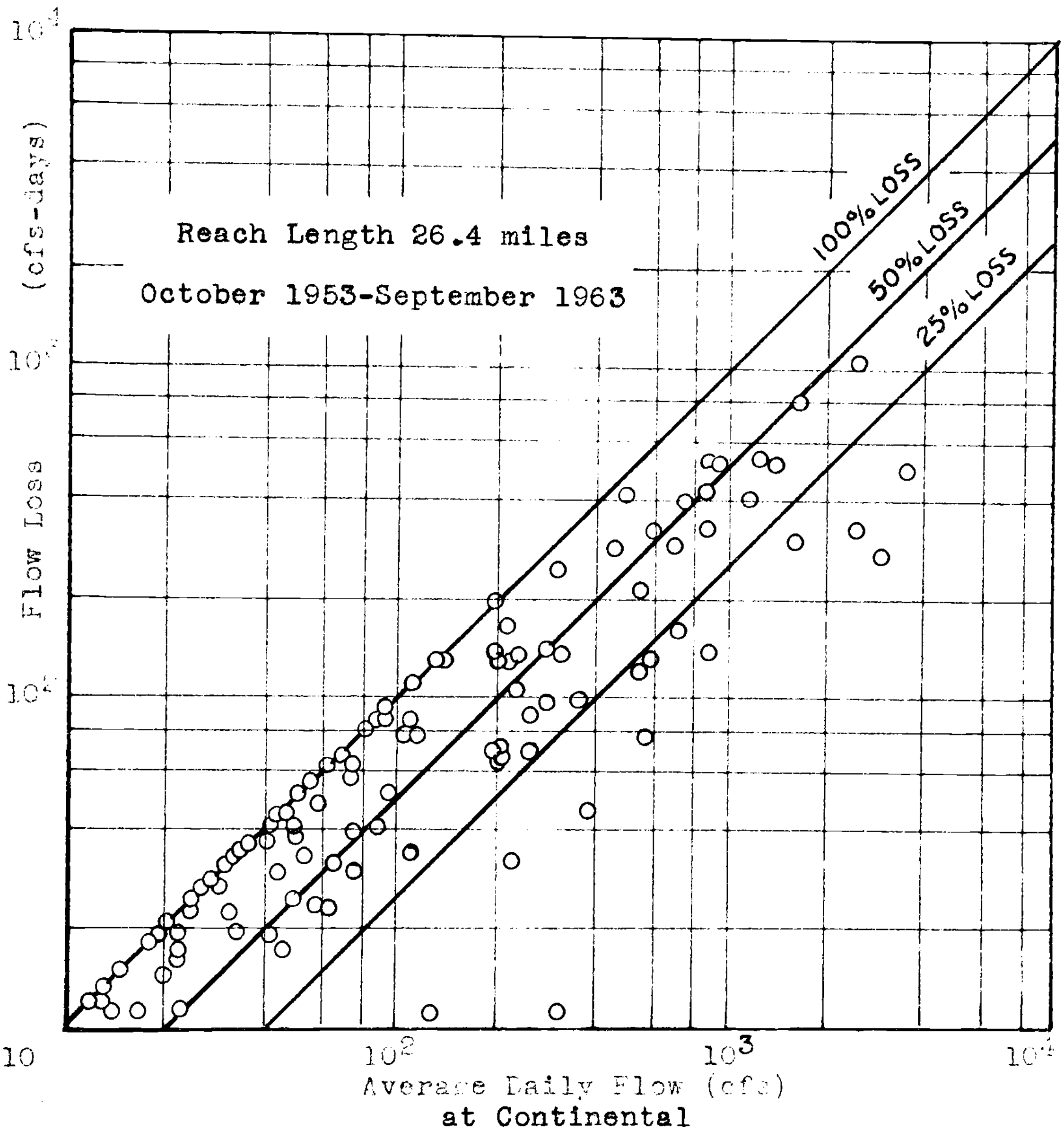


Figure 31 Flow Loss vs. Discharge
Continental to Tucson

flow of 195 cfs; the largest absolute loss, 1050 cfs-days, with an average daily flow of 2370 cfs. Not plotted were differences occurring on days when the flow at Tucson was greater the following day to avoid including losses caused by the time lag between the stations.

For average daily flows up to about 200 cfs there is a relationship between discharge and channel area such that increased discharge results in increased infiltration. At about 200 cfs the flow covers the full channel width. Because width does not increase appreciably with further increases in discharge, any increase in infiltration must result from increases in velocity and depth. Absolute values of infiltration increase above 200 cfs, but the percentage loss appears to decrease.

Of the 120 days when a difference existed, 61 percent showed a loss of more than 50 percent of the flow, 26 percent a loss of 25 to 50 percent, and 13 percent a loss less than 25 percent. The low percentage losses probably are incorrect because of the contributions from the numerous ungaged side washes.

Table VIII is an analysis of the losses for the flows of largest relative and absolute loss. The results compare favorably with the flume results for like velocities. Since flow in the Santa Cruz River channel is always silty, the suspended sediment index for these flows

TABLE VIII

ANALYSIS OF FLOW LOSSES CONTINENTAL TO TUCSON		
	Maximum Relative Loss	Maximum Absolute Loss
Average Daily Discharge		
Continental cfs	195	2370
Tucson cfs	0	1320
Difference cfs-days	195	1050
Reach Length miles	26.4	26.4
Loss acre-feet/mile	15	80
Channel Width feet	40	100
Channel Area acres/mile	5	12
Velocity FPS	2-3	5-8
Infiltration Rate ft/day	3	6.7
Comparable Flume Data		
Suspended Sediment Index percent	0.3	
Infiltration Rate ft/day (estimated for SSI above 0.6 percent and velocity above 5 FPS)	2	10

would probably approach the maximum for the particular velocity.

