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Field Performance of

LARGE CRITICAL-DEPTH FLUMES

for Measuring Runoff From

Semiarid Rangelands

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CONTENTS

FIELD PERFORMANCE OF LARGE CRITICAL-DEPTH FLUMES FOR MEASURING RUNOFF FROM SEMIARID RANGELANDS[1]

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INTRODUCTION

Hydrologic research on the 58-square-mile Walnut Gulch watershed at Tombstone, Ariz., began in 1953. Objectives of this work are to investigate net effects of a range conservation program on water yield and sediment movement from semiarid rangelands and to evaluate individual factors affecting runoff and sediment production from such lands. A drainage map of the watershed under study is shown in figure 1.

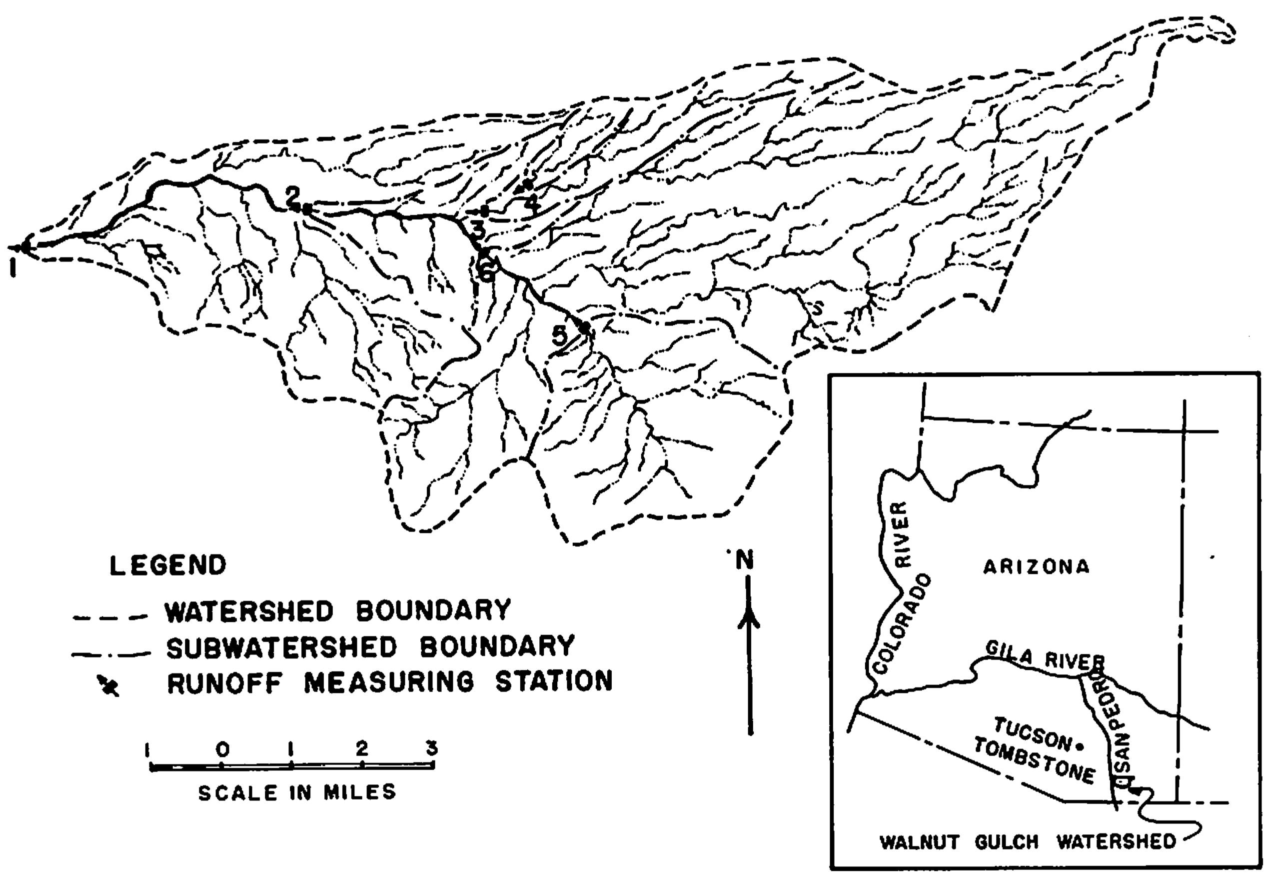

Figure 1.--Walnut Gulch experimental watershed.

[1] Contribution from the Southwest Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture in cooperation with the Arizona Agricultural Experiment Station.

[2] Hydraulic Engineer, Agricultural Engineer, and Agricultural Engineer, respectively, Tucson, Ariz.

Practically all the runoff results from small diameter, intense, convective thunderstorms occurring during July, August, and September. During the period of record, 80 percent of these runoff-producing storms have covered 4.5 square miles or less.[3] Flow events are characterized by high-velocity momentum waves that may override preceding flows and build up to high peak stages in a short time. They involve relatively little total runoff. Because of irregularity and instability of the channels and the nature of the flows--high velocity, short duration, and laden with trash and coarse sediment--conventional stream gaging methods are inadequate for obtaining records of the desired accuracy. Consequently, precalibrated, critical-depth, measuring flumes are used. The purpose of these structures is accurate measurement of both peak rates and amounts of runoff. It is desirable for purposes of analysis to record the stage-time graph so that the hydrographs may be obtained with a minimum of distortion.

Some ponding behind runoff measuring structures is unavoidable, and this may have significant effect on the hydrograph shape. One objective in design of the critical-depth flumes on the Walnut Gulch watershed has been to minimize the ponding effects, since maximum stage and changes in rate of rise of the hydrograph may be important parameters in interpreting such phenomena as channel loss.[4] Another major consideration has been sensitivity of the water-level record to changes in the stream stage under conditions of flash flow and heavy debris loads.

