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Final Report
Hydraulic Model Studies

STREAM GAGING CONTROL STRUCTURE
IN THE RIO GRANDE

for

International Boundary and Water Commission
United States Section

by

S. S. Karaki

Colorado State University
Research Foundation

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ACKNOWLEDGMENTS

Grateful acknowledgement is given to the staff of the Hydraulics Laboratory of Colorado State University for assistance given in the model studies reported herein. The laboratory studies were conducted with participation and consultation by members of the field investigating team:

S. S. Karaki, D. B. Simons, A. R. Chamberlain, M. L. Albertson and A. R. Robinson. Considerable laboratory assistance was provided by R. M. Haynie and G. L. Smith. Dr. J. D. Lawson of the University of Melbourne, Australia also assisted greatly in the early part of the laboratory investigations.

Acknowledgements are given also to engineers J. F. Freidkin and W. E. Walker of the International Boundary and Water Commission, for their many helpful suggestions during the model studies.

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SUMMARY

Model studies were conducted in the Hydraulics Laboratory at Colorado State University to successfully develop an artificial gaging station control structure with a stable stage-discharge relationship for construction in the Rio Grande with emphasis on the Del Rio site. The recommended structure was Weir G (Fig. 8). The minimum satisfactory crest width of the weir parallel to the direction of flow, was found to be 10 feet. The recommended upstream and downstream slopes were 2:1 and 3:1, respectively.

A chart for setting the sill elevation with respect to the tailwater level was developed experimentally. Sand bars in the upstream channel, if formed close to the structure, were found to influence the water surface profile normal to the mean flow direction. Therefore, sand and gravel bars which may form in close proximity to the structure during floods may require modification in shape, or on occasions, removal of the bars. Strategic location of a weir to avoid bars immediately upstream is important.

INTRODUCTION

Under the Water Treaty of 1944 between the United States and Mexico, national ownership of waters of the Rio Grande from Fort Quitman to the Gulf of Mexico is determined from stream flow records on the main river and on its principal tributaries in both countries.

In order to improve the accuracy of stream gaging, which is subject to the natural shifting of channel controls and to deposition of sediment at or near the gage wells, the United States Section of the International Boundary and Water Commission had tentatively concluded that artificial controls in the river were desirable. This decision was concurred by a team of engineers from Colorado State University, Fort Collins, Colorado who visited several proposed field installation sites at the request of the United States Section of the International Boundary and Water Commission. The results and conclusions of the field investigation by the group are embodied in a report to the Boundary Commission entitled, "Locating and Designing Structures to Improve Stream Gaging Accuracy in the Rio Grande River Basin," Report No. CER6OSSK34, dated June, 1960.

In concurring that artificial controls in the Rio Grande were desirable, the report further includes general recommendations for the type and locations of the control structures. Because of many factors which were unknown at the time of the field investigation, it was recommended that a model study be conducted to provide adequate data for designing the recommended control structures.

The model study was originally planned to be undertaken in two phases. The first phase was planned for a generalized two-dimensional study of various structure shapes. The second phase of the model studies was intended to include a three-dimensional model of the Del Rio site; specifically to establish structure location and fundamental dimensions to assure adequate performance with respect to local sediment deposition and scour. As the study developed, however, the three-dimensional model was found unnecessary. Instead, further generalized studies were made in an 8-ft wide flume to study the effects on the transverse water surface profile of local deposition upstream of the structure by mutual consent of Colorado State University and representatives of the Boundary Commission.

This report will be confined to the model studies conducted in the laboratory. The objectives of the laboratory studies were:

1. To determine the general shape of the structure cross-section consistent with efficient and effective hydraulic performance.
2. To establish a structure with a stable stage-discharge relationship.
3. Determine a suitable crest width of structure parallel to the direction of flow.
4. Establish the controlling design features of the structure, i.e., height and location of the sill on the crest.
5. Locate suitable positions on the structure for stage and discharge measurements.
6. Make a general study of the effects of sand bars upstream of the structure on the transverse water surface profile.

MODEL SCALE CONSIDERATIONS

Two-Dimensional Studies

An undistorted model scale of 1:5, model to prototype, was chosen for the two-dimensional studies conducted in two 2-ft wide flumes as explained in the next chapter. The choice of scale was based on the physical dimensions of the available laboratory flumes. Initially, tests were conducted in a flume with movable bed. Later, tests were made in a rigid bed flume. With the chosen model scale, excluding considerations of modeling the sediment, the following relationships apply:

$$L_r = \frac{L_p}{L_m} = 5$$

$$q_r = \frac{q_p}{q_m} = (L_r)^{3/2} = 11.2$$

$$V_r = \frac{V_p}{V_m} = (L_r)^{1/2} = 2.24$$

Wide Flume Studies

Tests in the 8-ft wide flume were confined to studies of the effects of sand bars in the upstream channel on the lateral profile of the water surface over the control structure. Because the stage-discharge curve would be based on point measurements of stage over the control structure, variations in lateral water surface profiles can yield misleading discharge values.

A vertical distortion in model scale was used in the large flume to permit modeling of a wide river with large flume discharges. The horizontal scale used was 1:45 model to prototype and the vertical scale was 1:15. Using these scales the following values are determined:

$$L_r = 45$$

$$y_r = 15$$

$$q_r = (y_r)^{3/2} = 58$$

$$q_r = L_r (y_r)^{3/2} = 2610$$

$$v_r = (y_r)^{1/2} = 3.88$$

EXPERIMENTAL EQUIPMENT

Flumes

Two flumes were used for the two-dimensional studies. The initial studies were conducted in a tilting flume with a movable bed. The flume was 60 ft long, 2 ft wide and 2.5 ft deep. The side walls were clear plexiglass which facilitated observations. Both water and sediment were recirculated through a 12 inch centrifugal pump. Discharge was controlled by a gate valve and measured by a calibrated orifice in the discharge line. The water level in the flume (downstream from the structure) was controlled by a slotted gate at the downstream end. A schematic diagram of the equipment is shown in Fig. 1.

The second flume used in the studies was a horizontal rigid bed, 2-ft wide flume, 25 ft long. Only clear water was used for the studies conducted in this flume.

The 8-ft wide flume used for the studies on lateral water surface profiles was a recirculating sand and water system. The total flume length was 180 ft, but only 40 ft of this length was used for the studies. Within the test length the movement of the sediment bed was restricted by an overlay of cheesecloth. In this manner, the location and size of the sand bars could be better controlled without movement of the bed itself. By restricting bed movement it was believed to better represent the actual conditions in the Rio Grande. This will be discussed in more detail in subsequent sections.