Similar analyses for maximum losses in the Tucson and Rillito Creek to Cortaro, and Vail to Rillito Creek reaches are given in Tables IX and X for the flow differences plotted in Figures 32-35. Again the results are consistent with the flume data except where there is doubt about the contribution to flow between the stations. For the Vail-Rillito Creek reach only those days were plotted when the other four stations of the Pantano Wash-Rillito Creek system had negligible flow.

Figure 36 shows the relationship for infiltration rate between stations and discharge at the upper station for all the flow losses analyzed in Tables VIII-X. The two values for the Tucson to Cortaro reach show a decrease in infiltration rate with increasing discharge. The apparently low loss for a large flood could result from ungaged side channel inflow. The remarkably high infiltration rate for the smaller discharge cannot be explained.

Natural Recharge

Two special studies were made of the natural recharge in Rillito Creek. The first by Schwalen (44) was for the period from March, 1959 to March, 1960 when an unusually long period of spring runoff occurred. A water budget analysis was made for the 1-year period based on

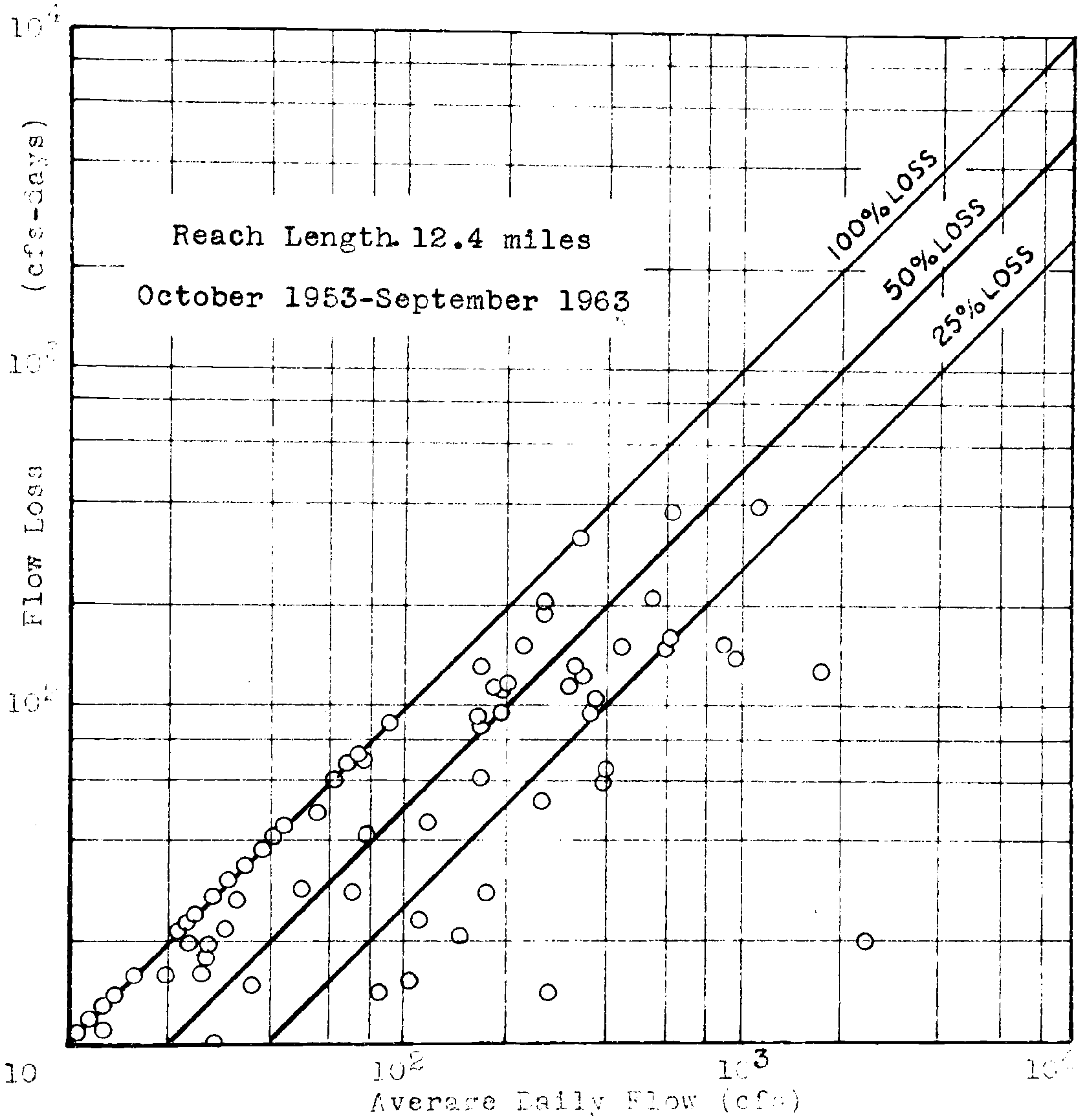
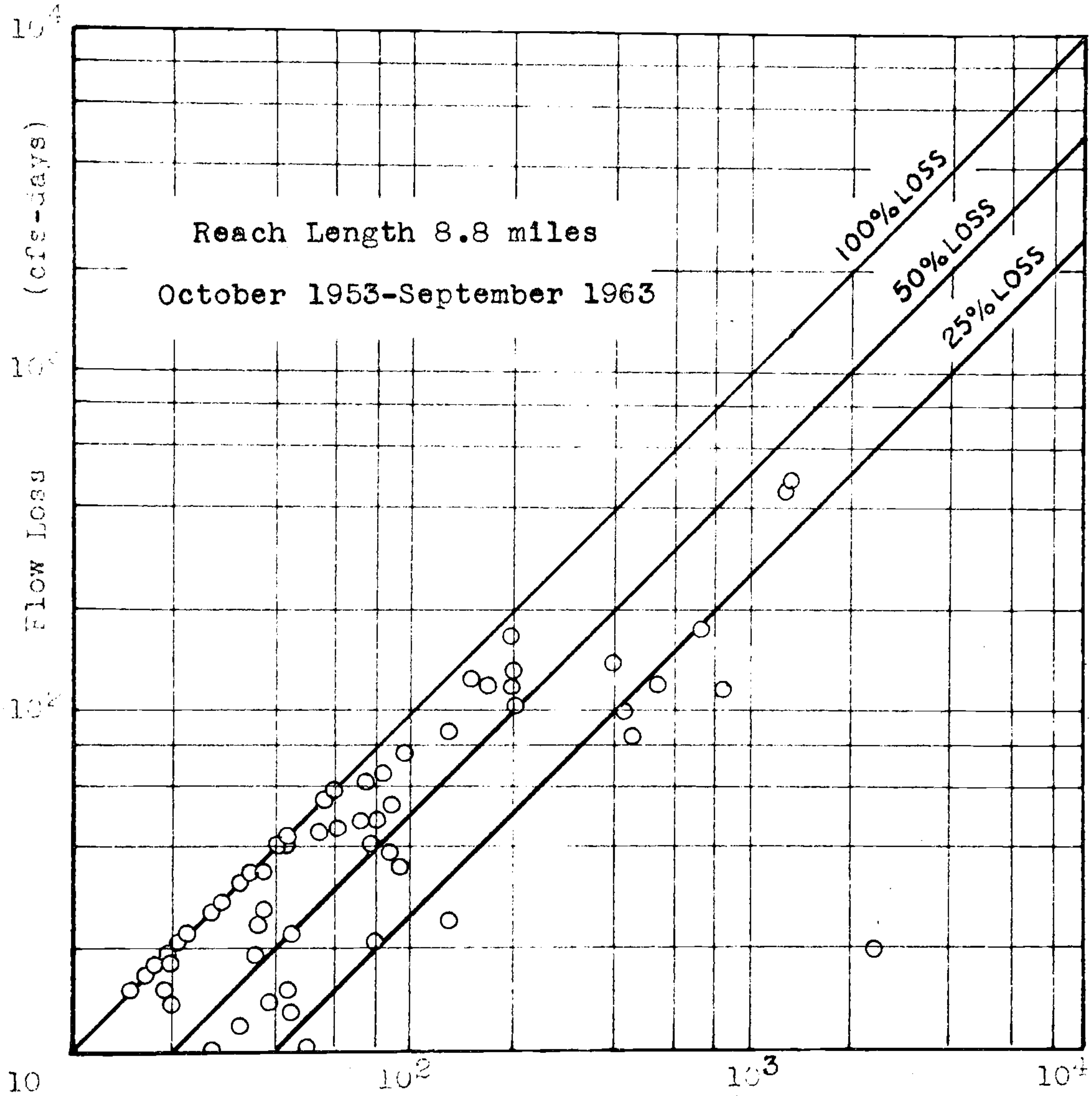