In 1953 and 1954, with very limited previous model studies, five critical-depth measuring flumes were built on Walnut Gulch watershed and its tributaries. Four of the flumes were subsequently severely damaged by scour below the structures. Experience with these earlier flumes led to more extensive model studies in cooperation with the Agricultural Research Service, Outdoor Hydraulic Laboratory, Stillwater, Okla. From this experience and laboratory study has developed a general design of a critical-depth runoff measuring flume adaptable to a wide range of site conditions and suitable for the type of flows that occurs from semiarid rangelands over much of the Western United States. During 1958-59, this general design was used in replacing the damaged structures at flume sites 2 and 3. The present report discusses performance of these two structures. Two additional flumes are under construction at new sites on the watershed and early installation of several others is planned.

DESCRIPTION AND FIELD PERFORMANCE OF FLUMES

The critical-depth flumes on Walnut Gulch (fig. 2) are designed with a broad entrance section approximately the size of the original channel section, a 15-foot-long contraction reach with warped sidewalls to force the flow through critical depth, and a 20-foot straight reach. The water-level gaging section is located in the middle of the straight reach (10 feet from the downstream edge of the flume). A bottom slope of 3 percent keeps the flow accelerating throughout the length of the flume and eliminates deposition of the heavy sediment load in the flume. Thus the head measurement is made in the section where the flow is supercritical. The water-surface elevation in the flume is measured by a float-actuated water-level recorder, operating in a stilling well that is built into the structure and connected to the measuring section by an intake system.

Drainage areas above the five critical-depth flumes now operating on the Walnut Gulch watershed range from 0.88 to 58 square miles. The original design capacities of these flumes,

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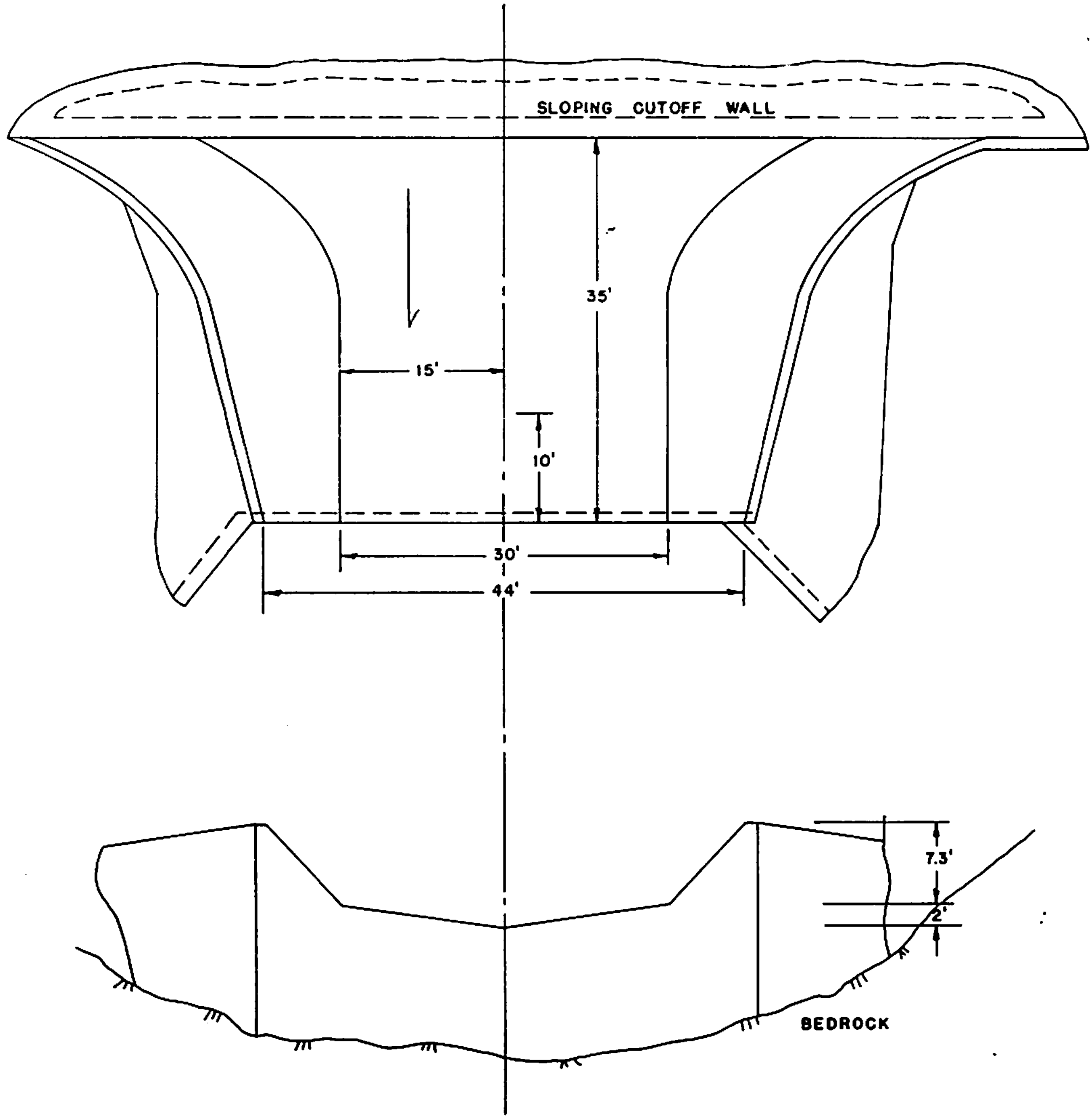
[3] Fletcher, J. E. Some properties of precipitation associated with runoff from Walnut Gulch watershed, Ariz. Paper presented at the Amer. Geophys. Union meeting, April 1961, Washington, D. C. (Pending pub.)