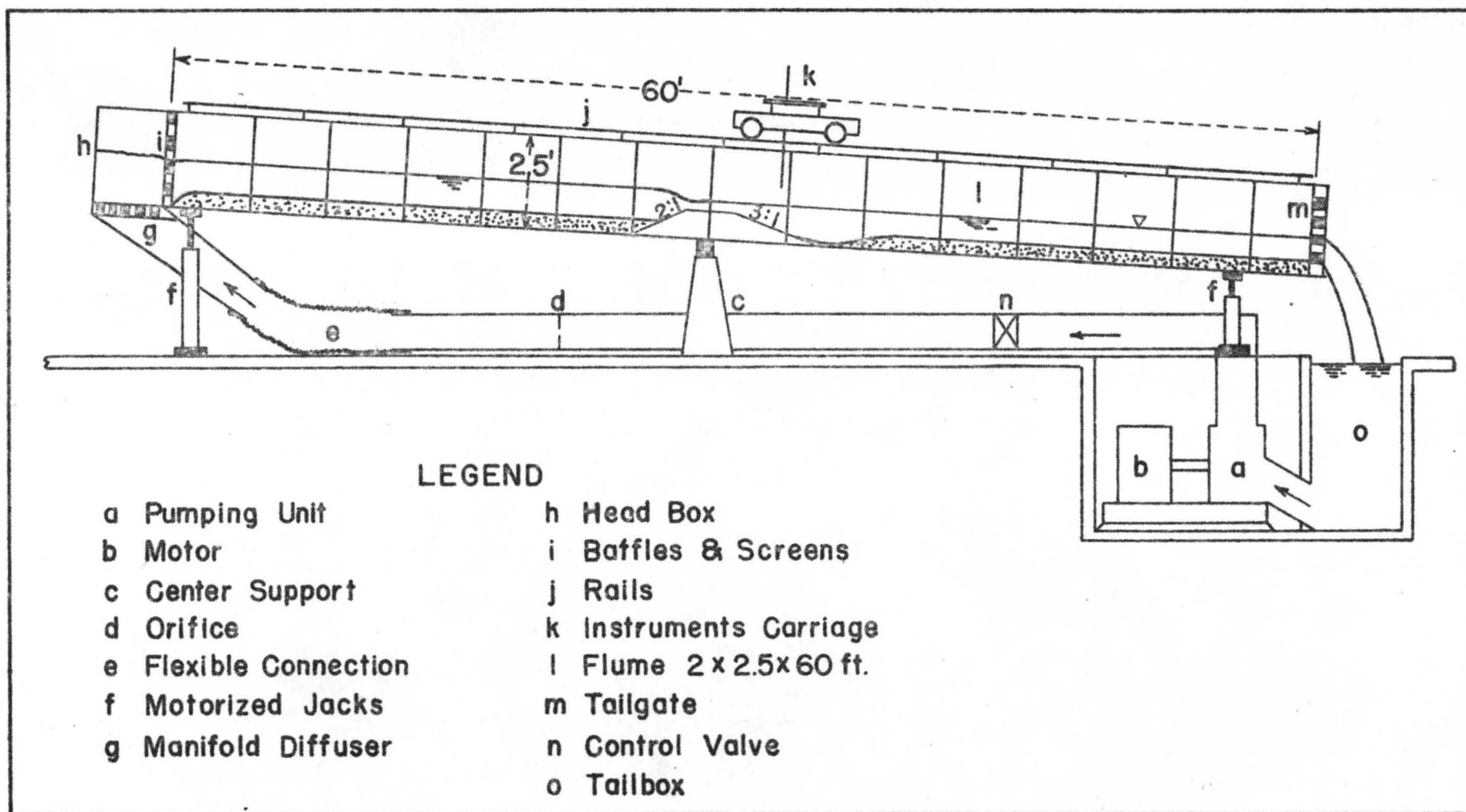


Fig. 1 Schematic Diagram of the Recirculating Flume

Sediment

Two types of sediment were used in the 2-ft tilting flume. The first was silica sand, having a median fall diameter (d_{50}) of 0.28 mm, and specific gravity of 2.65. Movement of particles for this sediment began at an average velocity of about 0.90 ft per second.

The second type used was light-weight material obtained from the Great Western aggregate plant in Laramie, Wyoming. Commercially the aggregate is used for concrete. The median fall diameter for this material was 0.37 mm with specific gravity of 1.78. Although detailed studies were not attempted to establish the velocity at which particle movement began, the observed velocity for incipient movement was much lower than for the first sediment used; at about 0.4 to 0.5 ft per second.

Weir Models

There were several variations in shape of broad crested weirs tested. The dimensions of these weirs are given in Figs. 2-8.

Weir A - The broad crested weir of Fig. 2 had the basic shape recommended in the Field Investigation Report. The upstream face was sloped at 2:1 and the downstream face at 3:1. The height of 16.2 inches was based on sand depth of 9 inches in the flume and crest height of 7.2 inches (3 ft prototype) above the average channel bed. The crest of the weir was 2.0 ft.

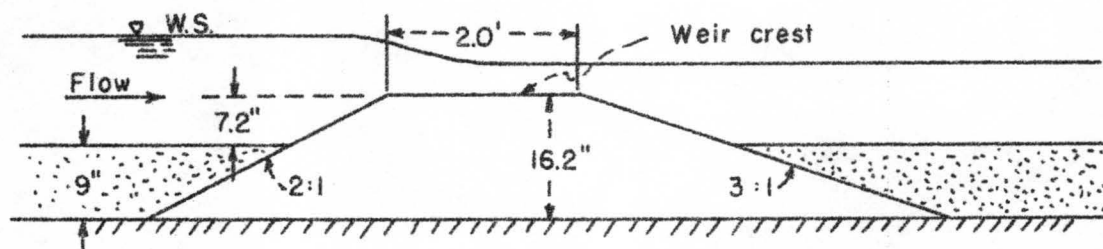


Fig. 2. Weir A

Weir B - The upstream and downstream slopes of this weir were changed to 3:1 and 5:1, respectively. Other dimensions were the same as in Weir A.

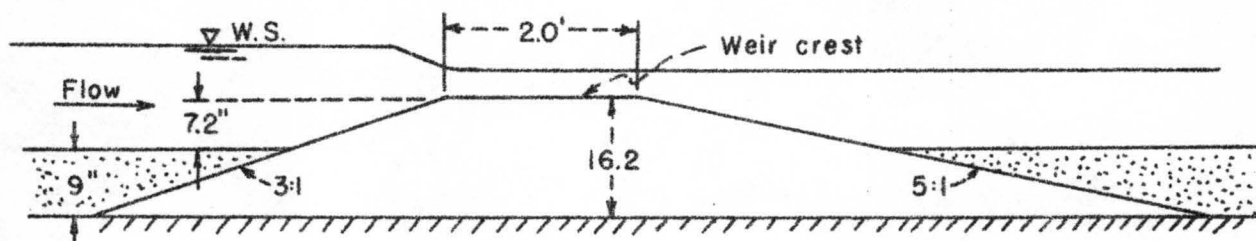


Fig. 3. Weir B

Weir C - A circular sill made of 3-inch pipe was placed at the upstream end of the flat crest of Weir A.