Figure 32 Flow Loss vs. Discharge--Tucson to Cortaro



at Rillito Creek

Figure 33 Flow Loss vs. Discharge
Rillito Creek to Cortaro

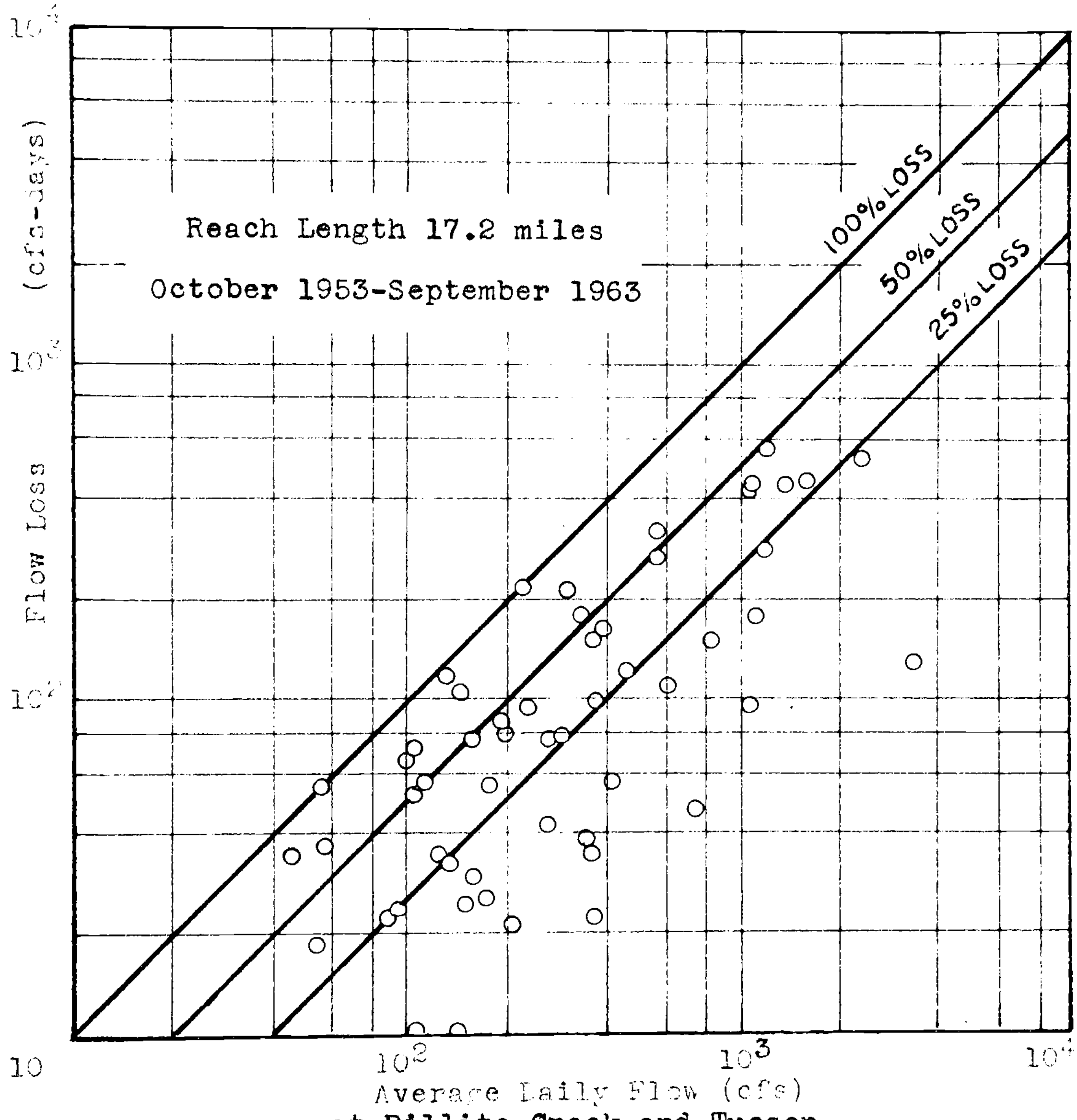


Figure 34 Flow Loss vs. Discharge
Tucson and Rillito Creek to Cortaro

TABLE IX

ANALYSIS OF FLOW LOSSES
RILLITO CREEK AND TUCSON TO CORTARO

	Maximum Relative Loss			Maximum Absolute Loss		
Average Daily Discharge						
Tucson cfs	325	0	Both 220	1110	0	Both 3950
Rillito Creek cfs	0	57		0	1320	
Cortaro cfs	0	0	0	720	825	3150
Difference cfs-days	325	57	220	390	495	800
Reach Length miles	12.4	8.8	17.2	12.4	8.8	17.2
Loss acre-feet/mile	52	13	26	64	110	94
Channel Width feet	60	20	40	80	80	100
Channel Area acres/mile	7	3	5	10	10	12
Velocity FPS	3-4	2-3	2-3	4-5	5-8	8-10
Infiltration Rate ft/day	7.4	4.3	5.2	6.4	11	7.8