[4] Keppel, R. V., and K. G. Renard. Transmission losses in ephemeral stream beds. Amer. Soc. Civ. Engin. Proc., Hydraulics Div. Jour. 88 (No. HY3) Part 1:59-68, illus.



SCALE 1" = 10'

Figure 2.--Critical-depth flume 3, Walnut Gulch watershed.

based on limited rainfall and runoff information, proved inadequate. During the first 2 years of observation, estimated 100-year return frequencies based on point-rainfall data were exceeded several times. On August 17, 1957, a peak discharge of 17,000 c.f.s. was measured at flume 2 on Walnut Gulch from a drainage area of approximately 44 square miles. This peak discharge resulted from runoff-producing rainfall over 30 square miles of the watershed with maximum point intensities approximating 5 inches per hour for 30 minutes.

Flume 3 on Walnut Gulch, which measures the runoff from a drainage area of 3.5 square miles, was rebuilt in 1958, and flume 2, which measures the runoff from a drainage area of 43.9 square miles, was rebuilt in 1959. Models for both flumes, which included several hundred feet of the approach and downstream channel, were studied in the Stillwater Outdoor Hydraulic Laboratory. To avoid backwater effects at high stages, the floor of each flume was raised between 2 and 3 feet above the natural channel elevation. These two flumes have rated capacities of 6,000 and 18,500 c.f.s., respectively. Design tests are now being completed in the Hydraulic Laboratory for reconstruction of flume 1, for the total 58-square-mile drainage area, with a capacity of 22,500 c.f.s. Although return frequencies for peak discharges are still under study, it is felt that these flumes are now designed with rated capacities more than adequate to measure the probable 100-year storm.

Flume 3 was constructed in accordance with the general design originally developed in the Hydraulic Laboratory in 1957. The geometry of flume 2, however, had to be modified. Its depth was decreased and its width increased because the maximum allowable head was limited by an adjacent railroad grade. To control low recession and base flows in this widened flume, a flat bottom section was designed with a 2-foot-deep, 5-to-1, V-notch at the center. This design has proved very satisfactory for flows with peaks greater than 3 feet. The recession hydrograph through the transition zone (around the 2-foot stage) seems to be reasonably consistent for larger flows.

Because of scour from accelerated velocities through the critical-depth flumes, downstream protection must usually be provided. Serious undercutting occurred on some of the earlier structures before the magnitude of the scour was fully appreciated. At flume 3, for example, the discharge for a peak stage of 8 feet is 4,100 c.f.s. The average velocity through the critical section for this peak flow is 17 feet per second. Since the flow continues to accelerate throughout the length of the flume, the average exit velocity is somewhat greater. (For uniform-flow conditions, the average velocity in the natural channel for this discharge is approximately 12 feet per second). The downstream channel is scoured to bedrock, and side eddies cause extreme erosion of the banks below the flume unless protection is provided.

The design criteria require that no sediment shall be deposited in the critical-depth flumes. This requirement is met in flumes 2 and 3 as now constructed, even with the heaviest of sediment concentrations in the flow. In the older flumes, which were built in 1953 and 1954, the flume floor is horizontal above the critical section and sediment collects on the flat bottoms of these structures.

The location for the stilling-well intake for gaging water elevation in the critical-depth flumes was carefully selected from model studies of the water-surface profile for various stages. Since stage is measured in a supercritical velocity section where a relatively small difference in stage is accompanied by a large change in discharge, water-surface profiles have been checked in the prototype to insure agreement with the model. Figure 3 shows the observed water-surface profiles at flume 2 for three levels of discharge. To avoid any appreciable change in stage during the time of observation, the water-surface elevations at the different sections were estimated quickly to the nearest tenth of a foot. Water-surface profiles thus obtained indicate a smooth transition as the water moves through the transition reach and on through the