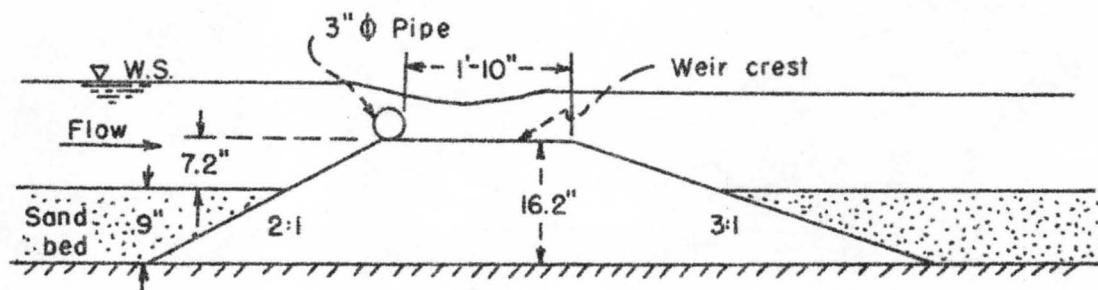


Fig. 4. Weir C

Weir D - The circular sill was placed at the downstream end of the flat crest of Weir A.

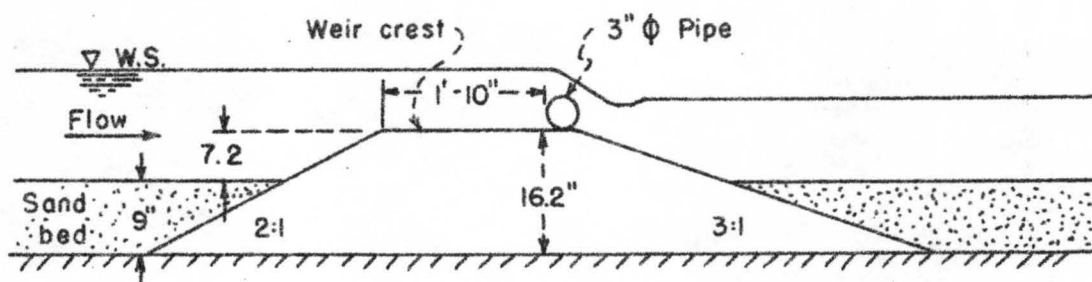


Fig. 5. Weir D

Weir E - The circular sill of Weir D was replaced by a square sill 2 inches high by 2 inches wide. The overall height of the structure was reduced to 10.25 inches to allow greater depths of flow in the flume. Part of the bed material was removed from the flume to permit the decrease in height.

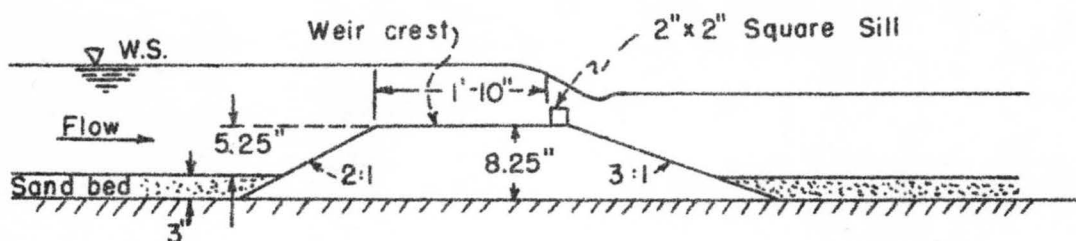


Fig. 6. Weir E

Weir F - Structure F was designed to keep the top of the structure free of sediment. This was accomplished by sloping the top of the structure upward at 1:11 to the high point of the crest.

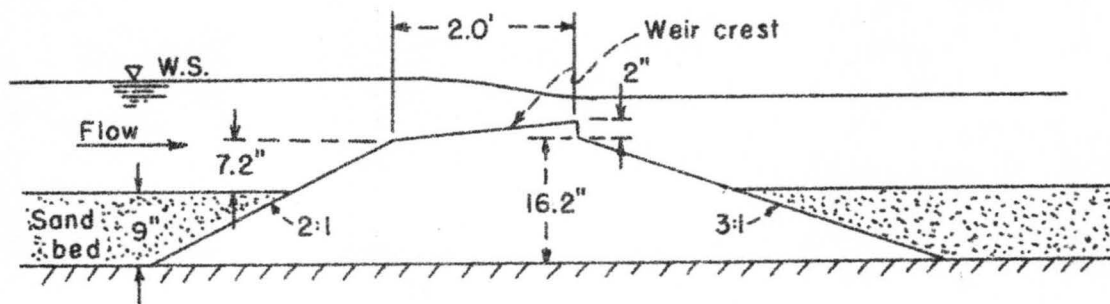


Fig. 7. Weir F

Weir G - This structure was a minor variation of Weir E, with a level section ahead of the sill. The downstream slope began at the top of the sill at a slope of 3:1. By starting the backslope at this point, the necessity for aerating the undermap of the flow was eliminated.

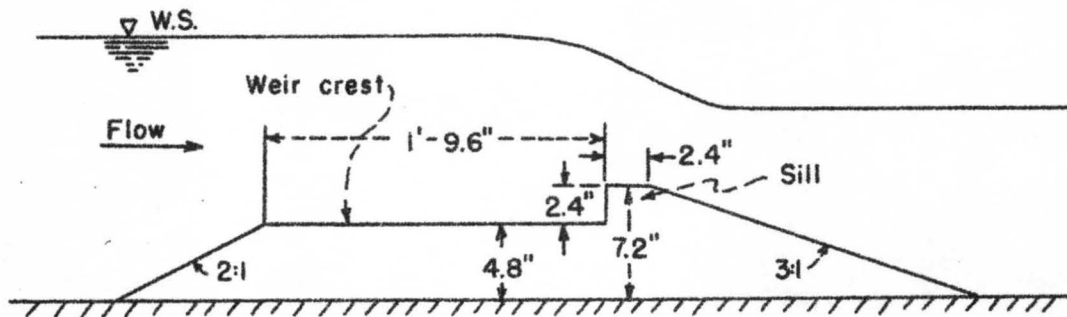


Fig. 8. Weir G Recommended Structure

EXPERIMENTAL PROCEDURES

The slope of the 2-ft flume was varied during the preliminary two-dimensional studies to determine its effect on the flow of water and sediment over the control structure. After these preliminary tests the slope of the flume was maintained constant.