Comparable Flume Data						
Suspended Sediment Index percent	0.5	0.2	0.4			
Infiltration Rate ft/day (estimated for SSI above 0.6 and velocity above 5 FPS)	6	3	2	8	10	10

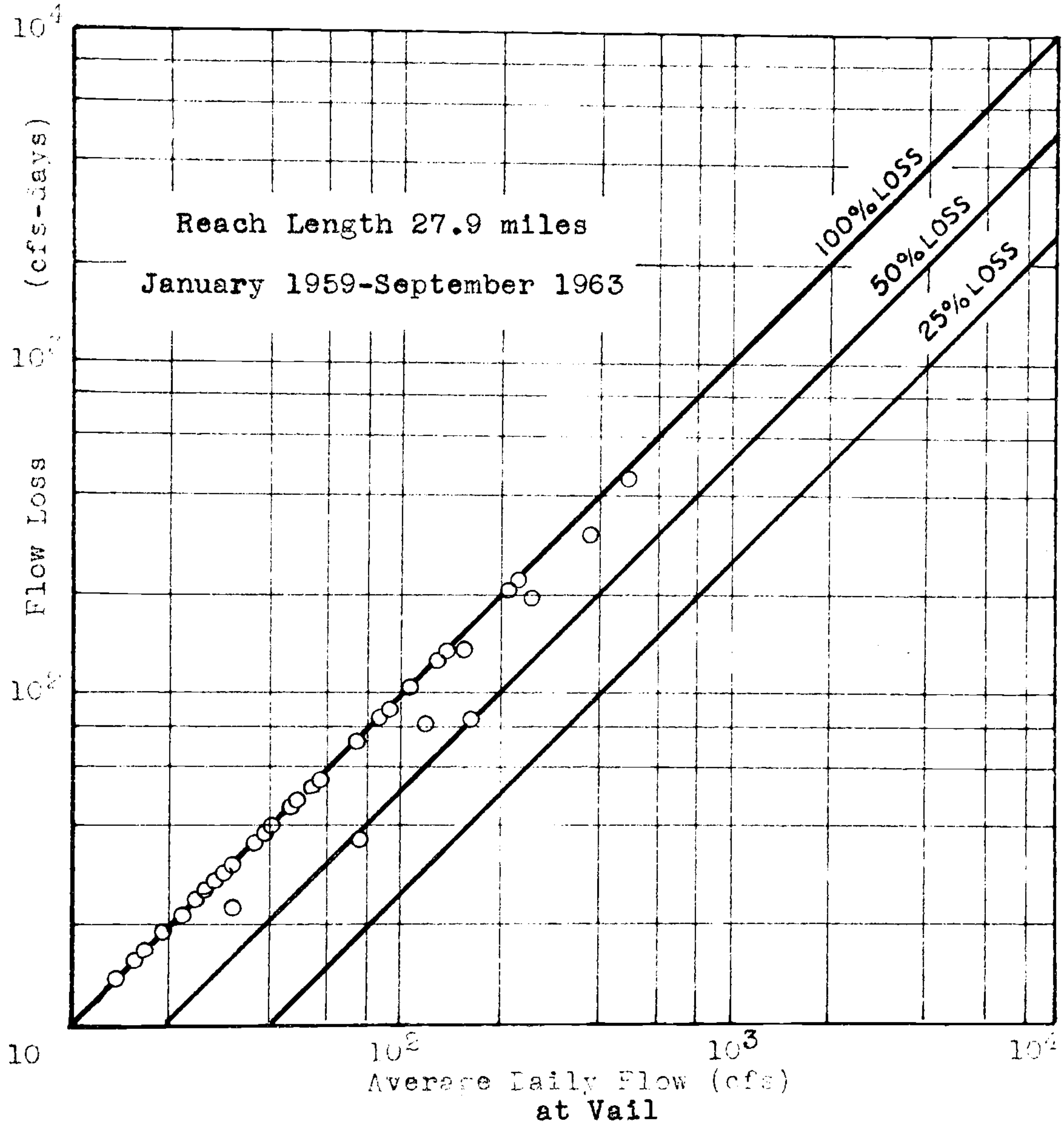


Figure 35 Flow Loss vs. Discharge
Vail to Rillito Creek

TABLE X

ANALYSIS OF FLOW LOSSES VAIL TO RILLITO CREEK

	Maximum Relative Loss	Maximum Absolute Loss
Average Daily Discharge		
Vail cfs	220	480
Rillito Creek cfs	0	15
Difference cfs-days	220	465
Reach Length miles	27.9	27.9
Loss acre-feet/mile	16	33
Channel Width feet	40	60
Channel Area acres/mile	5	8
Velocity FPS	2-3	4-5
Infiltration Rate ft/day	3.2	4.1*
Comparable Flume Data		
Suspended Sediment Index percent	0.3	
Infiltration Rate ft/day (estimated for SSI above 0.6 percent and velocity above 5 FPS)	2	10