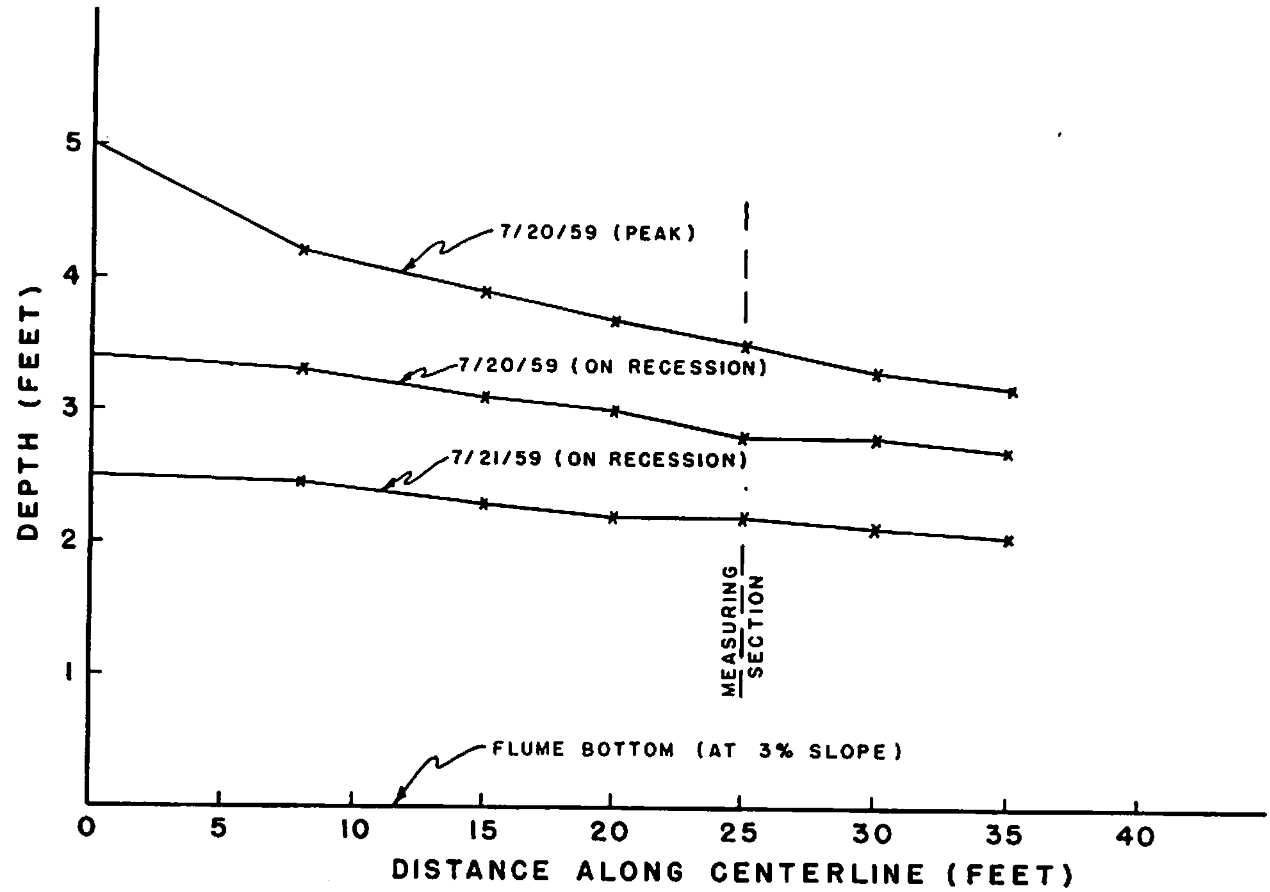


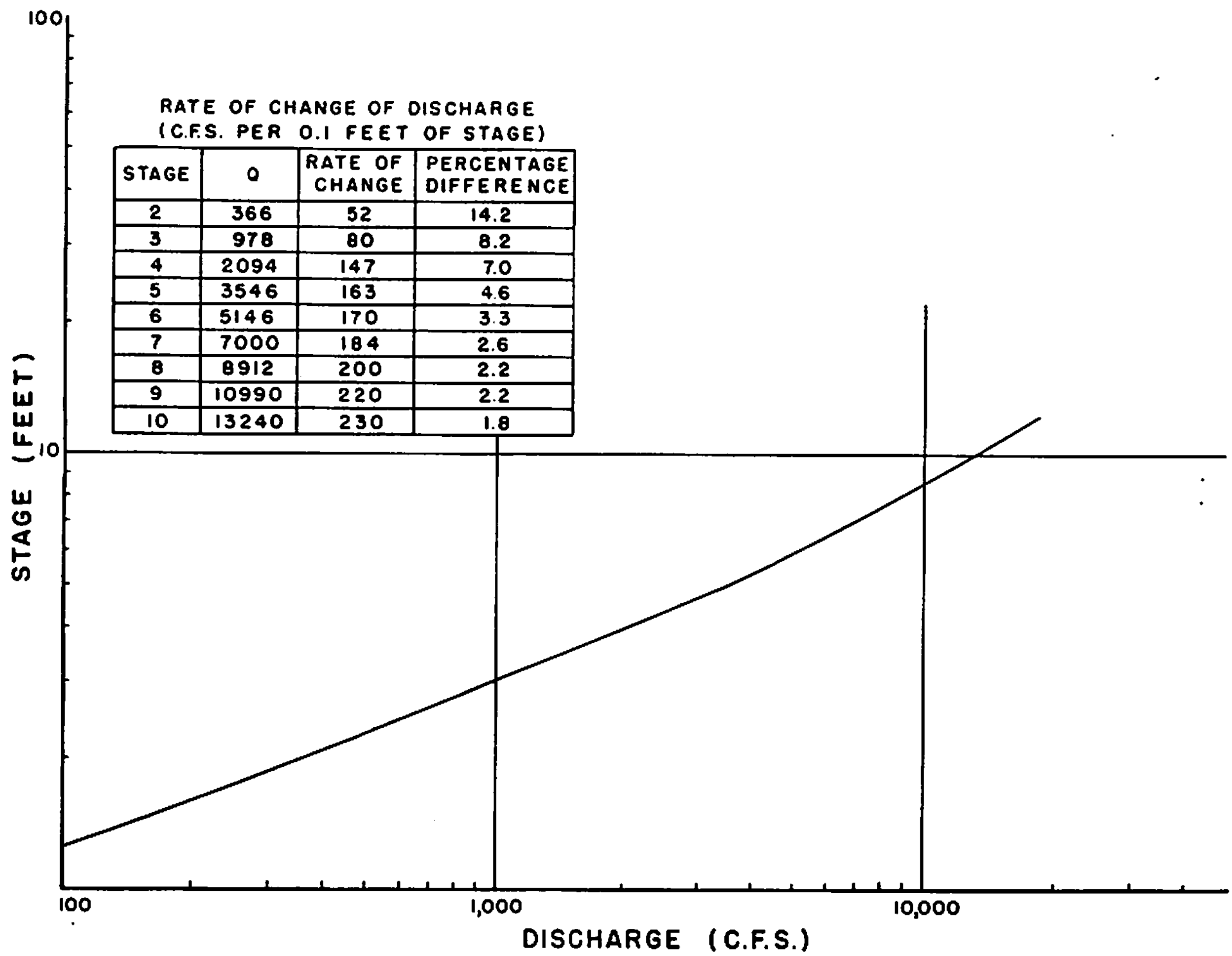
Figure 3.--Observed water surface profiles, flume 2 (left side, looking downstream), Walnut Gulch watershed.

straight reach. Uniform slope of the water surface in the straight reach implies stable conditions at the measuring section; that is, at any given stage, there is but one discharge rate.