To establish a test run in the movable bed flume, water was introduced into the flume from a source outside of the recirculating system and allowed to pond in the flume. When a sufficient ponding depth was developed, the pump was started and water and sediment were recirculated. By this procedure it was possible to avoid excessive and unrealistic channel bed movement during the initial starting stage. When recirculation was established, downstream flow depth was controlled by a gate at the end of the flume. Water surface elevations were measured with a point gage on a travelling carriage, and flume slopes were determined by level measurements.

The same precautions were not necessary for the rigid-bed 2 ft flume or the 8 ft flume. Water surface elevations for these latter flumes were also measured by point gage.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Weirs A and B

The results of studies with weirs A and B showed no readily evident effect on the discharge coefficient due to changes in slope of the upstream and downstream faces of the weir. The results are shown in Fig. 9 with coefficient of discharge C as a function of unit model discharge. The coefficient C was calculated from

$$Q = CLH^{3/2}$$

where

H = specific head above the weir

Observations were made on the transport of sediment at the weir during these tests. There appeared to be no observable difference in the movement of stream bed material over the structure whether at a slope of 2:1 as for Weir A or at a flatter slope of 3:1 as for Weir B. As the sand dunes which formed on the bed of the flume, moved downstream onto the structure, the dunes deteriorated in form in the region of accelerating velocity and the sediment washed over the structure. There was no deposition of sand on the weir crest.

Simulated step-wise hydrographs were run to investigate the effects of rising and falling river stage on the aggradation of the channel upstream of the structure. No attempt was made to relate this artificial hydrograph with runoff that might occur in the Rio Grande. The results shown in Figs. 10 and 11 indicate that in the recirculating flume the bed