*Flow may not have been continuous between stations

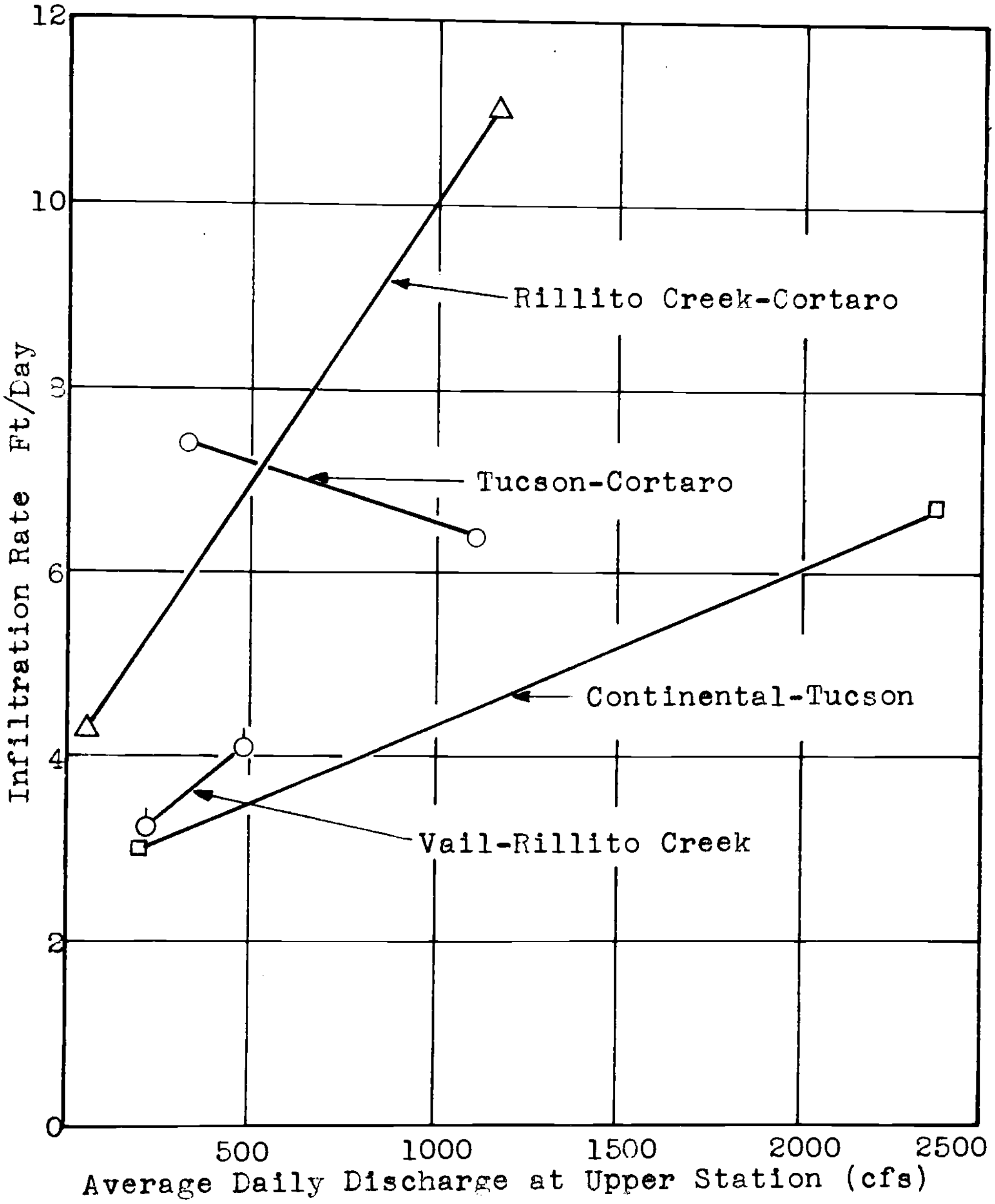


Figure 36 Infiltration Rate vs. Discharge at Upstream Station--Tucson Area

gaging station records, estimates of ungaged flow, net recharge to groundwater from increases in water level in wells (assuming 12 percent specific yield), and use of water by phreatophytes, irrigation and domestic wells. This recharge occurred over an area of about 20 miles of channel. Further analysis of the results of this study is shown in Table XI. The infiltration rate of 2.8 feet per day obtained is low because it is based on net recharge and does not include evaporation loss from the wetted channel. Also much of the effective flow occurred during cold weather when water temperatures were low.

The second study made in the Spring of 1962 was concerned only with the relatively clear runoff from melting snow. For a four month period of almost continuous flow observations were made of wetted channel area, and discharge measurements were made with a current meter and by the float-area method. An average infiltration rate of 3.6 feet per day occurred over a 16 mile reach with a maximum of 6.5 feet per day and a minimum of 2.4 feet per day. Flow losses were from 4-7 cfs per mile. At first glance the infiltration rates appear to be somewhat low for the relatively clear water in comparison with the results of the flume studies, but for the period studied velocities were usually less than 2 feet per second. In addition water temperatures were low.

