THE EFFECT OF SUSPENDED SEDIMENT AND DISCHARGE ON NATURAL INFILTRATION OF EPHEMERAL STREAMS

by

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ABSTRACT

Studies were conducted to evaluate the effects of suspended sediment and stream discharge, and their interrelationships, on intake rates in the Santa Cruz River. A lysimeter-flume, 100 feet long, 2 feet wide, and 5 feet deep, was constructed at the Field Laboratory. The interior boundaries of the unit were lined with butyl rubber to prevent leakage. A perforated pipe line was installed in the bottom of the lysimeter-flume to permit drainage of percolating water.

The unit was filled with representative materials from the contiguous river bed. Control sections were installed immediately before and after the flume to promote stabilization of flow conditions through the unit. A six-inch Parshall flume was located at the inlet of the upstream control section for measuring application rates during testing. A steel hopper, constructed and installed near the upstream control section, was used to store and meter sediment into the applied water in controlled amounts. The water supply for testing was obtained from the Field Laboratory.

Three flow rates, 300 gpm, 450 gpm and 600 gpm, and three sediment concentrations, 10,000 ppm, 20,000 ppm, and 30,000 ppm, were selected for experimentation. The nine possible treatment combinations from these application rates were replicated twice, so that a total of 18 trials were conducted. The combinations were tested in random order. During each trial, water and suspended sediment were metered onto the

lysimeter-flume at the required rates. Infiltration rates were determined by measuring the discharge from the interior drain line.

Recharge rates varied from 4.2 feet/day to 5.0 feet/day in the streambed model. In general, the effects of discharge and suspended sediment in Santa Cruz materials were similar to those reported for Rillito Creek materials. Increasing discharge rates appeared to increase infiltration rates indirectly through the effect of stream velocity on bed erosion and sedimentation. Increasing suspended sediment concentrations were found to be highly significant in reducing infiltration rates.

INTRODUCTION

Ground water, contained in underground reservoirs, represents a major source of the fresh water supply in the southwestern United States. Demands on this source for irrigation, industrial and municipal purposes increase yearly and will become accentuated with the rapid increase in population and per capita requirement. The low precipitation level of the Southwest and the irregular distribution of surface water supplies has placed a heavy demand on ground water supplies.

Koenig (1963) in a paper on the extent of the ground water supply in the United States estimated that in 1963 the current amount of ground water capable of being pumped and used was about 47,500 million acre feet. The corresponding amount of available surface water which can be recovered and used was estimated to be 13,410 million acre feet. It was also estimated that the present length of withdrawal of the water supplies in the United States without replenishment would be 47.4 years for our surface water and 168 years for our ground water supply.

The favorable conditions which exist in many parts of the United States do not exist throughout the West, particularly in the Southwest. In Arizona, where the current ground water usage is the third highest in the nation, the annual extractions of ground water exceeds the net natural recharge by four million acre feet per year (Maddox and Resnick, 1962). As a consequence of this overdraft, the depth to water tables is declining and in many areas is approaching

500 feet, considered as the maximum level of economic withdrawal for agriculture.

Infiltration is an important parameter in the definition of the hydrologic system of a watershed. In setting up a hydrologic analysis program on a watershed such as the Santa Cruz River system the extent of natural infiltration through the stream bed is of primary importance in maintaining a usable ground water system. These factors which influence stream bed infiltration are stream discharge, suspended sediment, bed slope, temperature, water viscosity, antecedent moisture, and the hydraulic conductivity of the channel alluvium. It appears that the two principal factors effecting streambed infiltration are stream discharge and suspended sediment content. Matlock (1965) studied the interrelationships of stream discharge and suspended sediment load on infiltration rates in Rillito Creek sediments using a tilting bed flume. He found that infiltration rates in these sediments are proportional to stream velocity and inversely proportional to suspended sediment content. These trends are presumably definitive; however, it is felt that corroborative studies would be of value for the materials of other drainages of the Tucson Basin, such as those in the Santa Cruz River.

The objectives of the study reported herein were (1) to estimate the natural recharge rate of a portion of the Santa Cruz River, and (2) to determine the effects and interrelationships of discharge and suspended sediment on natural recharge in Santa Cruz River sediment. In order to achieve these objectives a stream channel model study was constructed contiguous to the Water Resources Research Center field laboratory, The University of Arizona, Tucson. The model consisted of a lysimeter-flume containing riverbed materials to which various levels of stream discharge and suspended sediment were applied. Differences in infiltration rates due to these two variables were monitored.

LITERATURE REVIEW

Natural recharge to ground water aquifers is a consequence of infiltration and percolation. Infiltration is the process whereby water enters the surface strata of the soil. Percolation is the gradual passage of the infiltrated water through underlying materials into an aquifer and may occur as the result of:

1. Stream bed percolation;
2. Deep percolation of rainfall;
3. Deep percolation occurring as a result of irrigation; operation of cesspools and septic tanks; water supply and sewage conduits; and discharge of industrial waste;
4. Subsurface inflow.

Stream bed percolation and deep percolation of rainfall are considered as the two principal mechanisms for natural recharge, with streambed percolation predominating in the Southwest. Initially, the permeability of the geologic strata below the stream channels seems to be the factor controlling percolation rates. Subsequently as the ground water mound builds up to the level of the stream bed, the hydraulic gradient of the mound becomes the controlling factor (The Committee on Ground Water, 1961). In other words, "the composition of surface soil, and the geologic and subsurface hydrologic conditions directly affect infiltration rates." It has been found (ibid.) that for a given natural ground slope the long time infiltration rate, defined as "that rate which will exist after spreading water for a period of from two to four weeks depending upon the character of the surface and subsurface conditions" is higher in recent alluvial streambeds than on any other part of an alluvial fan. The infiltration rate for any given area will also increase with an increase in natural ground slope up to a certain point beyond which the rate will decrease. It appears that the stream velocity has more effect on the infiltration rate than the actual ground slope.

A laboratory study was conducted by Matlock (1965) using a 100-foot tilting bed flume. The purpose was to determine the relationships between the velocity of flow, silt content of water, and the infiltration rate in an alluvial channel of Rillito Creek. By using the tilting bed flume he obtained a range of velocities and sediment conditions to simulate any natural streamflow. Some inconsistencies between treatments were found in the infiltration rates with varying sediment loads, mainly because of the inability to return the bed materials to the same initial conditions as before. A relationship between velocities and infiltration rates with varying sediment loads is given in Figure 1. Values of the suspended sediment index, SSI, used in this figure, are equivalent to parts per million ppm expressed as percentage (e.g., SSI of 0.1% equals 1000 parts per million). In general the infiltration rates increased with increasing velocities from two to five feet per second. The relationship between velocity and infiltration rate for all tests is shown in Figure 2. According to Matlock infiltration rates for velocities below two feet per second were much the same as those for higher velocities of two to four feet per second with clear water. However, silty water with flows of less than two feet per second resulted