GAGING WELL INTAKE SYSTEM

Intake design for the water-level gaging, or stilling, well becomes very important in the large, accurate streamflow-measuring structures such as these being built by the Agricultural Research Service. The intake system, ideally, must transport water quickly from the intake openings to the stilling well and must damp out minor surging that may take place in the flume. Figure 4 shows the error in discharge for various flow depths that might be incurred from a 0.10-foot error in measuring the stage at flume 2. Usual intake designs are unsatisfactory for measuring flash flows with widely ranging and rapidly changing stages and heavy sediment and trash loads.

Figure 5 shows detail of the intake systems for flumes 2 and 3. The stilling wells are at a considerable distance from the intake orifice plates in the flumes. Even with very small openings (6 inches long and 1/8 to 1/4 inch wide) in these intake plates, considerable sediment is deposited inside the intake system; the system must be large enough to store the sediment from more than one flow without becoming blocked, which would distort the hydrograph of the succeeding flow. Also, the intake system must be large enough to permit easy cleanout access at any point between the intake plate and the stilling well. Therefore, a relatively large volume of water is necessary to fill the intake system.



RATE OF CHANGE OF DISCHARGE
(C.F.S. PER 0.1 FEET OF STAGE)

STAGE	Q	RATE OF CHANGE	PERCENTAGE DIFFERENCE
2	366	52	14.2
3	978	80	8.2
4	2094	147	7.0
5	3546	163	4.6
6	5146	170	3.3
7	7000	184	2.6
8	8912	200	2.2
9	10990	220	2.2
10	13240	230	1.8

Figure 4.--Partial rating curve for flume 2 (100-18,000 c.f.s.), Walnut Gulch watershed.

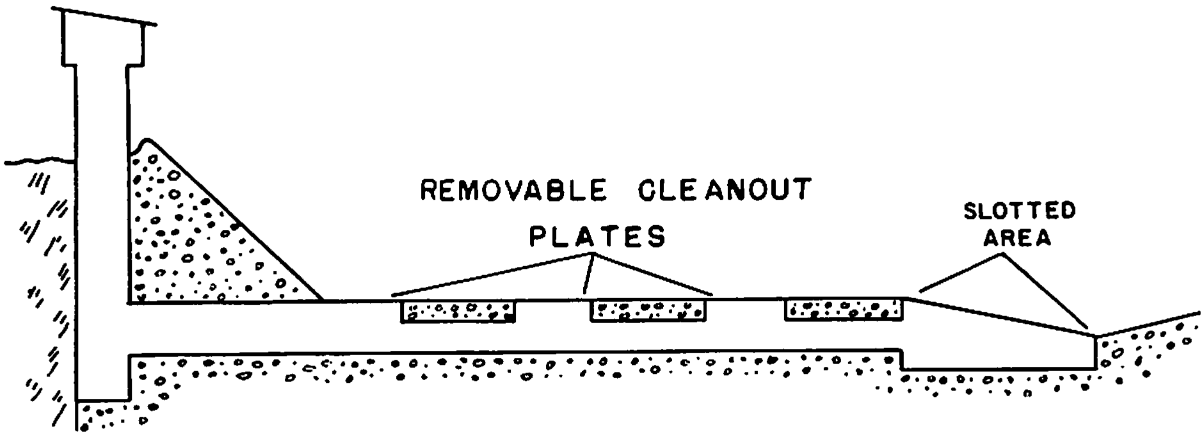
Model tests have been conducted by other investigators on various types of intake designs. These tests were limited to relatively low velocities and sediment loads--much lower than those encountered in the ephemeral streams of the Southwest. The model tests, however, did indicate that a perforated intake plate in the flume perimeter must be perfectly smooth and carefully placed in a plane parallel to the direction of flow. If the plate is rough in the region of the intake openings or if the plate is not parallel to the flow, there may be considerable difference between the water-surface elevation in the stream and that in the stilling well.

Model tests made by the U.S. Geological Survey[5] indicate that the more desirable intakes have opening areas of several square inches (for example, a 3-inch pipe for a stilling well 2.5 feet in diameter). Unfortunately, large openings allow much sediment to be deposited immediately within the intake system, which forms a relatively impervious obstruction. Recession of the hydrograph is badly distorted; unless the intake system is cleaned after each flow event, subsequent records are lost.

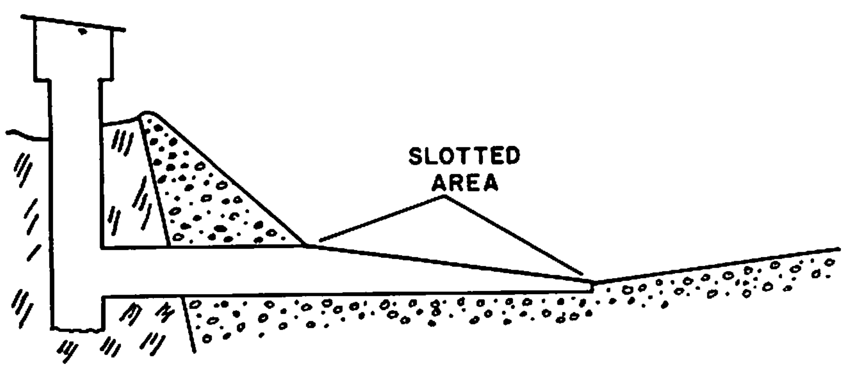
The small intake openings required to minimize the sediment intake retard the flow into the intake system. This causes a time lag between the water-surface elevation in the critical-depth

[5] Pierce, C. H. Investigations of methods and equipment used in stream gaging. Part 2. Intakes for gage wells. U.S. Geol. Survey Water-Supply Paper 868-B, 75 pp., illus. 1941.