TABLE XI

NATURAL RECHARGE IN RILLITO CREEK MARCH 1959-MARCH 1960	
Surface Inflow	46,250 Acre-Feet
Surface Outflow	18,100
Net Loss	28,150
Recharge Remaining March 1960	14,500
Water Use	
Phreatophytes	3400
Irrigation	2800
Domestic	3000
Total	23,700
Unaccounted	4450
Reach Length	20 miles
Flow Loss	1410 AF/mile
Days Flow Effective	100 days
Daily Infiltration/Mile	14 AF/mile/day
Average Channel Width	50 feet
Channel Area	6 acres/mile
Average Velocity	2-3 FPS
Infiltration Rate	2.8 ft/day

Attempts to determine recharge from average annual flow at the USGS gaging stations cannot succeed because of the large amounts of ungaged inflow between stations. An analysis can be made based on an estimated average annual recharge of 70,000 acre-feet for the total area, a figure obtained in previous studies. (44) Results of this analysis are shown in Table XII and again appear plausible and consistent with the flume studies. Actual infiltration rate would be higher if the loss by evaporation from the wetted channel could be evaluated.

Recharge of Sewage Effluent

A study of recharge from sewage effluent flow in the Santa Cruz River channel was made for a 30-day period in 1964 by the Agricultural Engineering Department. For the 6-mile reach between the City of Tucson sewage treatment plant and the USGS gaging station at Cortaro a loss of 3.3 cfs per mile was found with an average infiltration rate of 2 feet per day. Velocity varied from 0 to 3 feet per second. The silt content was negligible, but higher velocity flow contained some settleable solids from the sewage plant. Below the Cortaro gage losses of only 1 cfs per mile occurred. The reduced rate below the gage is attributed to the lower velocities and consequent biological accumulation. Above the gaging station the peak

TABLE XII

ANALYSIS OF NATURAL RECHARGE IN TUCSON AREA	
Average Annual Recharge	70,000 Acre Feet
Total Channel Length (includes 25 miles ungaged)	115 miles
Recharge per mile	600 AF/mile
Average Channel Width	50 feet
Channel Area	6 acres/mile
Average Days of Flow	30 days
Daily Recharge per mile	20 AF/mile/day
Infiltration Rate	3.3 ft/day

velocities were sufficient to "clean" the channel daily. The infiltration rate of 2 feet per day is reasonable for the low average velocity and the solids content of the water. A lower rate would probably result for the same total flow if it were released at a constant velocity.

Summary

The overall correlation of the field data with the flume results is good. The analyses of flow losses between gaging stations are particularly encouraging. Measurements to replace the estimated quantities, and the division of the channel into smaller sections for more complete description should lead to closer correlation. The natural recharge studies in Rillito Creek are also consistent with the flume study. Of interest is the fact that the dramatic flow losses of the spring runoff are not occurring with a high infiltration rate because of velocity and temperature limitations. The real importance of this runoff is in its duration. The artificial recharge of sewage effluent in the Santa Cruz River is hydraulically feasible, but the low infiltration rate shows the need for improving the quality of the water discharged into the channel or releasing the water at higher rates to increase the flow velocity.

CONCLUSIONS

Preliminary Experiments

The results of the preliminary tests made on samples from Rillito Creek to obtain more detailed information about an alluvial channel will support the following conclusions.

1. The characteristics of the bed material are extremely variable and, in general, reflect the past history of the channel. The coarser material is found near the mountains with increasingly fine materials downstream, but side channel inflow has some modifying effect. The sediments 6 inches below the surface are slightly more uniform than those on the surface.

2. The suspended sediment content of flood waters is also quite variable and depends on the source of the flood waters, flow velocity, and bed conditions. Relatively clear flow in Rillito Creek increased in sediment content with distance as fine materials were picked up from the bed. When velocity decreased, consequently reducing the capability to transport the suspended material, the sediment content decreased. Silty flow increased in suspended sediment with distance downstream as additional runoff carrying large amounts of fine material entered the channel from side washes.

3. Disturbed sample permeability tests of river bed sediments show the same variation as do the mechanical analyses of the samples. The coarser and/or more uniform samples have higher permeabilities than do the finer and/or less uniform samples. The downward flow of silty water through the samples causes a rapid reduction in permeability, but does not produce the same type of silt deposits seen in the river bed.

4. Cylinder infiltration tests using clear water in the dry river channel with no visible silt deposit show infiltration rates of hundreds of feet per day for a short time, tens of feet per day for longer periods. A silt layer of only 1/16 to 1/8-inch thickness reduced infiltration rates markedly while a 3 to 4 inch thick silt layer permitted essentially no infiltration.

Flume Experiments

Flow in the flume was essentially two-dimensional with little or no opportunity for meandering or bank undercutting which are important processes in a natural channel. Recognizing this limitation the following conclusions can be drawn from the flume study.

1. Infiltration rates vary with the flow velocity in the range from 2 to 5 feet per second. Below 2 feet per second the infiltration rate may be higher for relatively clear water than it is for higher velocities with consequent

bed movement, but silty water will result in an immediate decrease in infiltration rate and ultimate bed sealing. Velocities above 5 feet per second were not studied but with dune action should have higher infiltration rates because of the increasing percentage of fine material in suspension. The increase can continue until the permeability of the bed surface is no longer the limiting factor. The relationship between infiltration rate and velocities under plane-bed conditions cannot be determined from the results available.

2. For a constant flow velocity in an alluvial channel the infiltration rate will have an inverse relationship to the concentration of the suspended sediment. With clear water, particle rearrangement and packing at the bed surface will reduce the infiltration rate and provide a limit. With silty water the bed will adjust to achieve an equilibrium with the flow conditions resulting in deposition and reduced infiltration rates or pick up of fine material and increased infiltration rates.

3. Streambed adjustment to a change in suspended sediment content through the removal or deposition of fine materials will require a finite period of time.

4. The concept that a wash load composed of fine materials can be carried without any effect on the bed composition cannot be accepted. Any material found in the

flow must be also found in the bed as demonstrated by the immediate decrease in infiltration rate on adding "wash load" materials. The layering of fine material under the zone of dune action would further increase the requirement of fine material beyond that in the moving bed material supporting the suspended concentration.