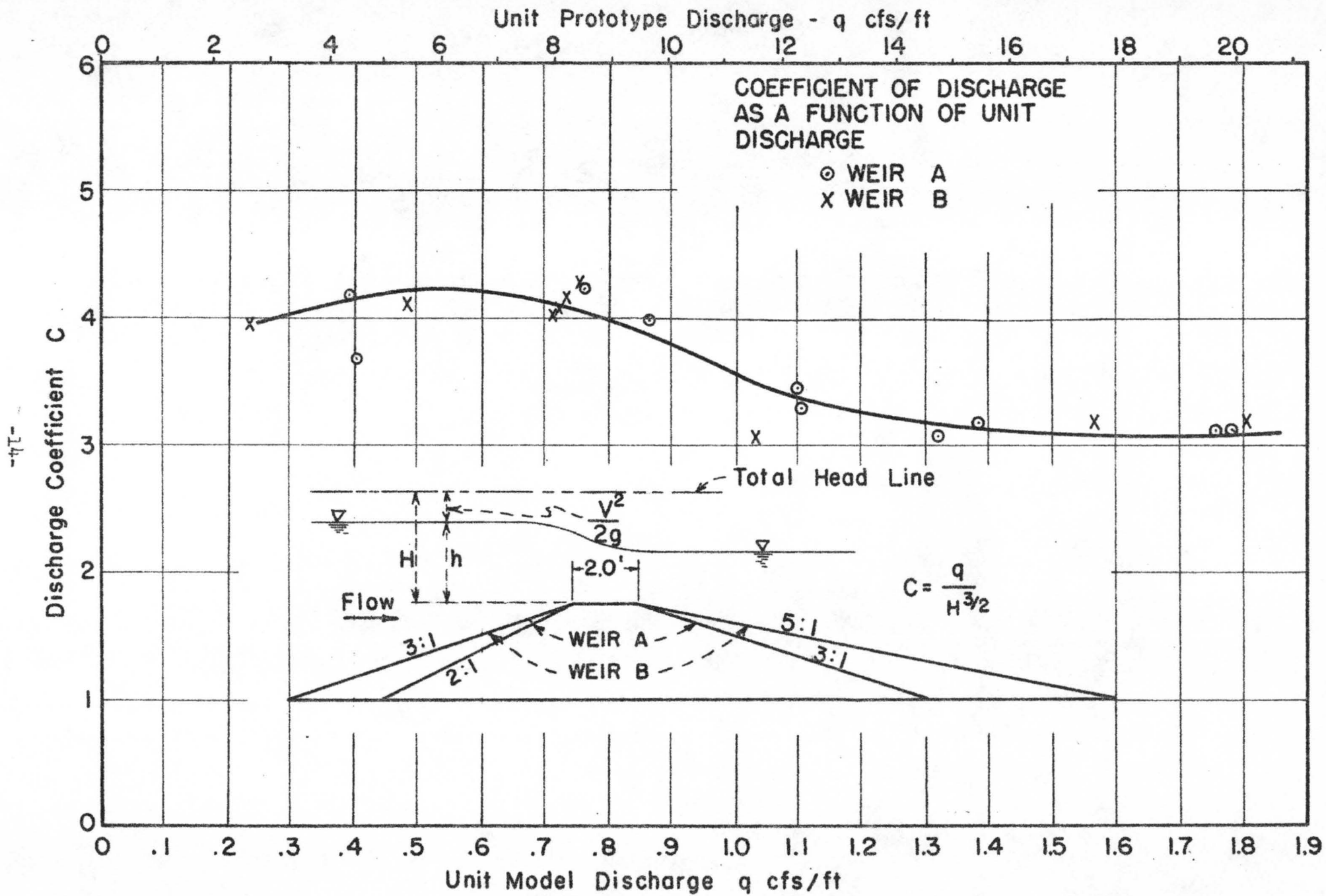


Fig. 9

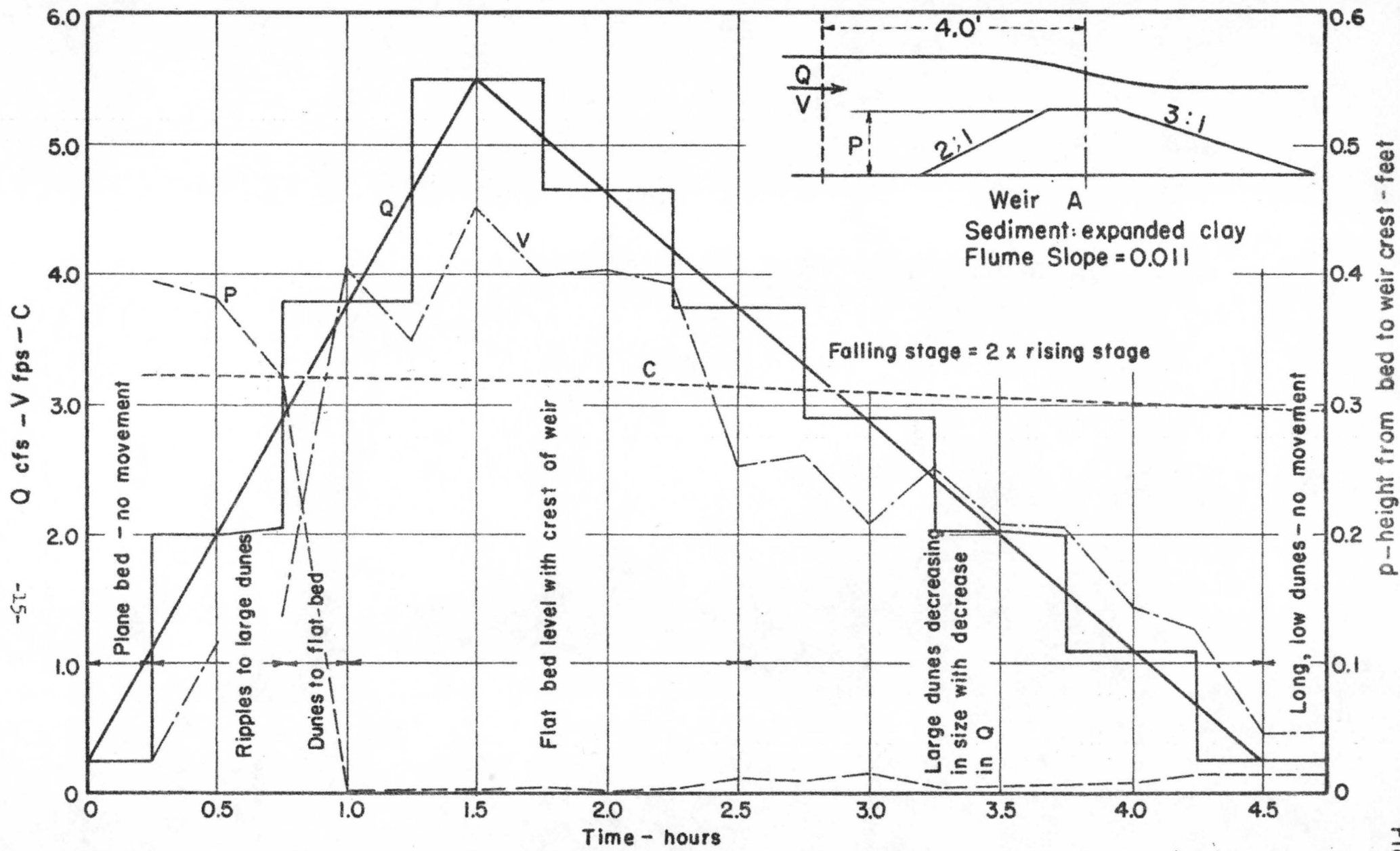


FIG. 10 SIMULATED HYDROGRAPH

Fig. 10

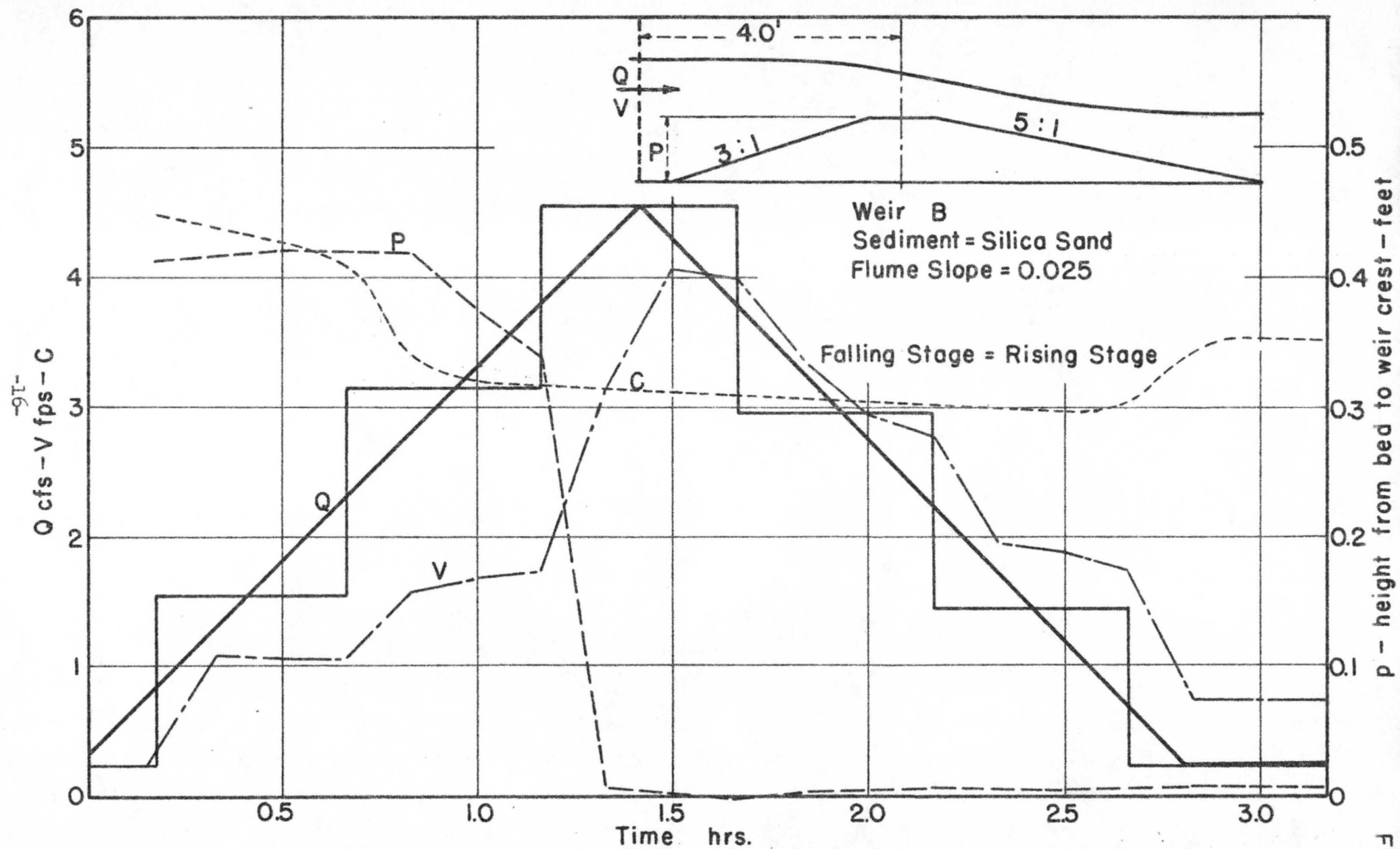


Fig. II Simulated Hydrograph

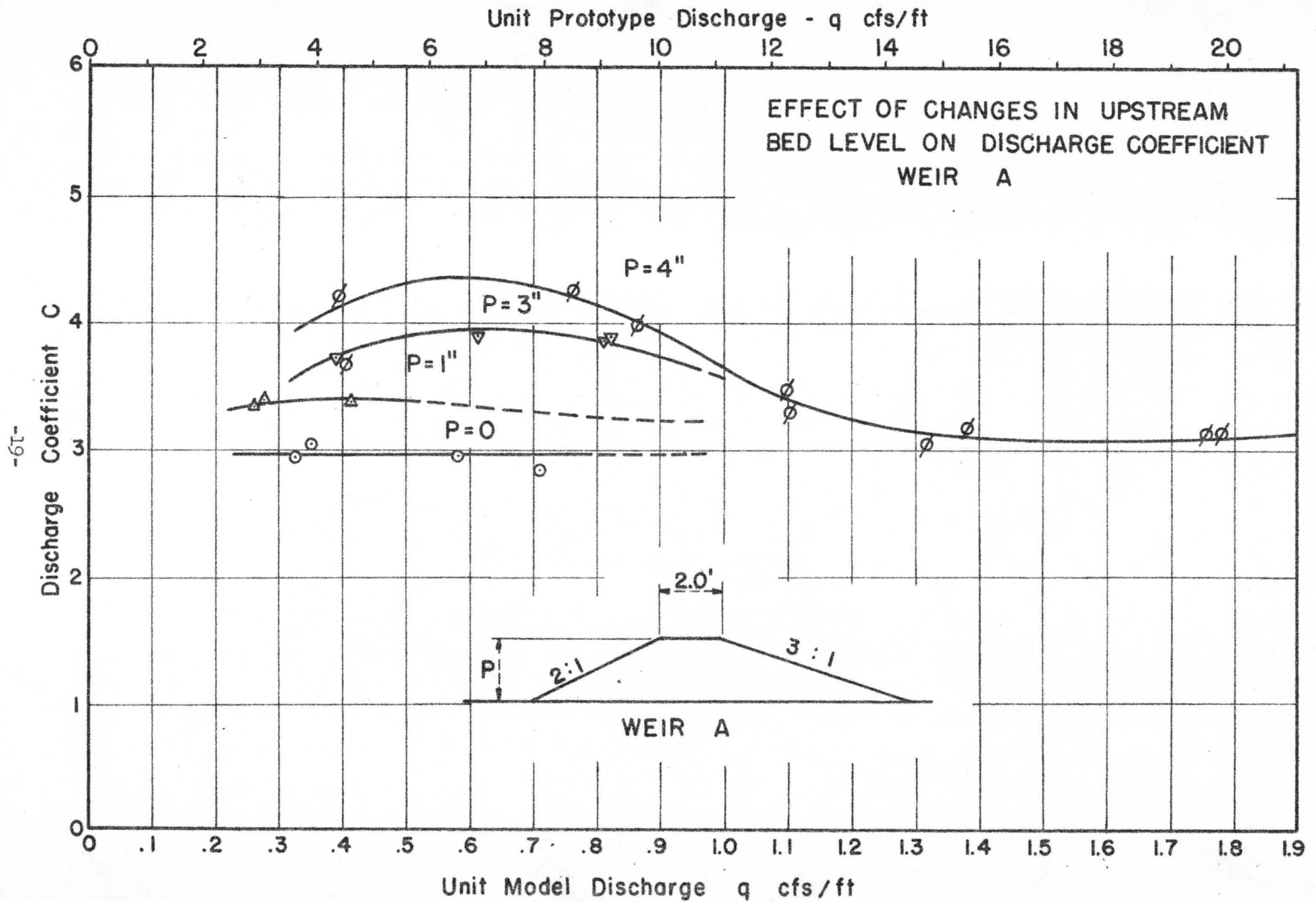
aggraded rapidly with increasing discharge and maintained its level near the crest height of the structure. (Trace the values of p with time).

Observations made during the field investigation of the Rio Grande indicated that the level of sediment deposition upstream of several existing weir structures was at an appreciable depth below the tops of the weirs. The apparent difference in aggradation between laboratory studies and prototype can be qualitatively explained by comparing the two systems. In the laboratory studies, a recirculating flume of both sand and water was used. The supply of sediment to the upstream end of the flume was dependent upon the amount of sediment transported into the tailbox (see Fig. 1). Generally, all of the sediment entering the tailbox is pumped to the head of the flume. If there is an unbalance in total sediment transport upstream and downstream of the weir in the flume, an adjustment will occur. With the existence of a control structure in the flume, the velocity upstream of the structure for flows not fully submerging the weir will generally be less than the velocity downstream. (At least, it was initially when the sand bed thickness was the same throughout the flume). More sediment is therefore transported from the downstream channel into the tailbox (and subsequently to the headbox) than is transported over the structure, thus aggradation will result. This was evident in Figs. 10 and 11 in the decreasing values of p with time. If, however, the sediment supply to the upstream end of the flume is somehow restricted, increase in discharge and velocity will cause degradation of the upstream channel. Actually, during these tests the former condition prevailed. The latter condition was enforced for the studies in the 8 ft flume to avoid the difficulty experienced in the smaller flume.