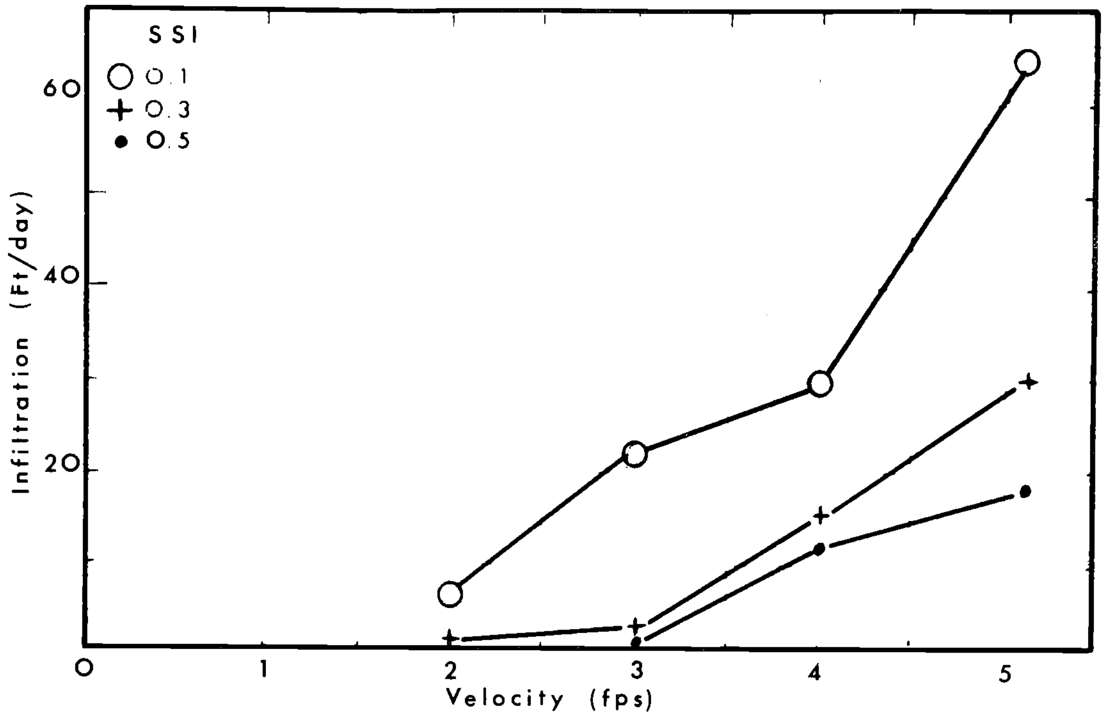


FIGURE 1. Infiltration vs. Velocity for Three Levels of SSI After Matlock (1965)

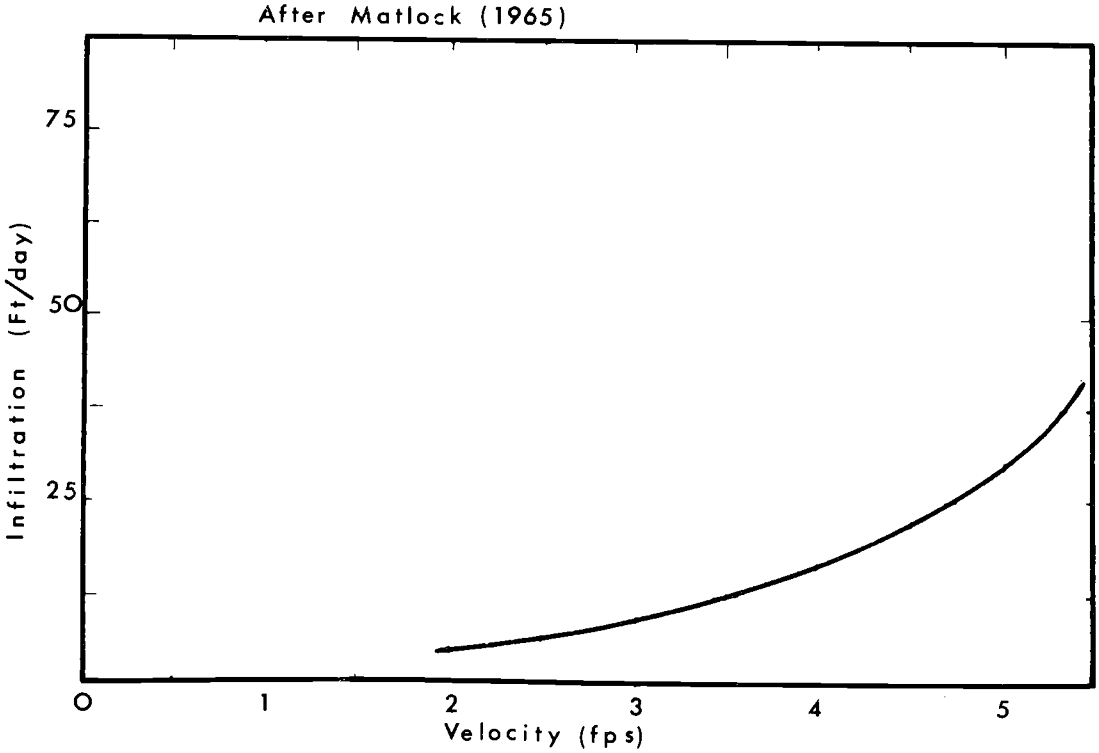


FIGURE 2. Infiltration vs. Velocity for All Tests After Matlock (1965)

in decreases in infiltration rates and ultimately in bed sealing. For a constant flow velocity in an alluvial channel the infiltration rate is inversely proportional to the suspended sediment index.

Except for the results of the study reported above, data on the combined effects of the two variables, suspended sediment and discharge on natural recharge are relatively scarce. Studies reported in the literature have been mainly concerned with parameters other than those of interest here. Peripheral results were obtained, however, which provide clues on the effects of velocity and sediment load on infiltration rates. The effects of velocity on canal seepage and seepage measurements using a bell type seepage meter were studied by Bouwer, Myers and Rice (1962). Because a still water body exists inside a seepage bell during seepage measurements the influence of velocity becomes a questionable factor when tests are conducted in open channel flow. Bouwer, _et al_. (ibid.), therefore, established a laboratory flume study to determine the direct effect of velocity on seepage rates in open channel flow and the effect of velocity distortion patterns around a bell type seepage meter on the local head environment of the bell. Seepage rates were determined for various velocities and seepage intensities. Tests were conducted with both sand and gravel as bed media and each test was always initiated and concluded with ponded water to insure a constant hydraulic conductivity for all tests. The test results did not indicate any measurable direct effect of velocity on seepage. Therefore, the seepage from still bodies of water can in principle be used to evaluate seepage of clear water in open channel flow. Bouwer, _et al_., (ibid.), indicated that velocity has an indirect effect on seepage by influencing erosion, sedimentation, and wetted perimeter.

Vanoni (1941) conducted a flume study to determine the characteristics of transportation of suspended sediment load. He found that there was an apparent reduction in flow resistance with turbid water by observing the velocity profiles taken during the course of the experiment. For a given discharge q the average velocity v was larger with sediment entrained in the flow than for the clear flow. The increase in velocity with the suspended sediment loads were first attributed to a decrease in the roughness of the bottom material caused by the deposition of fines among the coarser bed materials. Subsequent analysis indicated that the suspended sediment load decreased the universal constant for turbulent exchange K thereby increasing the velocity gradient for a given shear stress. Consequently the velocity at any level must also increase. Vanoni (ibid.) states that in order for the stream to carry the suspended matter against the force of gravity, energy must be applied to the sediment particles. This energy comes from the vertical components of turbulance associated with the stream. Entrained sediment tends to dampen out these turbulent motions more rapidly than if this sediment matter were not present.

Buckley (1922-1923) observed that suspended sediment loads reduced channel resistance during his study of the influence of silt on stream velocity on the Nile River. He found that this reduction in resistance was attributed to the damping effect of a heavily loaded layer of water on the turbulence of the stream near the bed. He inferred that the greatest reduction would be when the stream is depositing because then the layer near the bed would be the most dense.