5. The past history of a natural channel may be the most important single factor in determining the infiltration rate. In addition to the flood flows and the changes they make in the streambed, man's use of the channel must be considered. Pits dug for sand supply will become lined with silt quickly when flow starts producing a limiting layer at a depth where its removal by natural phenomena is extremely unlikely. Silty waste waters are frequently discharged in the channel increasing the silt content of the bed and reducing infiltration rate. Increasing channel width for flood control purposes reduces average flow velocity and consequently the sediment transporting capacity. Silt bars are deposited, native vegetation starts to grow, and the river attempts to return to its previous width. Some uses of the river during dry periods between floods may, however, improve infiltration rates by breaking up any previously deposited silt layers.

6. Disturbed sample laboratory permeability tests or infiltration tests of dry river bed materials can have

results as much as 100 times higher than those found in natural channels with flowing water. Low permeability layers formed at the surface or below the zone of dune action provide the ultimate limit for infiltration rates with flowing water. The areal extent of the layers will be more important than their thickness although complete sealing may require a silt deposit several inches thick.

Application of Results

One immediately evident use of the results would be in predicting the recharge from a given flood event when flow regime, evaporation loss, and sediment transport information are available. A reach in the river could be rated for discharge vs. infiltration rate. With suitable storage facilities floods can be managed to provide optimum recharge. Detention will reduce the sediment content, and release at controlled velocities will minimize the effects of the remaining sediment. Channels can be designed to maintain velocities for floods of different size and can also be treated between floods by scarifying or other processes to improve infiltration rates.

To extend the results of the investigation other factors affecting the velocity, sediment load, and bed materials must be considered. More data must be obtained concerning flood hydrology in ephemeral channels. What is the relation between rainfall and runoff? How much is the character of the sediment load influenced by the source of the flood? What are the dimensions of the most important floods from the standpoint of recharge--width, length, duration, frequency, velocity, sediment load, etc.?

Disposition of the water that infiltrates through the bed is not completely known. How does the water move away from the stream bed? What is the evaporation loss from the wetted channel?

The long term effects of channel modification must be studied in order to minimize the bad effects and maximize the good. More consideration of ephemeral channels as an important natural resource for groundwater recharge is warranted. Possible treatments for the surface layer to improve the infiltration rates can be investigated to determine their economic feasibility.

Because the infiltration process in sandy channels is closely related to dune action another area for increased study is the significance of dune formation not so much from the standpoint of the individual dunes but, rather, the overall effect of the dune pattern on the streambed infiltration characteristics.

LIST OF REFERENCES

1. Babcock, H. M. and E. M. Cushing, "Recharge to Ground Water from Floods in a Typical Desert Wash," Trans AGU, Vol. 23, 1942, pp. 49-56.

2. Banks, H. O. and others, "Artificial Recharge in California," paper presented before the Hydraulics Division, ASCE, Austin, Texas, Sept. 1954.

3. Baver, L. D., Soil Physics, John Wiley and Sons, Inc., 1956, pp. 247-261.

4. Behnke, Jerold J. and Leonard Schiff, "The Hydraulic Conductivity of Selected Uniform, Stratified, and Mixed Sands with Emphasis on Groundwater Recharge Problems," paper presented at 2nd Western National Meeting AGU, Stanford, Calif., Dec. 1962.

5. Behnke, Jerold J. and Leonard Schiff, "Hydraulic Conductivity of Uniform, Stratified, and Mixed Sands," Journal of Geophysical Research, Vol. 68, No. 16, 1963, pp. 4769-4775.

6. Bouwer, H erman, L. E. Myers and R. C. Rice, "Effect of Velocity on Seepage and Its Measurement," Trans ASCE, Vol. 128, Pt. III, 1963, pp. 279-292.

7. Conkling, Harold, "Utilization of Groundwater Storage in Stream System Development," Trans ASCE, Vol. 111,

8. Cornish, John H., "Flow Losses in Dry Sandy Channels," Journal of Geophysical Research, Vol. 66, No. 6, 1961, pp. 1845-1853.

9. Crooke, Howard W. and John M. Toups, "Groundwater Basin Management and Artificial Recharge in Orange Co., California," U. S. Dept. of Agriculture, Agricultural Research Service, Proc. 1961 Biennial Conference on Ground Water Recharge, 1962.

10. Curry, R. Bruce and R. P. Beasley, "Flow of Colloidal Suspensions Through Porous Media as Related to Reservoir Sealing," Trans ASAE, Vol. 5, No. 2, 1962, pp. 160-164.

11. Duley, F. L., "Surface Factors Affecting the Rate of Intake of Water By Soils," Proc. Soil Science Society of America, Vol.4, 1939, pp. 60-64.

12. Eaton, E. Courtland, "Flood and Erosion Control Problems and Their Solution," Trans ASCE, Vol. 101, 1936, pp. 1302-1331.

13. Fair, Gordon M. and John C. Geyer, Water Supply and Waste Water Disposal, John Wiley and Sons, Inc., 1954, pp. 665-666.

14. Ghosh, Gaurchandra, "Media Characteristics in Water Filtration," Proc. ASCE, Journal of the Sanitary Engineering Division, Vol. 84, No. SA1, 1958, paper 1533.

15. Grover, Ben L. and others, "The Effects of Surface Sediments on Water Spreading," paper presented at 2nd Western National Meeting AGU, Stanford, California, Dec. 1962.

16. Haise, Howard R. and others, "The Use of Cylinder Infiltrometers to Determine the Intake Characteristics of Irrigated Soils," U. S. Dept. of Agriculture, Agricultural Research Service, ARS 41-7, 1956.

17. Harmeson, Robert H. and Orville W. Vogel, "Artificial Recharge and Pollution of Ground Water," Ground Water, Vol. 1, No. 1, 1963, pp. 11-15.