In the field system, that is in the Rio Grande in the reach from Langtry to Del Rio, it is visualized that a condition varying between the two extremes cited above probably occurs. During floods, tributaries may contribute considerable quantities of alluvial material to the main river. When the flow in the tributaries recede significantly and sediment inflow to the main river stops, the transport capacity of the residual flow in the main river is probably still sufficient to transport the available fine sediment material downstream over the structure. It is possible also that an unbalance may occur in nature as it did in the 2-ft flume, where the sediment supplied by a number of tributaries may equal or exceed the total transport capacity of the main river thus causing deposition in the river channel. This is not likely to occur in the reach of the Rio Grande from Langtry to Del Rio, especially with fine sediment. It is possible for this to occur, however, with large materials (cobbles and boulders) and if the location of the structure in the river is very near heavily contributing tributaries.

The hydrograph studies also indicated variation of the discharge coefficient with both discharge and upstream aggradation. (Note changes of C and p with time on Fig. 11). Results of studies conducted with changing values of p , where p is the height of the weir above the upstream bed, are given in Fig. 12.

The values of C vary with both p and unit discharge q , for q less than 1.3 cfs per ft in the model (approximately 14.5 cfs per ft prototype). When the bed was level with the crest, C remained essentially constant. The change in the discharge coefficient was probably



due to changes in the pressure profile along the crest and velocity profiles in the vertical over the crest of the structure with changing flow depths and upstream bed levels. This seemed to be borne out by the fact that there was essentially no variation of C when the bed was level with the crest of the structure. Actual measurements of velocity and pressure profiles were not made, however.

The change of C with p represents a disturbing phenomenon in attempting to obtain a stable stage-discharge relationship of the flow over the structure. A shifting rating curve for the artificial control below a discharge of about 10,000 cfs would be unsuitable in the Rio Grande.