Keppel and Renard (1962) state that the transmission losses in ephemeral streambeds are influenced by peak discharge at the upstream gaging station, duration of flow, width of channel, quantity and texture of the channel alluvium, and the antecedent moisture of the channel alluvium. Keppel and Renard measured and evaluated transmission losses in an ephemeral tributary of the San Pedro River. The tributary is the main drainage from the Walnut Gulch Experimental Watershed, Tombstone, Arizona. The stress channel is composed of unconsolidated sand and gravel deposits underlain with conglomerate bedrock. The sands and gravels vary in depth from six to fifteen feet. The streambed geology is characteristic of many of the ephemeral streams in southern Arizona. In two reaches of channel losses of up to 25 acre feet per mile of channel were measured. This value closely approached a computed value of 30 acre feet per mile based on calculated values of pore space and volume of alluvium in the channel bed. For discharge rates from 1000 to 1500 cubic feet per second cfs the transmission losses by infiltration and percolation seemed to level out, as evident in Figures 3 and 4. It appears that for flow rates in this range the stream bed is completely covered and loss rates start to decrease. That is, the wetted area approaches a maximum value and any increases in streamflow rates do not appreciably add to the wetted area. Subsequently the head of water in the channel plays a more important role in governing the recharge rate. The water that enters the alluvium of the stream channels may either

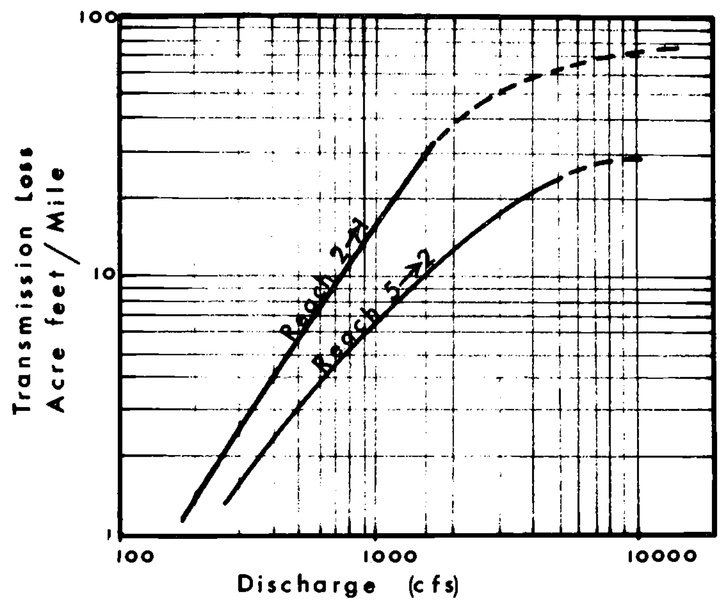


FIGURE 3. Transmission Loss in Acre Feet/Mile vs. Peak Discharge for the San Pedro River

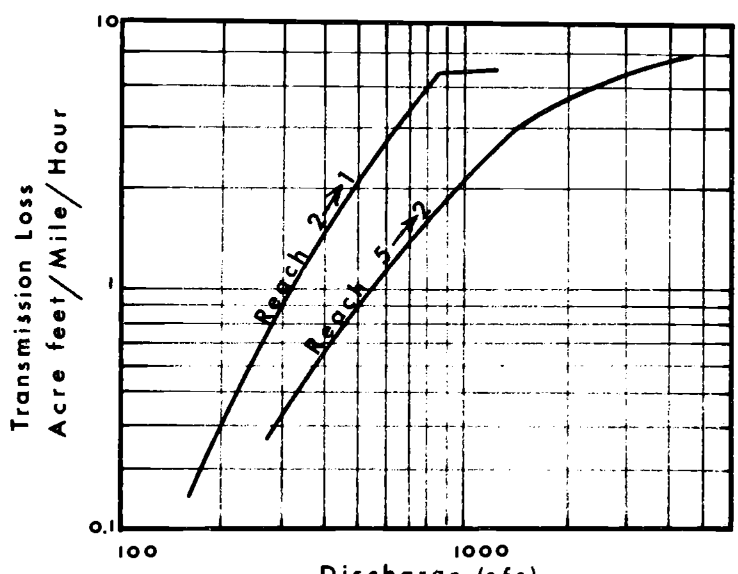


FIGURE 4. Transmission Loss in Acre Feet/Mile/Hour vs. Peak Discharge for the San Pedro River

contribute to the water table, or be lost by evaporation and riparian transpiration, the usual case at Walnut Gluch Watershed (ibid.).

Two studies similar to those of Keppel and Renard were conducted by the Agriculture Engineering Department of the University of Arizona on the Rillito Creek, near Tucson (Schwalen, 1960 and 1962). The first was a one-year water budget study from March, 1959, to March, 1960. The second study was conducted in the spring of 1962.

The one-year water balance study was based on gaging station records of the United States Geological Survey; estimated ungaged flow; net recharge to ground water from increases in the various wells in the area (assuming a twelve percent specific yield); estimates of consumptive use by stream bank vegetation; and water use from wells for irrigation and municipal use. The natural recharge was measured for about twenty miles of stream bed. The calculated infiltration rate (2.8 feet per day) was determined from the net recharge of the area excluding total evaporation losses from the wetted channel surface. The major flows for the effective period of recharge occurred during cold weather when viscosity and water temperatures were low. Thus the calculated infiltration rate is somewhat conservative. Matlock (1965) formulated a table (Table 1), which summarizes the data of this study.

The second study was conducted in the spring of 1962. During this time of year water is predominately snow melt from the higher mountain slopes and entrained sediment is usually negligible because of the low steady velocities. This stream flow is normally the most effective for natural recharge. The average infiltration rate for a sixteen mile section of the channel was 3.6 feet per day.

TABLE 1

Natural Recharge in Rillito Creek
March 1959 - March 1960

Surface Inflow	46,250 Acre-Feet
Surface Outlow	18,100
Net Loss	28,150
Recharge Remaining March 1960	14,500
Water Use:	
Phreatophytes	3,400
Irrigation	2,800
Domestic	3,000
Total	23,700
Unaccounted	4,450
Reach Length	20 Miles
Flow Loss	1,410 Acre-Feet/Mile
Days Flow Effective	100 Days
Daily Infiltration/Mile	14 Acre-Feet/Mile/Day
Average Channel Width	50 Feet
Channel Area	6 Acres/Mile
Average Velocity	2-3 fps
Infiltration Rate	2.8 Feet/Day

In a stream channel model study which was discussed herein precise inferences cannot be made without some prior knowledge of the interrelationships of the variables involved. When considering saturated vertical flow, the velocity can be defined by Darcy's equation:

$$V = K\ (h_s + y)\ /\ y$$

where K is the hydraulic conductivity, h_s is the depth of water on the soil surface, and y is the length of the saturated flow path. The quantity $(h_s + y)/y$ expresses the head loss per unit distance. The infiltration rate f, therefore, equals the velocity of flow V if defined as the quantity of water flowing normal to a unit area in a unit time. Using this definition V may be expressed in acre feet per acre per day (i.e., feet per day) (Schiff, 1953).

Schiff (ibid.) observed that increases in hydraulic head due to rising water depths will appreciably increase the infiltration rate when y is small. He also observed that as y increases the quantity $(h_s + y)/y$ will approach unity; therefore, when h_s is small in relation to y any small changes in h_s will have a negligible effect on infiltration. Philip (1957) states that the effect of h_s on infiltration is dissipated with increases in y because of the viscous shearing stresses within the soil media.

Philip (1957) solved a generalized form of the diffusion equation to express the total infiltration of water applied to a soil of uniform initial soil moisture as an infinite power series. The equation is as follows:

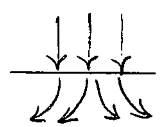
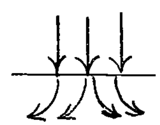
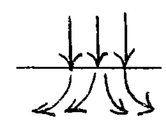
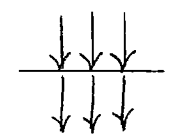
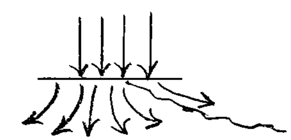
$$i = St^{1/2} + At + Bt^{3/2} + \ldots .$$

where i is the cumulative infiltration, t is time, and S, A, B, and the following constants of the equation are functions of the initial and surface water content of the soil and the soil diffusivity. Philip (ibid.) coined the expression "sorptivity" for the S term of the power series because of the importance of absorption on the initial infiltration rate. For vertical inflow the terms of the series converge rapidly leaving only the first few terms of the equation. With t approaching infinity the equation becomes unreliable and the infiltration rate approaches the hydraulic conductivity of the soil. Philip explained the effects of various factors on infiltration in terms of sorptivity S. As the initial soil moisture increases S reduces at a linear rate. As water head increases above the soil surface sorptivity is increased; therefore, the infiltration rates increase. However, as time approaches infinity, the effects of head and initial soil moisture become negligible as the importance of sorptivity becomes small. Philip has shown that for a uniform soil under all conditions of infiltration the rates will converge to the same asymptotic value.