SCALE 1" = 10'



FLUME #2
INTAKE SECTION
INTAKE 2' WIDE



FLUME #3
INTAKE SECTION
INTAKE 2.5' WIDE

Figure 5.--Flume intake systems, Walnut Gulch watershed.

flume and that in the stilling well. If the resulting time lag is sufficient to distort the hydrograph unduly, some method of correction must be devised. A similar lag occurs between the stilling well and the flume during the recession of flow; but, since the stage drops much more slowly than it rises, the recession lag is generally negligible.

Figure 6 shows the hydrographs for two typical flows through flume 2 in 1961. The solid lines represent the discharge as recorded by the water-level recorder in the stilling well; the dotted lines represent the discharge based on observations of the water-surface elevation in the flume for the same period of time. When the lag becomes negligible, the solid and dotted lines coincide. If no correction for lag were made, there would be a 14-percent error in the measured total volume of the smaller of the two flows and a 5-percent error in that of the larger. Since an intensive study of water-yield influences is one of the primary goals of the project, these discrepancies would be highly significant.

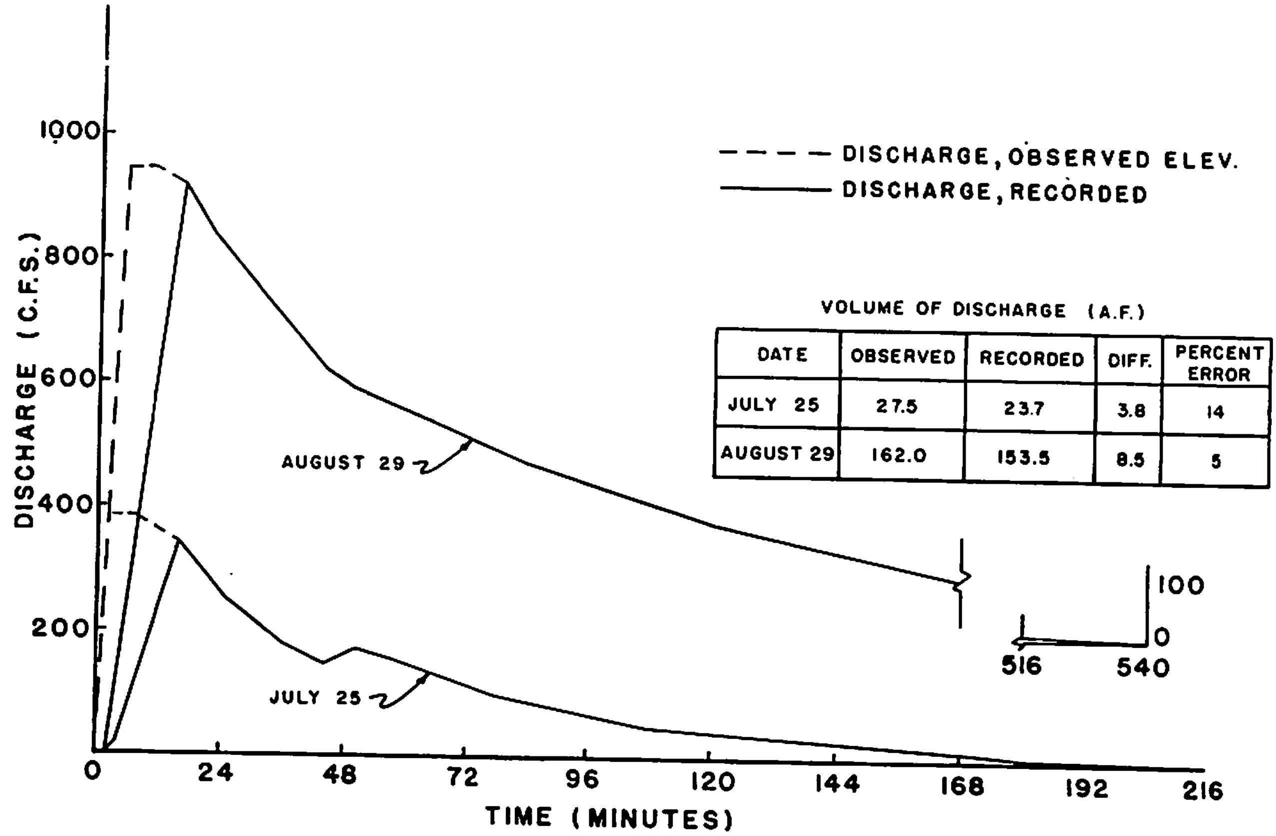
Discharge through the intake-plate openings was approximated by the equation for discharge through an orifice into the atmosphere, where $Q = CA\sqrt{2gh}$. Figure 7 shows, at flume 2, the theoretical lag for the intake system plotted against maximum stage and the observed effective lag for a series of storms plotted against similar stages. Twenty-two percent of the intake slots were widened from 1/8 inch to 1/4 inch in May 1961; this accounts for the two theoretical lag curves shown. Maximum head (stage) over the intake slots was assumed to occur instantaneously; a situation that is closely approximated by the extremely rapid rises that are characteristic of the flows experienced.

The effective lag for flow events plotted on figure 7 for 1959 and 1961 pertains to abrupt translatory waves. Theoretically, widening 22 percent of the intake slots from 1/8 inch to 1/4 inch should not have reduced the lag time so drastically. The apparent explanation is that the 1/8-inch slots are more readily blocked by the coarser suspended sediment and bedload material. Unfortunately, the simple expedient of widening all the slots to 1/4 inch or of increasing the number of 1/8-inch slots does not solve the problem. With the wider slots, the intake system accumulated sediment much more rapidly during the 1961 flows. It was necessary to remove this sediment immediately after each flow to insure adequate records of succeeding flows. As more 1/8-inch slots are cut in the plate, each opening acts less independently, and the entrance efficiency is reduced. Also, the increased quantity of fine sediment, while not filling the entire intake structure, forms an impervious dam immediately within the intake system. Attempts at balancing size and number of intake slots against amount and texture of deposit in the intake system revealed the inevitability of some time lag in such systems under the prevailing conditions of heavy sediment load and rapid changes in stage; therefore; records must be adjusted.