Weir C

Weir C was conceived as a variation of Weir A to provide a more stable discharge coefficient. The stability of C is evident in Fig. 13 when compared to the coefficients of Weirs A and B. While a more stable coefficient was obtained for this structure, the undesirable feature of this weir was that high velocities were created on the crest of the structure because of the convergence of the streamlines downstream of the sill. The high velocities would render difficulty in obtaining current meter measurements on the structure. Furthermore, at certain tailwater conditions considerable wave action was generated, and a hydraulic jump could also develop. Under these conditions meaningful stage and discharge measurements would be impossible.

Weirs D and E

Weirs D and E were tested subsequently to overcome the undesirable features of Weir C while still maintaining the stability of the discharge

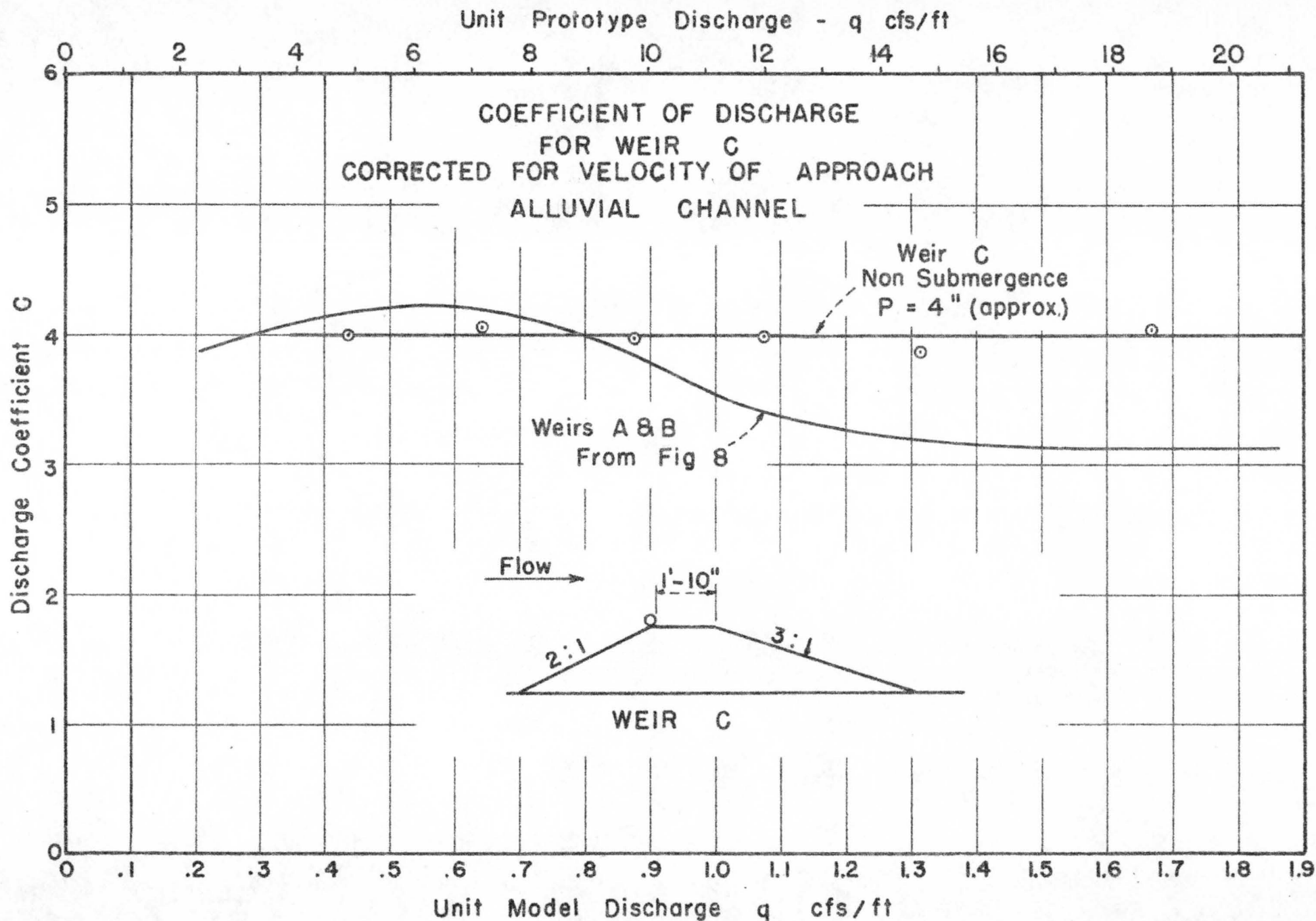


Fig. 13

coefficient. Fig. 14 shows the results of the tests. With the sill located on the downstream end of the normal broad crested weir, the flow over the crest of the structure was subcritical. It would be easier therefore, to obtain current meter measurements on the structure. Note that there was a significant difference in the discharge coefficient between the rounded sill and the square sill.

Weir F

A modification of Weirs D and E was made in Weir F. By providing an adversely sloping crest, sediment deposition on a substantial portion of the crest was prevented. The sloping crest, however, created non-uniform flow and considerable difficulty would be experienced in obtaining current meter measurements of discharge. Stage measurements to a sloping water surface would not be particularly objectionable as long as the rating remained constant. The variation in coefficient of discharge is shown in Fig. 15.

Weir G

Weir G is a modest variation of Weir E with the only change being the point at which the downstream slope of the structure begins. By starting the downstream slope at the top of the sill, necessity for aerating the undernap of the overfall was eliminated. Most of the studies conducted on Weir G were made in the clear-water 2-ft flume.

Water Surface Profiles - Water surface profiles over the weir at various unit discharges are shown in Fig. 16. The dimensions are given in terms of the prototype. For unit discharges up to about 25 cfs per ft there is a level water surface over approximately the middle one-third of the