Table 2 shows a qualitative comparison of infiltration formulas as arranged by Amorocho (1967). From this table one can readily compare some of the infiltration formulas in the literature with conditions which occur in natural streams such as the Santa Cruz River.

TABLE 2

A Qualitative Comparison of Infiltration Formulas and Those Conditions Likely to Occur in a Natural Basin

	Horton	Kostiakov	Holtan-Overton	Philip	Natural Conditions
Formula	$f = f_c + (f_0 - f_c)e^{-K_f t}$	$f = \alpha b t^{(\alpha - 1)}$	$f = f_c + aF_p^{\;2}$	$f = \frac{1}{2} S t^{-\frac{1}{2}} + A$	
Type	Empirical	Empirical	Empirical	Analytic	
Schematic flow field					
Area of inflow	Small	Small	Small	Unlimited	Large
Medium	Relatively Homogenous	Relatively Homogenous	Relatively Homogenous	Homogenous	Heterogenous
Flow field	Approx.	Approx.	Approx.		
	Axi-symmetric	Axi-symmetric	Axi-symmetric		Complex
	Three-dimensional	Three-dimensional	Three-dimensional	Uni-dimensional	Three-dimensional

MATERIALS AND METHODS

The effects of the variables, stream discharge and suspended sediment on natural recharge rates were evaluated in a lysimeter-flume, constructed such that various stream discharges and suspended sediment contents could be flowed over it. A selected combination of these two variables was randomly obtained to produce nine treatment combinations which were replicated twice. Infiltration rates in feet per day were then determined for the eighteen treatment combinations.

The lysimeter-flume and appurtenances were constructed at the Water Resources Research Center Field Laboratory at the University of Arizona. The location of this site, relative to the City of Tucson is shown in Figure 5, together with a schematic representation of the research facilities associated with the lysimeter-flume study. The contiguity of the area to the Santa Cruz River is also shown in Figure 6.

Materials

Preliminary Studies

In order to obtain preliminary data for the design of the model auxiliary investigations were conducted in the laboratory and in the bed of the Santa Cruz River.

The primary objectives of the field studies, conducted during riverflow in the summer 1966, were to determine the effect of change in total sediment load and river discharge on transmission losses, *in situ*, and to obtain data on the ranges of discharge and suspended