The nature of the flow event must be known before a time-lag correction can be applied to the stage-time record obtained from the water-level recorder. There is no substitute for personal observation of a flow event approaching and passing through a flume. If the flow event is unobserved, as is most often the case where several measuring stations are involved, other means are necessary to refine the form of the hydrograph.

Several water-level recorders in small stilling wells with direct intakes are located at 2,000-foot intervals upstream from flume 2. Records from these instruments are being used for a detailed study of translatory wave movements. Since the intake slots in these wells are situated near the bank rather than in midstream, they often do not record the beginning of the flow; but they provide a good record of peak time and rate of rise near the peak. These records may be very helpful in determining the actual rate of rise at flume 2.

Besides personal observation and records from related stream gages, methods must be developed to correct for intake lag. One such method is based on the assumption that the distance



DATE	OBSERVED	RECORDED	DIFF.	PERCENT ERROR
JULY 25	27.5	23.7	3.8	14
AUGUST 29	162.0	153.5	8.5	5

Figure 6.--Hydrographs of flows July 25 and August 29, 1961, flume 2, Walnut Gulch watershed.

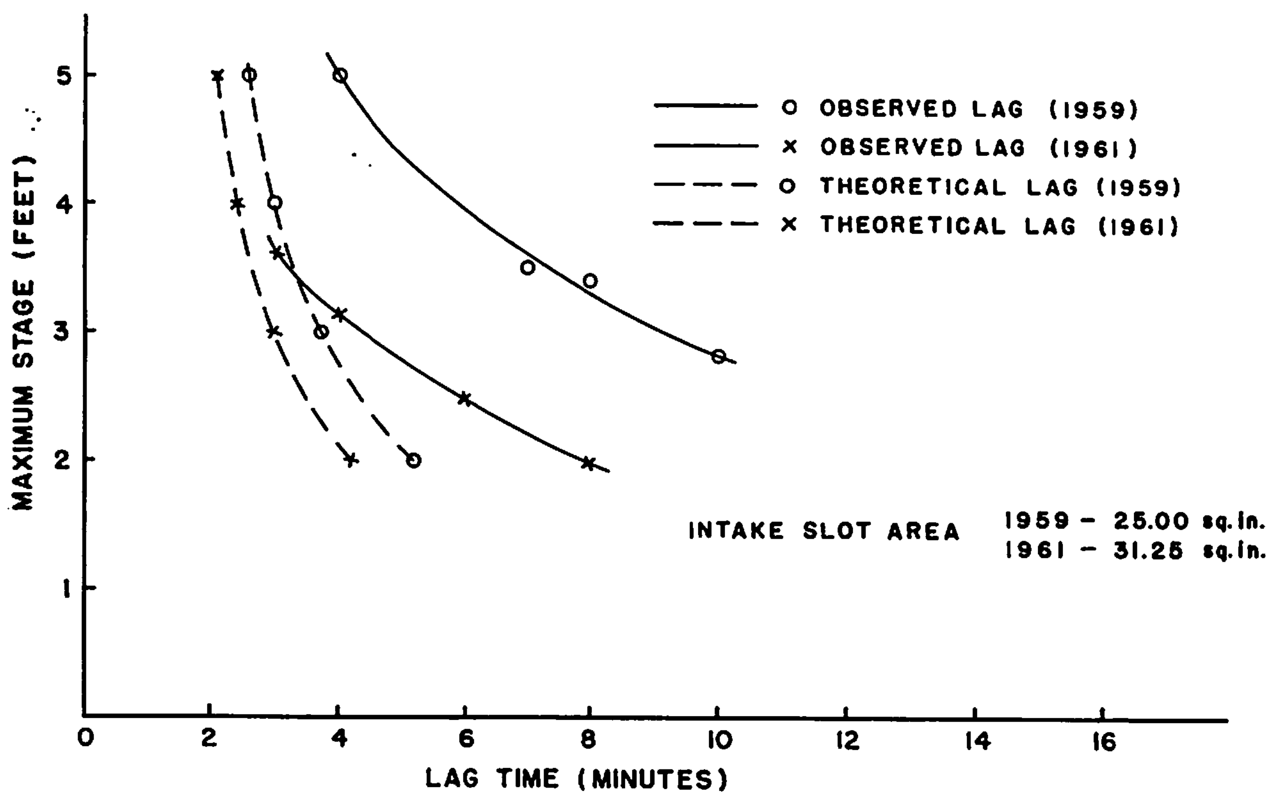


Figure 7.--Maximum stage versus theoretical and observed effective gaging-well intake lag time, flume 2, Walnut Gulch watershed.

the flow has traversed a dry channel has a profound effect upon the rate of rise. Heavy precipitation in the upper regions of the watershed above flume 2 results in a rapidly rising flow at the flume. In contrast, similar precipitation immediately upstream from the flume produces a more gradual rise (fig. 8). Since not all storm events are clearly discrete in time and space, and since consecutive reaches of channel may be either wet or dry, considerable additional data are necessary before this method can be generally adopted.