18. Hydrology Handbook, ASCE Manuals of Engineering Practice No. 28, 1949, pp. 61-62.

19. Johnson, A. I., "A Field Method for Measurement of Infiltration," U. S. Geol. Survey Water Supply Paper 1544-F, 1963.

20. Jopling, Alan V., "Laboratory Study of Sorting Processes Related to Flow Separation," Journal of Geophysical Research, Vol. 69, No. 16, 1964, pp. 3403-3418.

21. Karr, William V., "Organic Sediments in River Beds," Ground Water, Vol. 1, No. 3, 1963, p. 12.

22. Kazmann, Raphael G., "River Infiltration as a Source of Ground Water Supply," Trans ASCE, Vol. 113, 1948, pp. 404-421.

23. Kazmann, Raphael G., "The Induced Infiltration of River Water to Wells," Trans AGU, Vol. 29, No.1, 1948, pp. 85-89.

24. Kazmann, Raphael G., discussion of (23), Trans AGU, Vol. 29, No. 6, 1948, pp. 928-929.

25. Keppel, R. V. and K. G. Renard, "Transmission Losses in Ephemeral Sand-Gravel Bed Streams of the Southwest," Proc. ASCE, Journal of the Hydraulics Division, Vol. 88, Hy3, 1962, pp. 59-68.

26. Klaer, Fred H. Jr., "Bacteriological and Chemical Factors in Induced Infiltration," Ground Water, Vol. 1, No. 1, 1963, pp. 38-43.

27. Kramskey, Meyer, "Artificial Methods of Ground Water Recharge," paper presented at the annual meeting ASAE, Santa Barbara, California, June, 1958.

28. Laursen, Emmett M., miscellaneous class lectures in Sediment Transportation, Univ. of Arizona, 1964.

29. Laverty, Finley B., "Correlating Flood Control and Water Supply, Los Angeles Coastal Plain," Trans ASCE, Vol. 111, 1946, pp. 1127-1144.

30. Lee, Charles H., "The Determination of Safe Yield of Underground Reservoirs of the Closed Basin Type," Trans ASCE, Vol. 78, 1915, pp. 148-218.

31. Mitchelson, A. T. "Underground Storage by Spreading Water," Trans AGU, Vol. 15, 1934, pp. 522-523.

32. Mitchelson, A. T. and Dean C. Muckel, "Spreading Water for Storage Underground," U. S. Dept. of Agriculture, Tech. Bull. 578, 1937.

33. Muckel, Dean C., "Replenishment of Ground Water Supplies by Artificial Means," U. S. Dept. of Agriculture, Agricultural Research Service, Tech. Bull. 1195, 1959.

34. Muckel, Dean C., "Some Factors Affecting the Rate of Percolation on Water Spreading Areas," Trans AGU, Vol. 17, 1936, pp. 471-474.

35. Muckel, Dean C., "Water Spreading for Ground Water Replenishment," Agricultural Engineering, Vol. 29, No. 2, 1948, pp. 74-76.

36. Musgrave, G. W. and G. R. Free, "Preliminary Report on a Determination of Comparative Infiltration Rates on Some Major Soil Types," Trans AGU, Vol. 18, 1937, pp. 345-349.

37. Peterson, H . V., discussion of (25), Proc. ASCE, Journal of the Hydraulics Division, Vol. 88, HY5, 1962, pp. 339-343.

38. Richter, R. C. and R. Y. D. Chun, "Artificial Recharge of Groundwater Reservoirs in California,"paper presented to the Irrigation and Drainage Division, ASCE, Cleveland, Ohio, May 1959.

39. Robinson, A. R. and Carl Rohwer, "Measuring Seepage from Irrigation Channels," U. S. Dept. of Agriculture, Agricultural Research Service, Tech. Bull. 1203, 1959.

40. Schiff, Leonard, "The Status of Water Spreading for Ground Water Replenishment," Trans AGU, Vol. 36, No. 6, 1955, pp. 1009-1020.

41. Schiff, Leonard, "Ground Water Recharge Methods Based on Site Characteristics and on Sediment in Flood Water," International Commission on Irrigation and Drainage, Proc. 5th Congress, Vol. 18, pp. 17-31.

42. Schiff, Leonard and Curtis E. Johnson, "Some Methods of Alleviating Surface Clogging in Water Spreading with Emphasis on Filters," Trans AGU, Vol. 39, No. 2, 1958, pp. 292-297.

43. Schiff, Leonard and others, "Activities of the Ground Water Recharge Research Project," U. S. Dept. of Agriculture, Agricultural Research Service, Proc. 1961 Biennial Conference on Ground Water Recharge, 1962.

44. Schwalen, H. C., unpublished data, Agricultural Engineering Dept., Univ. of Arizona.

45. Sharp, A. L. and K. E. Saxton, "Transmission Losses in Natural Stream Valleys," Proc ASCE, Journal of the Hydraulics Division, Vol. 88, HY5, 1962, pp. 121-142

46. Sonderegger, A. L., "Remarks on Water Spreading," Trans AGU, Vol. 17, 1936, pp. 474-476.

47. Thomas, H. E., "Artificial Recharge of Ground Water by the City of Bountiful, Utah," Trans AGU, Vol. 30, No. 4, 1949, pp. 539-542.

48. Tibbetts, Fred H., "Water Conservation Project in Santa Clara County," Trans AGU, Vol. 17, 1936, pp. 458-465.

49. Todd, David K., Ground Water Hydrology, John Wiley and Sons, Inc., 1959, pp. 50-52, 255.

50. Turner, S. F. and others, "Ground Water Resources of the Santa Cruz Basin, Arizona, U. S. Geol. Survey Report, Tucson, Arizona, May 1943, pp. 35-53.

51. Volk, K. Q., "Economic Limits of Conservation of Flood Waters by Spreading," ASCE, Report on Progress Conference on Water Conservation, March 1935, p. 43.

52. Whetstone, George A., "Mechanism of Ground Water Recharge," Agricultural Engineering, Vol. 35, No. 9, 1954, pp. 646-647, 650.