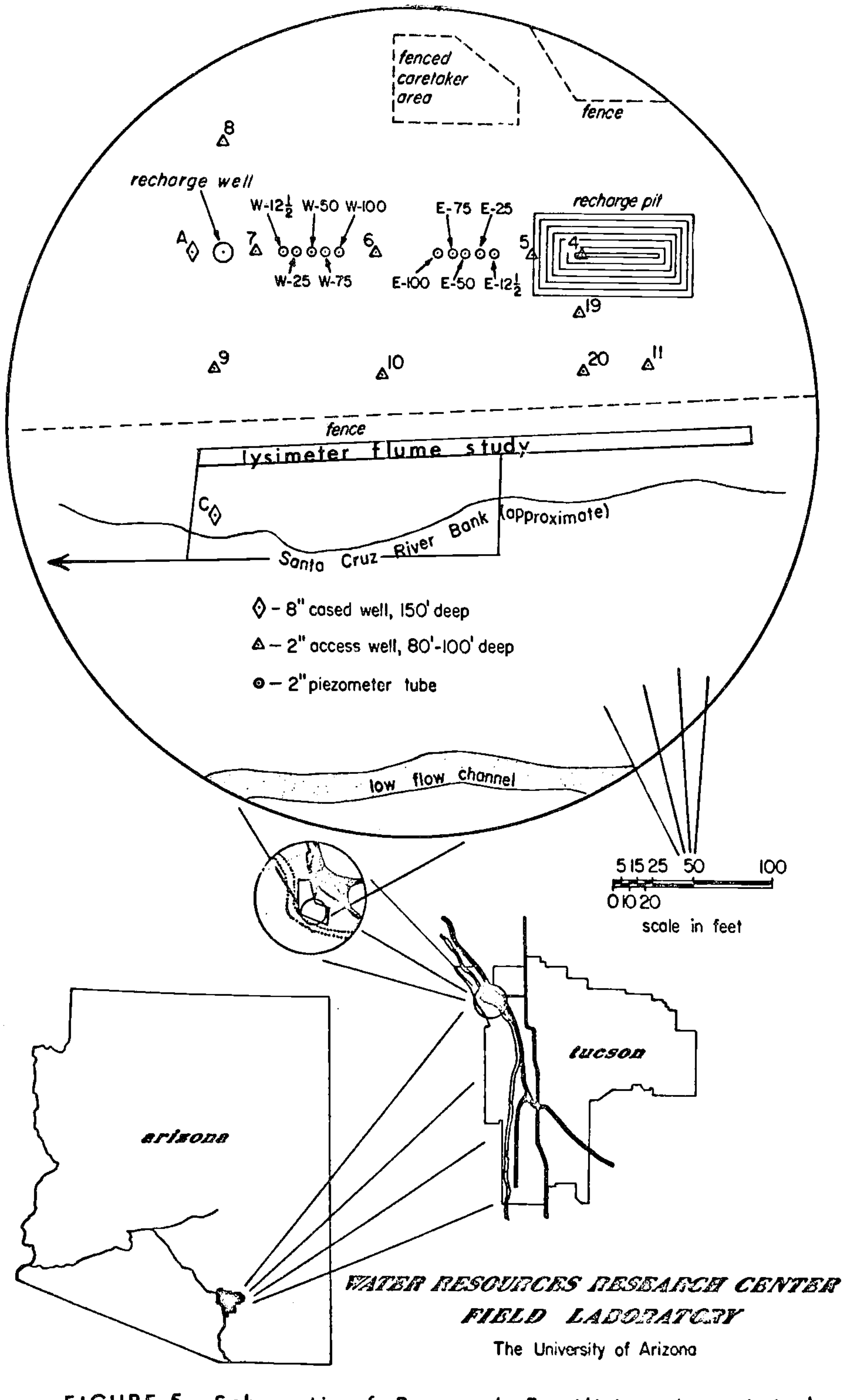


FIGURE 5. Schematic of Research Facilities Associated with Lysimeter-Flume Study

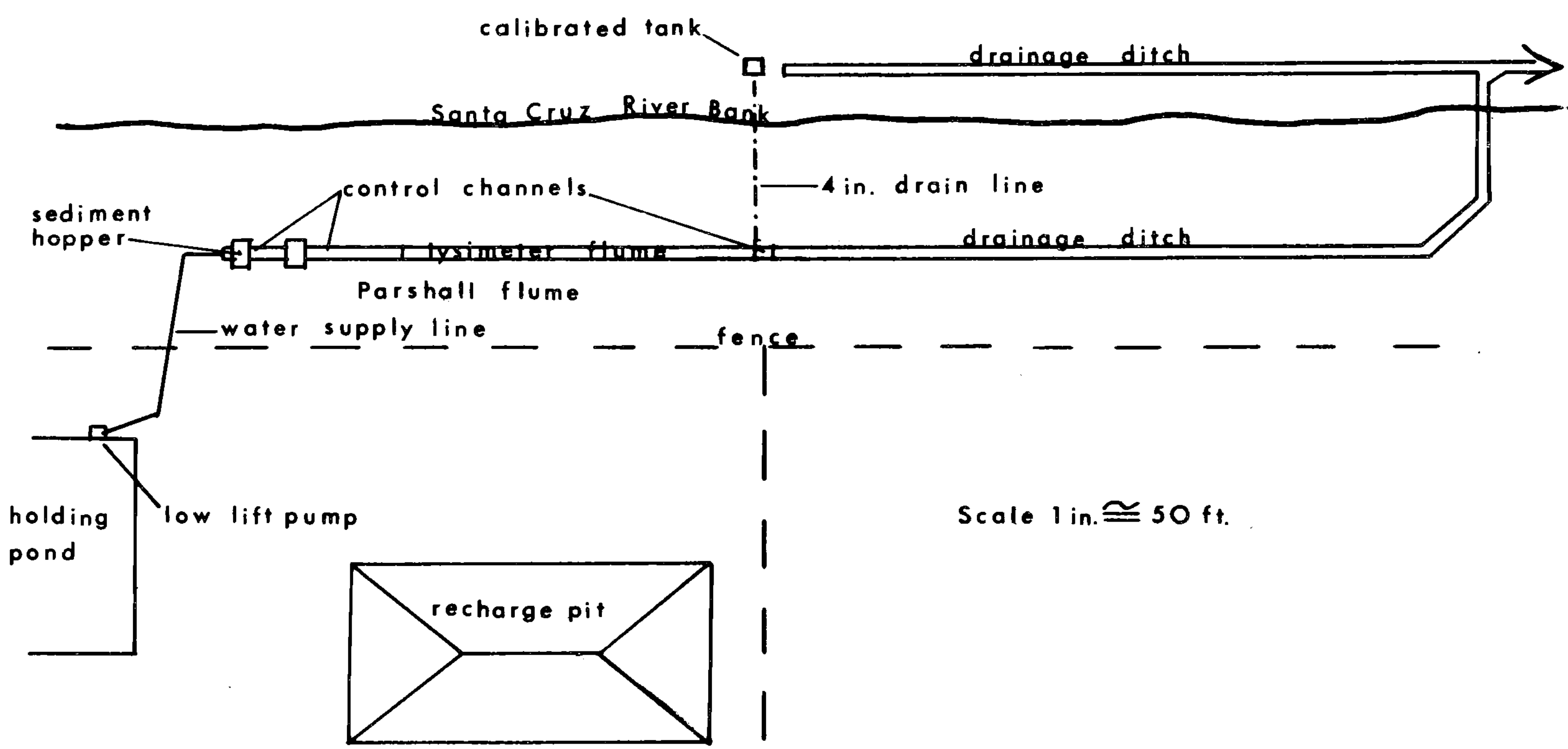


FIGURE 6. Schematic of Lysimeter–Flume and Appurtenances

sediment loads in summer riverflows of the Santa Cruz River. In July and August, 1966, discharge measurements were taken in the Santa Cruz River with a Price Current Meter at two arbitrary stations, picked for their relative straightness and smoothness of flow. Velocity measurements were determined at both stations at ten foot intervals across the channel at 0.2 and 0.8 of the total depth at those points. The differences in discharge rates between the stations were used to estimate the transmission losses between the two stations. Sediment samples were obtained simultaneously with flow measurements and at various times thereafter. The measured streamflow ranged from 2300 cfs to 40 cfs with accompanying sediments ranging from 100,000 ppm to 15,000 ppm. The high values of turbidity reflected initial scouring of the riverbed sediment deposited by the previous flow. The turbidity value subsequently decreased with time as the flow decreased allowing the suspended sediment to settle out on the riverbed. Physical limitations precluded obtaining representative transmission losses.

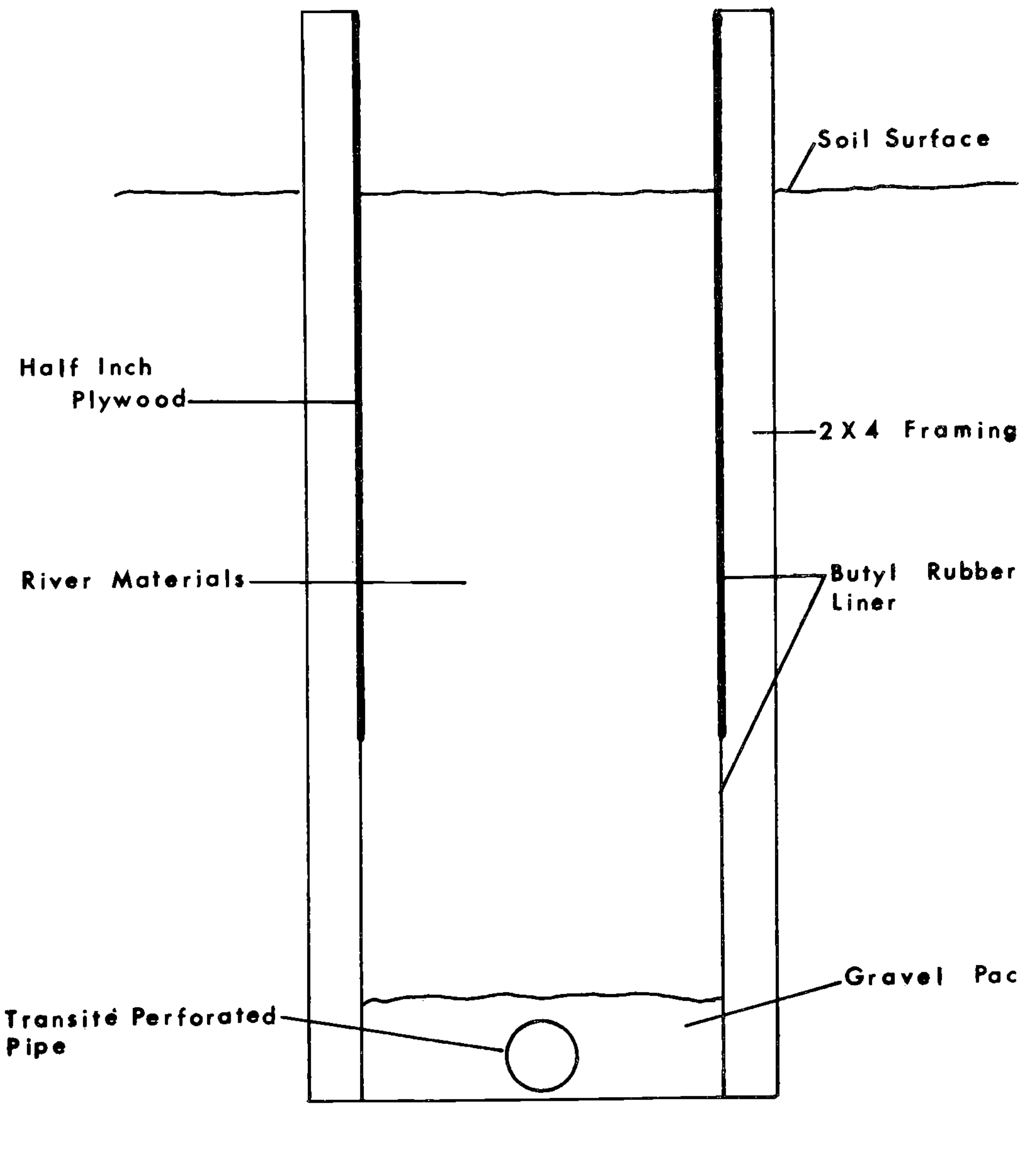
A second field study was initiated in the spring of 1967 to obtain estimates of transmission losses, in situ, under controlled conditions. Two earthen borders were constructed in the channel bed of the Santa Cruz River producing a channel one hundred feet long and three feet wide. Two nine-inch Parshall Flumes were installed at the inlet and outlet for measuring discharge differences from which transmission losses, in situ, could be determined. The water supply was obtained from a holding pond located on the research area. The average application rate for a period of two weeks was 290 gpm (gallons per minute).