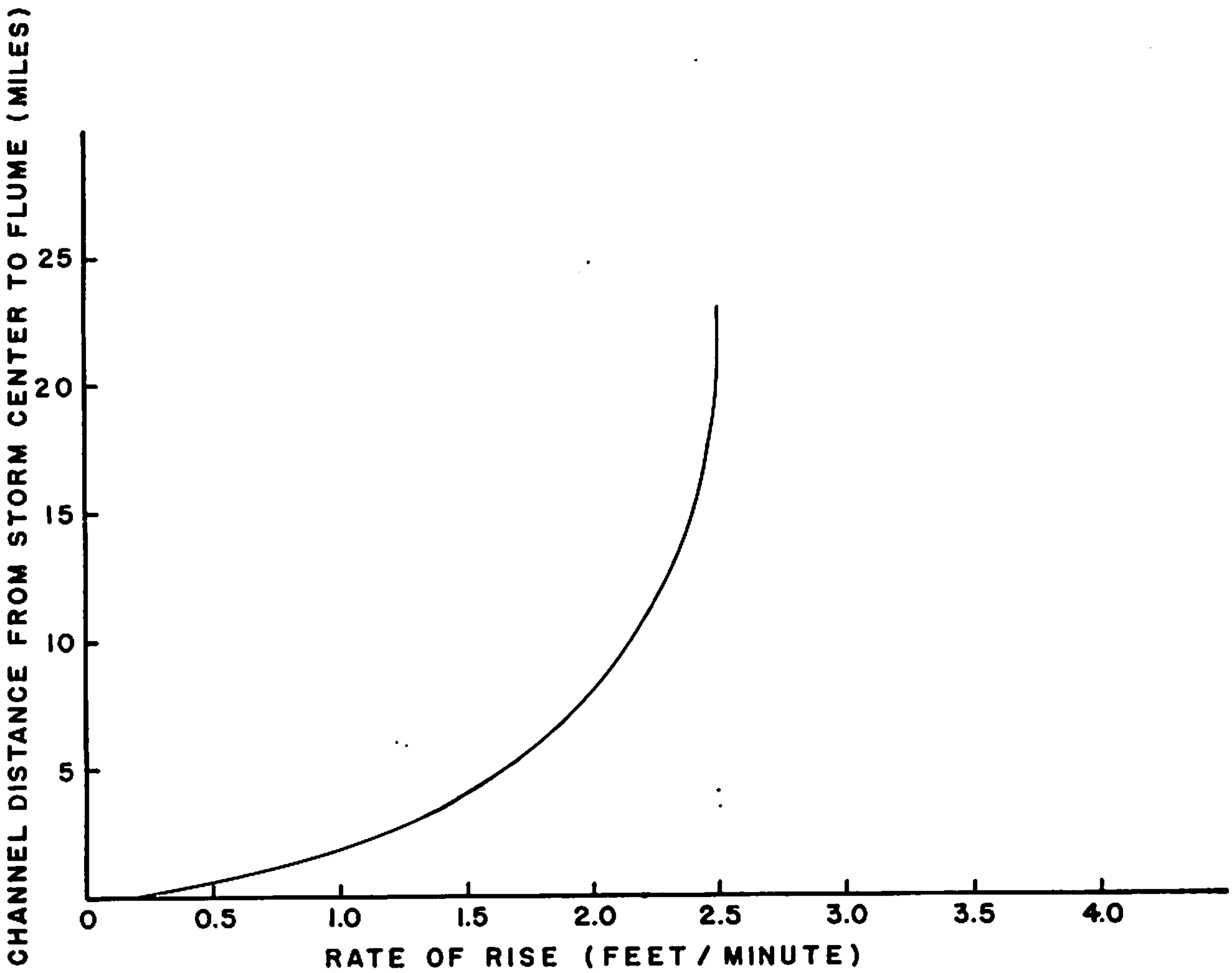


Figure 8.--Rate of rise at flume 2 versus storm location, Walnut Gulch watershed.

The Agricultural Research Service is interested in other automatic methods for recording the hydrostatic pressures in critical-depth flumes. With further development and modification, bubbler gages with more rapid response or diaphragm recorders with greater range than those now available might be used to avoid the time lag and other problems inherent with float-type water-level recorders and stilling well intake systems for measuring flash flows in ephemeral streams, carrying heavy sediment loads.

EFFECTS OF RUNOFF STRUCTURES ON NATURAL STREAM REGIME

The critical-depth flumes discussed here are permanent concrete structures set generally on bedrock. As such, they form barriers in the natural channels and cause definite changes in subsurface-surface interflow and related hydrologic performance of the watershed. Immediately above flume 2, for example, a large pocket of porous material in an intrusive mass of granodiorite is filled annually by percolation from surface runoff in the channel. Construction of flume 2 raised the outlet level and increased the surface area of water in this pocket; and more water is lost locally from this minor ground water basin to evaporation and transpiration. Also, some water that previously was temporarily stored in this basin and moved out eventually as subsurface flow through the channel gravels is now brought to the surface and trickles through flume 2. Although this trickle of flow is a relatively low discharge, the total volume for several months often amounts to an appreciable quantity. In 1959 this base flow amounted to 3.5 acre-feet, which was 4 percent of the total annual water yield from the approximately 44-square-mile watershed. No such appreciable base flow has been recorded at the other structures. Considerable work remains to be done in watershed research to evaluate the hydrologic effects of the runoff-measuring structures.

As a result of their retarding effect on the channel flows, the runoff-measuring structures may also indirectly affect erosion and sediment transport. Channel aggradation and degradation are helpful in assessing the sediment yield of a watershed. Since the channel bottom above a runoff-measuring flume is fixed by the flume invert, a series of such structures closely enough spaced could stabilize the channel gradient. Aggradation and degradation in limited reaches can still be observed, but net watershed sediment production may be significantly changed and long-range changes in other influencing factors may be hidden.

CONCLUSIONS

Large critical-depth flumes developed by the U. S. Department of Agriculture, Agricultural Research Service, provide a good automatic measure of the runoff from flashy, sediment-laden flows characteristic of many of the ephemeral streams in the Southwest..

Because of the relatively few runoff events and the need to obtain all possible information from these events, personal observations to augment automatic flow-measurement records are very desirable.

Recorder-well intake systems are a relatively weak point in the flume design, and future investigation in this field is needed.

Changes in the natural channel conditions by the flume may be important in studies both directly and indirectly related to water and sediment yields.

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