Initial transmission losses exceeded 90 feet per day and approached a rate of 30 feet per day asymptotically after two weeks of flooding. These rates were not considered to be representative of actual rates because of lateral subsurface flow.

The laboratory experiments were conducted to determine the percentage reductions in recharge rates for the bed materials at the site by sediment deposition. Two cylindrical plastic columns, four inches in diameter and twelve inches long, were filled to a depth of six inches with river material. A constant-head water reservoir was attached to the columns. Intake rates were then measured from a drain line located at the bottom of the cylinders. As an asymptotic infiltration rate was approached a fine layer of sediment was introduced into each column. For sediment layers of 0.75 inch and 0.375 inch, intake rates were reduced 40 percent and 35 percent, respectively.

Lysimeter Construction

Based on the results of the preliminary studies a model, consisting of a lysimeter-flume, was installed at the Water Resources Research Center field laboratory to simulate natural conditions of a portion of the Santa Cruz River. A schematic representation of the lysimeter-flume and appurtenances is shown in Figure 6. The lysimeter-flume, constructed from marine plywood and two by fours, consists of a box 100 feet long, two feet wide, and four feet deep installed in a five-foot trench (Figure 7). The framing was placed in the trench so that one foot was left above ground to provide free board for the stream channel. Three feet of the framing extended below ground. The interior of the framing was



Scale 1 Inch = 1 Foot

FIGURE 7. Cross Section of Lysimeter – Flume

lined with a twenty mill prefabricated butyle rubber lining. The below ground portion was lined for a total depth of five feet and was sealed at the bottom to prevent leakage. One hundred feet of four-inch diameter perforated asbestos-cement pipe was placed lengthwise in the bottom of the lysimeter-flume to facilitate drainage. The pipe was covered with six inches of pea gravel to reduce clogging of the perforation. A seventy-foot section of four-inch asbestos cement water pipe was connected to the drain line to conduct the infiltrated water to a calibrated volumetric bucket for rate determinations.

Samples of Santa Cruz riverbed materials were characterized by observations at six locations to ensure selection of representative materials for the lysimeter and to determine the degree of natural layering of the deposited materials at depths less than six feet. Textured analysis of these materials were obtained from the M. M. Sundt Construction Co., Tucson, Arizona (see Table 3). The bed materials were of a uniform sand and coarse gravel mixture. Apparently layering of deposited material does not occur to any great degree at depths of six feet or less except for fine silty-clay surface materials deposited during riverflow recession stages.

Based on these results a representative sample of bed materials, obtained from the channel of the Santa Cruz River, was placed within the lysimeter-flume to a depth of four and one-half feet. The remaining portion of the framing provided freeboard to accommodate discharge.

TABLE 3

Textural Analysis of Materials Located in the Santa Cruz River[1]

U.S. Series Sieves Sizes meshes/inch	Percent Retained percent	Textural Classification
	Average of six test holes	
200	95.5	4.5% silt-clay
40	79.7	20.3% sand
8	44.0	56.0% sand
4	45.3	64.7% gravel
1/4	41.3	68.7% gravel
3/8	35.7	74.3% gravel
3/4	26.5	83.5% gravel
1 1/2	16.7	93.3% gravel

1. Courtesy M. M. Sundt Construction Co., Tucson, Arizona.

Channel and Hopper Construction

Control sections were built upstream and downstream of the channel of the lysimeter-flume to enhance the uniform dispersion of suspended sediments before entering the test unit and to promote a uniform flow pattern through the unit (see Figure 6 for dimensions). The control sections were constructed from plywood framed sides spaced two feet apart and covered with six mil polyethelene plastic. The bottoms of the control sections were dug three inches below the surface datum of the lysimeter-flume and filled with coarse concrete in order to maintain a uniform bed roughness; thereby, minimizing bed cutting due to changes in bed roughness between the lysimeter and control sections.

In order to introduce controlled amounts of natural suspended sediment into the applied water a sediment hopper was constructed and installed at the upstream control section (Figure 6). The steel hopper was constructed in the shape of a truncated pyramid with a capacity of 93 cubic feet. The hopper was constructed so that sediment loads could be regulated to the desired concentration by the use of an adjustable grate at the bottom of the hopper. The sediment would fall from the hopper into the upper control channel which was of sufficient length to insure complete dispersion of the sediment throughout the channel cross section prior to entering the lysimeter.

Water and Sediment Supply

The water supply was obtained from a concrete holding pond located at the Water Resources Research Center field laboratory. This pond is operated as a stilling basin and resevoir for industrial effluent (blowdown water) obtained from the Tucson Gas and Electric Company, Grant Road Plant. The effluent is used for artificial recharge studies at the field laboratory. During periods of high application rate when this source was of insufficient quantity, supplemental well water was obtained at the research site.

The water supply was pumped to the research site through an eight-inch transite pipeline by a low-lift electrical centrifugal pump. A six-inch gate valve was installed in the line at the pump in order to obtain the desired quantities of flow. The sediment was obtained from a flood plain deposition area along the Santa Cruz River. The sediment deposit consisted of a sand loam material of 46 percent sand, 45 percent silt, and 9 percent clay.

Methods

Treatment Application Rates

Three levels of discharge were subjected to the lysimeter, 300, 450, and 600 gpm.

Sediment was introduced into the water as it entered the upper control channel prior to entering the lysimeter. Three levels of sediment concentrations were used, ten, twenty, and thirty thousand ppm. These levels were maintained throughout each trial with the adjustable grate at the bottom of the hopper. The three levels of stream discharge and suspended sediment produced nine different treatment combinations which were replicated twice.

Physical Measurements

Stream discharge rates were measured and recorded by a 6-inch Parshall Flume and a Type F Stevens Recorder throughout each test. The discharge was maintained constant throughout the test duration.

The first phase of each trial consisted of calibrating the lysimeter-flume by applying clear water at the test rate. Once saturation was reached and infiltration rates approached an asymptotic level the sediment was added to the stream. Infiltration rates were then continually monitored until a lower asymptotic infiltration level was reached which reflected the sealing effect of the suspended sediment.

Infiltration rates were obtained by measuring the time required to fill a calibrated bucket and these times were then converted to infiltration rates in feet per day.

Suspended sediment contents were determined by weight. A 500 milliliter sample of sedimentated water was obtained every five minutes during each test. The suspended sediment load of the stream was determined by the weight differences of equal volumes of clear water and sedimented water and expressed in milligrams per liter or parts per million. The concentrations of the individual samples were averaged to determine the mean suspended sediment load of the stream during each test.

Bed Surface Management

The surface of the lysimeter-flume was removed to a depth of one foot after each treatment to ensure removal of the deposited sediment layer left from the previous flow. The lysimeter-flume was then filled to its original level with clean river material. The bed surface was then covered with copper sulfate granules to prevent any microbial growth.

Data Analysis

A 3 x 3 factorial analysis was used to test the effect of stream discharge and suspended sediment on infiltration. In a factorial analysis if the influence of one variable (suspended sediment, for example) is suspected of changing with levels of another variable (stream discharge, for example) then this behavior can be tested. When the two or more variables are tested in all possible combinations then the resulting treatments are said to be factorial (see Table 4). Using a design such as this, one can determine if there is any differential effect of one variable on another, both of which may be at two or more levels, and their ultimate influence on some parameter. The data from this experiment was collected in such a manner so that it could be placed into the 3 x 3 factorial analysis.

TABLE 4

Lysimeter-Flume Treatments

Suspended Sediment Content	Discharge		
ppm	gpm		
	A_1	A_2	A_3
	(300)	(450)	(600)
B_1 (10,000)	A_1B_1	A_2B_1	A_3B_1
B_2 (20,000)	A_1B_2	A_2B_2	A_3B_2
B_3 (30,000)	A_1B_3	A_2B_3	A_3B_3

RESULTS AND DISCUSSION

The results of the nine treatments, each replicated twice, are presented in Table 5 in terms of the ratio of the infiltration rate for turbid water to that for clear water. Ratios of the infiltration rates were taken in order to compensate for differences between treatments and replications of parameters other than those of interest in this study. Absolute values of the infiltration rates ranged on an average from 4.2 feet/day to 5.0 feet/day. These rates were somewhat higher than the rates reported by Matlock (1965) of 3.6 feet/day for Rillito Creek and by Todd (1959) of 3.8 feet/day for the Santa Cruz River.

The experimental results are also presented graphically in Figure 8, in which the mean infiltration ratio for each treatment is plotted as a function of the discharge rate. It is apparent from an examination of this figure that, in general, the infiltration ratio is decreased by an increase in the concentration of suspended sediment. The ratio increased with increasing discharge rate for an applied sediment concentration of 10,000 ppm. Anomalies are apparent in the curves for the 20,000 ppm and 30,000 ppm levels. In particular, values of the infiltration ratio for the 20,000 ppm level increased between 300 gpm and 450 gpm, and subsequently decreased between 450 gpm and 600 gpm. However, the infiltration ratio values for the 30,000 ppm level decreased between 300 gpm and 450 gpm and then increased between 450 gpm and 600 gpm. The final values of the infiltration ratio, at 600 gpm for both the 20,000 ppm and 30,000 ppm levels were greater than the values of 300 gpm.

TABLE 5

Lysimeter-Flume Treatment Results

Treatment	Replications I	Replications II	Treatment Total (T_t)	Treatment Mean ($\bar{y}$)
	Infiltration Ratio $\frac{\text{I sedimented } H_2O}{\text{I clear } H_2O}$			
A_1B_1	.91	.93	1.84	.92
A_1B_2	.77	.77	1.45	.77
A_1B_3	.73	1.68	1.41	.71
A_2B_1	.87	.96	1.83	.92
A_2B_2	.91	.92	1.83	.92
A_2B_3	.67	.69	1.36	.68
A_3B_1	.98	.98	1.96	.98
A_3B_2	.81	.92	1.73	.86
A_3B_3	.86	.84	1.70	.85
Replication Total (T_t)	7.51	7.69	15.20 = G	

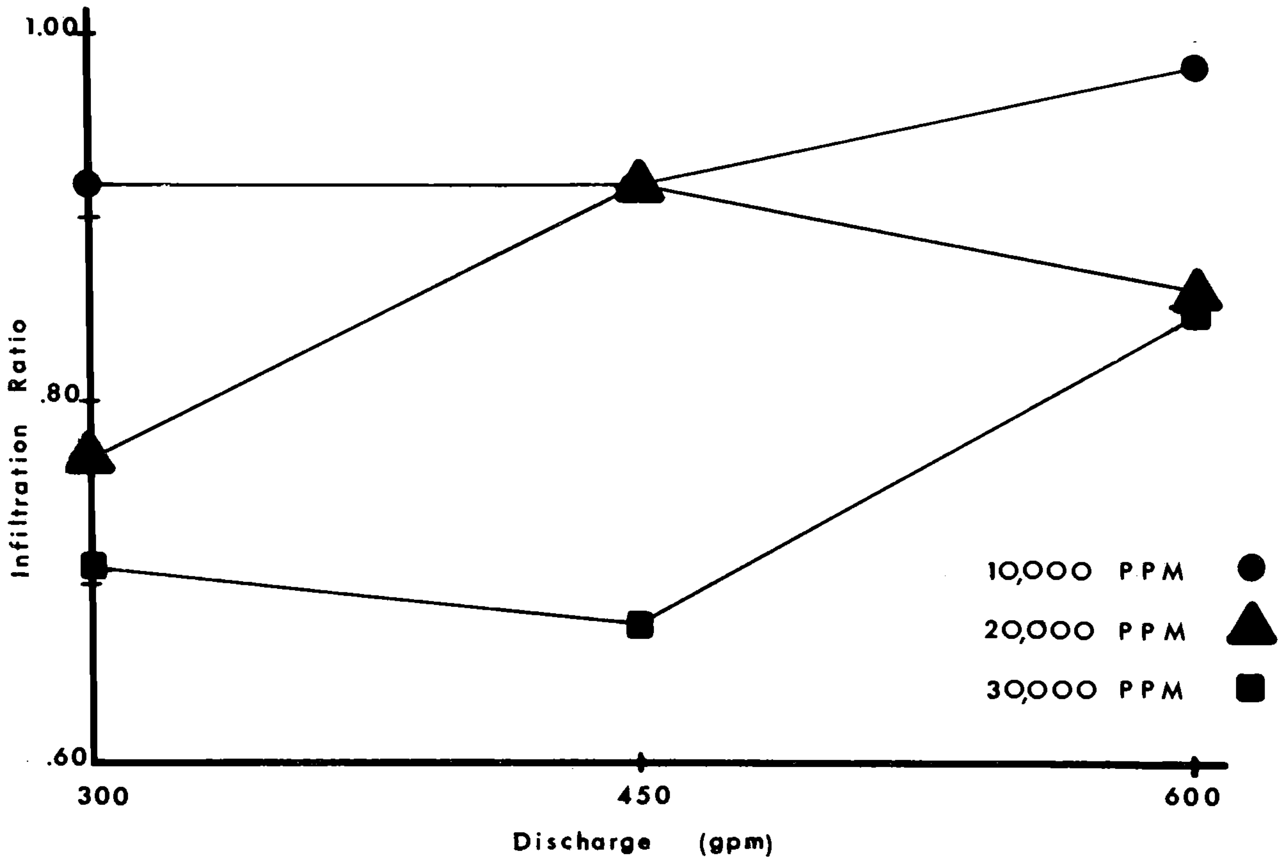


FIGURE 8. Infiltration Response to Three Levels of Stream Discharge and Suspended Sediment

The analysis of variance for the experiment is shown in Table 6. Variation in the data could be attributed to a variety of factors any one of which could mask out the effect of the other. By an analysis of variance one is able to partition the variation of an experiment into three components due respectively to the effect of the treatment, the environment and experimental technique effects, and the residual or error effect.

The variation due to environment and experimental technique (replications) was small and was non-significant at both the 5 percent and 1 percent confidence limits. Treatments were significant and were partitioned into three parts. Discharge (factor A) was found to be significant at both the 5 percent and 1 percent limits. Suspended sediment (factor B) was found to be highly significant and was the primary source of variation. The interaction (A x B) was found to be significant at the 5 percent limit but non-significant at the 1 percent limit. There was small variation due to the A x B interaction which therefore was not significantly important. This was computed by multiplying the standard error of the mean $s_{\bar{y}}$ by the "shortest significant range" (SSR) which is obtained from tables developed by Duncan (1955). The standard error of the mean is defined as:

$$s_{\bar{y}} = \sqrt{s^2/n}$$

where n is the number of replications and s^2 is the error mean square of the analysis of variance given in Table 5. For the conditions of the experiment expressed herein the standard error of the mean equals 0.0255. When the treatment differences exceed the computed LSR they are significant; otherwise, they are not significant.

TABLE 6

Analysis of Variance

Source of Variation	Degrees of Freedom (d.f.)	Sum of Squares (SS)	Mean Squares (ms)	Observed F	Required F 5%	Required F 1%
Total	17	.1850	.0109	8.3846		
Replications	1	.0018	.0018	1.3846	5.3177	11.259
Treatments	8	.1730	.0216	16.6154	3.4381	6.0289
Discharge (A)	2	.0305	.0152	11.6923	4.4590	8.6491
Sus. Sed. (B)	2	.1124	.0562	43.2308	4.4590	8.6491
A X B	4	.0301	.0075	5.7692	3.8378	7.0060
Error	8	.0102	.0013 = s^2			

In general, those treatments associated with a given sediment load were not significantly different from one another but were significantly different from those treatments associated with other sediment loads. The exceptions to this were the treatment combinations A_1B_2 and A_1B_3, A_2B_2 and A_2B_1, and A_3B_2 and A_3B_3 described in Table 4. These treatment combinations are those producing the anomalies discussed previously. The effects of those treatments on the infiltration rate in the lysimeter-flume which were not significantly different for two suspended sediment levels is not clearly understood. Although the analysis indicated a significant effect of total stream discharge on infiltration rates, it appears that the effect was not due to an increase in discharge _per se_ but rather to an indirect effect by increasing erosion and sedimentation. This can be seen by the fact that discharge was found to be barely significant at the 1 percent level.

The effect of suspended sediment was highly significant and was the primary source of variation. As suspended sediment increased the infiltration rate decreased due to the increased deposition of fines on the soil surface of the lysimeter-flume.

The effects of head changes were not measured in this experiment because it was assumed that once a saturated state was reached in the lysimeter-flume the small changes in head in the magnitude of 0.5 to 1.0 inches were small in relation to the five foot saturated depth of lysimeter-flume and were therefore of little consequence on the infiltration rates.

In a semi-arid region such as the Tucson basin the salvage of all available water supplies is of primary importance in retarding the depletion of the ground water supply. The Santa Cruz River, one of the two principal drainages in southern Arizona, is classified as an ephemeral stream flowing in response to precipitation and subsequent surface runoff. Influent seepage (natural infiltration) during riverflow can be classified as salvable water as opposed to that water which is lost to evapotranspiration.

Studies were conducted by the Water Resources Division, United States Geological Survey to estimate the recharge efficiency of the Santa Cruz River between the Congress Street gaging station and the Cortero Road station (Burkham, 1968). Recharge efficiency can be defined as the percentage of the quantity lost between these two gaging stations attributable to natural recharge. It was (ibid.) determined that from 50 percent to 90 percent of the river discharge which is lost between these two stations can be attributed to natural recharge. The percentage loss attributed to natural recharge depends upon the season of flow and the amount of evapotranspiration taking place at any given point along the river reach. Empirical equations were developed from the data obtained at the two gaging stations which give the discharge loss in cfs between the two stations:

$$q \text{ loss} = 1.4 \, (q \text{ inflow})^{0.8}$$

where q inflow is the discharge in cfs going through the Congress Street gaging station. The total amount recharged was obtained as follows:

$$q \text{ recharge} = .50 \text{ to } .90 \, (q \text{ loss})$$

Using these equations it is possible to estimate the amount recharged into the streambed for the given channel reach of the Santa Cruz River as described previously. For example, using the runoff event of December 20, 1967, of 12,000 cfs (measured at the Congress Street gaging station, United States Geological Survey):

$$q\ loss = 1.4\ (12{,}000)^{0.8}$$

$$= 1.4\ (1834) = 2567.6\ \text{cfs}$$

or

5083.8 acre feet/day

$$q\ recharge = .80\ (q\ loss)$$

$$= .80\ (2567.6) = 2054.1\ \text{cfs}$$

or

4067.1 acre feet/day

A problem related to natural infiltration in river bed materials is that of characterizing percolation flow patterns in the highly stratified sediments underlying ephemeral stream channels. In otherwords, "Disposition of the water that infiltrates through the streambed is not completely known. How does the water move away from the streambed?" (Matlock (1965). Studies by Wilson and DeCook (1968) during runoff events in the Santa Cruz River in the winter of 1965-66 provided clues on the changes in the subsurface water regime at the Water Resources Research Center field laboratory. The principal experimental facilities employed in the studies were 10 access wells (see Figure 5) used in conjunction with a recording moisture logger. Subsurface moisture changes were monitored in these wells before, during and after each runoff event. The moisture logs manifested the growth and dissipation of two mounds in the region above the normal groundwater surface. At the peak of recharge the upper mound was located in permeable materials from about 25 feet to 35 feet below the ground surface. The lower mound extended from 40 feet to the normal groundwater surface, 80 feet. Drainage of the water in these mounds into the phreatic groundwater during the recessional stage was slow but eventually complete.

Corroborative data on the subsurface disposition of recharged water were obtained at the Field Laboratory during runoff in the Santa Cruz River during December 1967. A peak flow of 12,000 cfs on December 20, 1967 (measured at the Congress Street gaging station, United States Geological Survey), creating an eight foot stage at the site, was particularly significant in recharge. Moisture logs obtained on successive days after this peak were similar to those obtained during the 1965-1966 events. The changes in volumetric moisture content were estimated for a subsurface section of material along a 500 foot stretch of the Santa Cruz River and extending inland 500 feet on both sides of the river to a depth of 80 feet below ground surface. Three days after the peak flow of December 20 the change in moisture content throughout this section was about 34 million gallons or 100 acre feet. In addition, the inland velocity of the recharge wave was estimated to be from 150 to 200 feet/ day.

Although it appears that natural recharge is of a substantial quantity the question can be asked as to whether the natural recharge rate could be increased by proper flood water munipulation or treatment. Turbidity seems to be the primary factor for decreasing natural recharge. Wilson (1967) has demonstrated that grass filtration of storm runoff is an effective method for suspended sediment removal. It seems reasonable that grass filtration strips located along a river such as the Santa Cruz could be used as an initial treatment followed if necessary by some secondary flocculating treatment for sediment removal. Following this the water could then be artificially recharged by some appropriate method.

Pit recharge, well injection, and basin recharge are the primary methods of artificial recharge, and are principally used when natural recharge is of an insufficient quantity to maintain a static water table. The costs associated with most artificial recharge methods are usually high and their usage will be limited to areas where high dollar value is placed on the stream discharge lost from the basin.

However, considering methods for increasing the natural recharge in a streambed, the economic cost-return ratio is the factor governing the selection of any particular method. In lieu of constructing special recharge facilities away from the river, structures may be placed within the established permeable sections of the natural streambed to enhance natural infiltration. Consequently, the cost for construction and water control will be kept to a minimum. Kramsky (1958) states that:

> . . . improvement of streambed percolation represents one of the most efficient and economical methods of artificial recharge; and should be utilized to its fullest capacity. This can be accomplished by widening, leveling, and scarifying the channel bottom. Small check dams and dikes are sometimes provided to reduce velocities and spread the flow over the entire width of the channel. These checks may be temporary earthen structures protected by brush and wire, or of more permanent concrete construction, as dictated by relative economics of initial cost versus maintenance and replacement expense. This

> method is particularly suitable to arid regions where stream flows are flashy and of short duration; and where wide, meandering channels are formed. Being dry most of the time, these streambeds can be easily maintained, and it is seldom that expensive permanent works are warranted.

Management practices such as those suggested by Kramsky (ibid.) seems to be far better suited to the water problems associated with a drainage basin such as the Santa Cruz River basin than any other alternative method. It is felt that with proper control structures placed in the many tributaries and permeable reaches of the Santa Cruz River, natural infiltration could be significantly enhanced with minimal capital expenditures.

CONCLUSIONS

Based on the results of the streambed model study using Santa Cruz River sediments the following conclusions were made:

1. Recharge rates ranged from 4.2 feet/day to 5.0 feet/day in the streambed model.

2. In general, treatment effects of discharge and suspended sediment in Santa Cruz River materials were similar to those of an earlier study in Rillito Creek bed materials. Stream discharge seemed to increase infiltration although of small significance and was felt to be more of an indirect factor in influencing infiltration; whereas, suspended sediment content was highly significant in reducing infiltration.

3. It appears that the natural recharge of the Santa Cruz basin is of a large quantity. Further studies (*in situ*) in the Santa Cruz and Rillito drainages would be of great value in determining the degree that suspended sediment content and discharge affect these losses on a quantative basis rather than a qualitative basis such as was done in this experiment. In addition to these studies, subsurface dispositions investigations would provide further clues toward the management of a basin wide water resources plan.

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