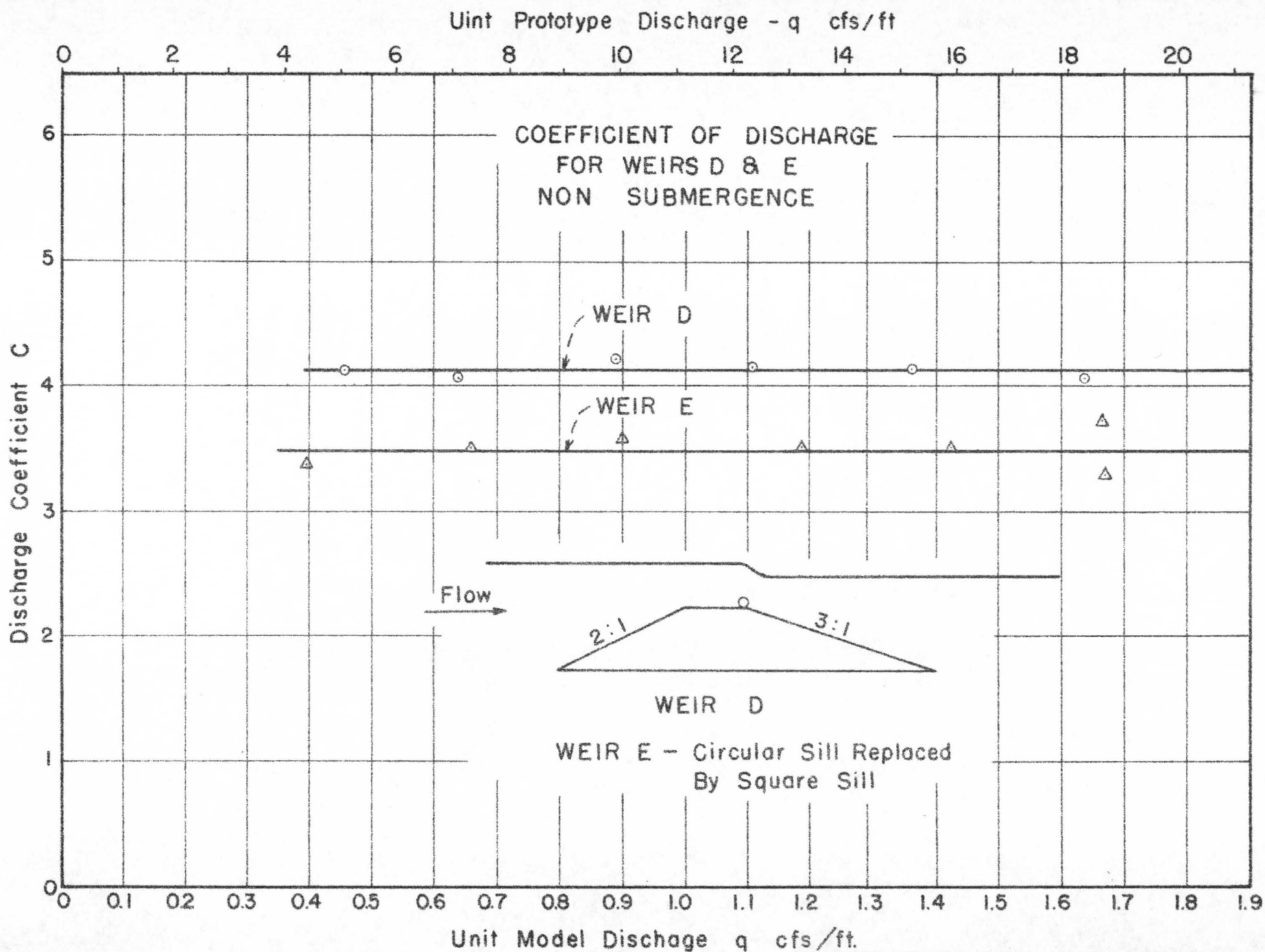


Fig. 14

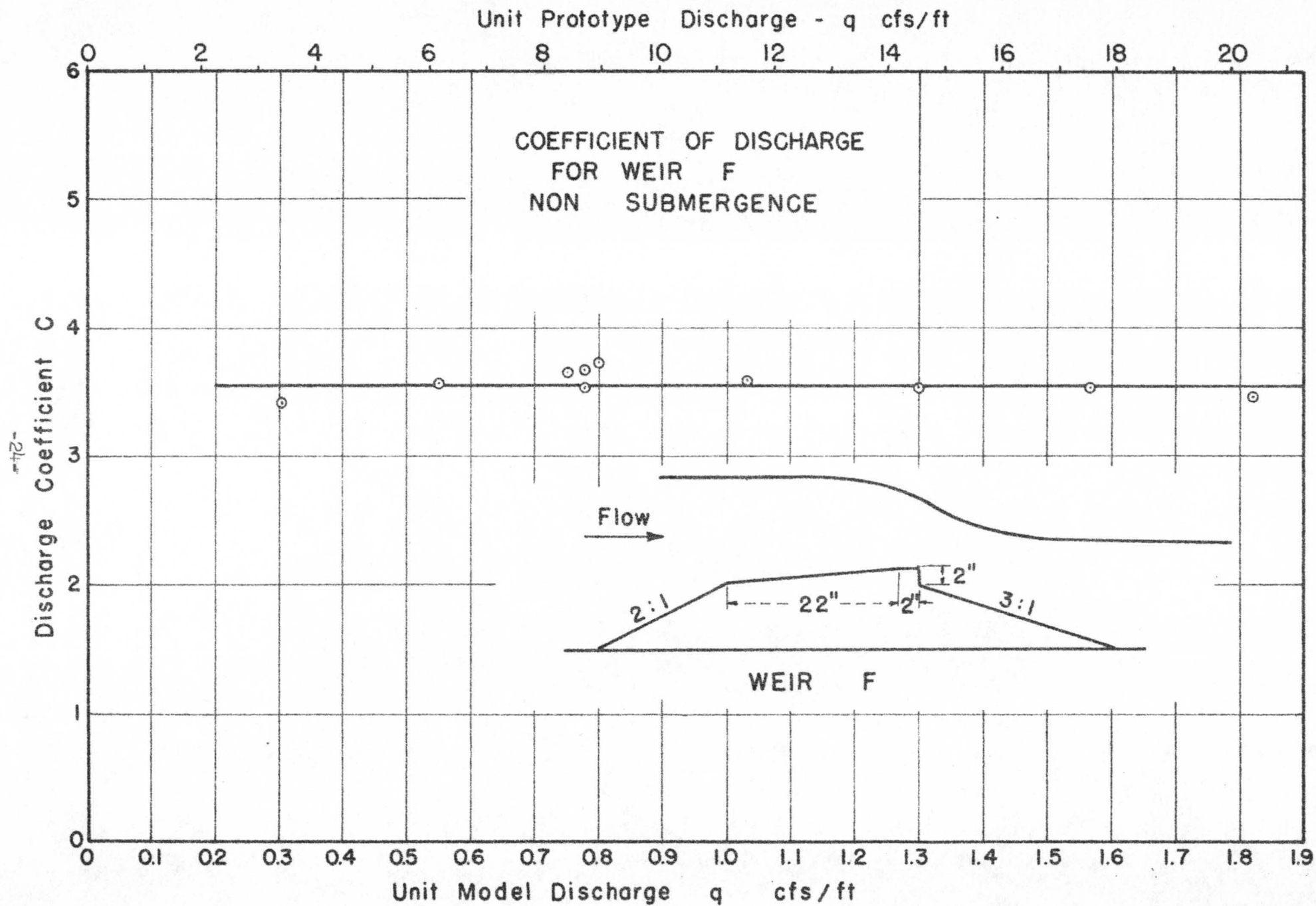


Fig. 15

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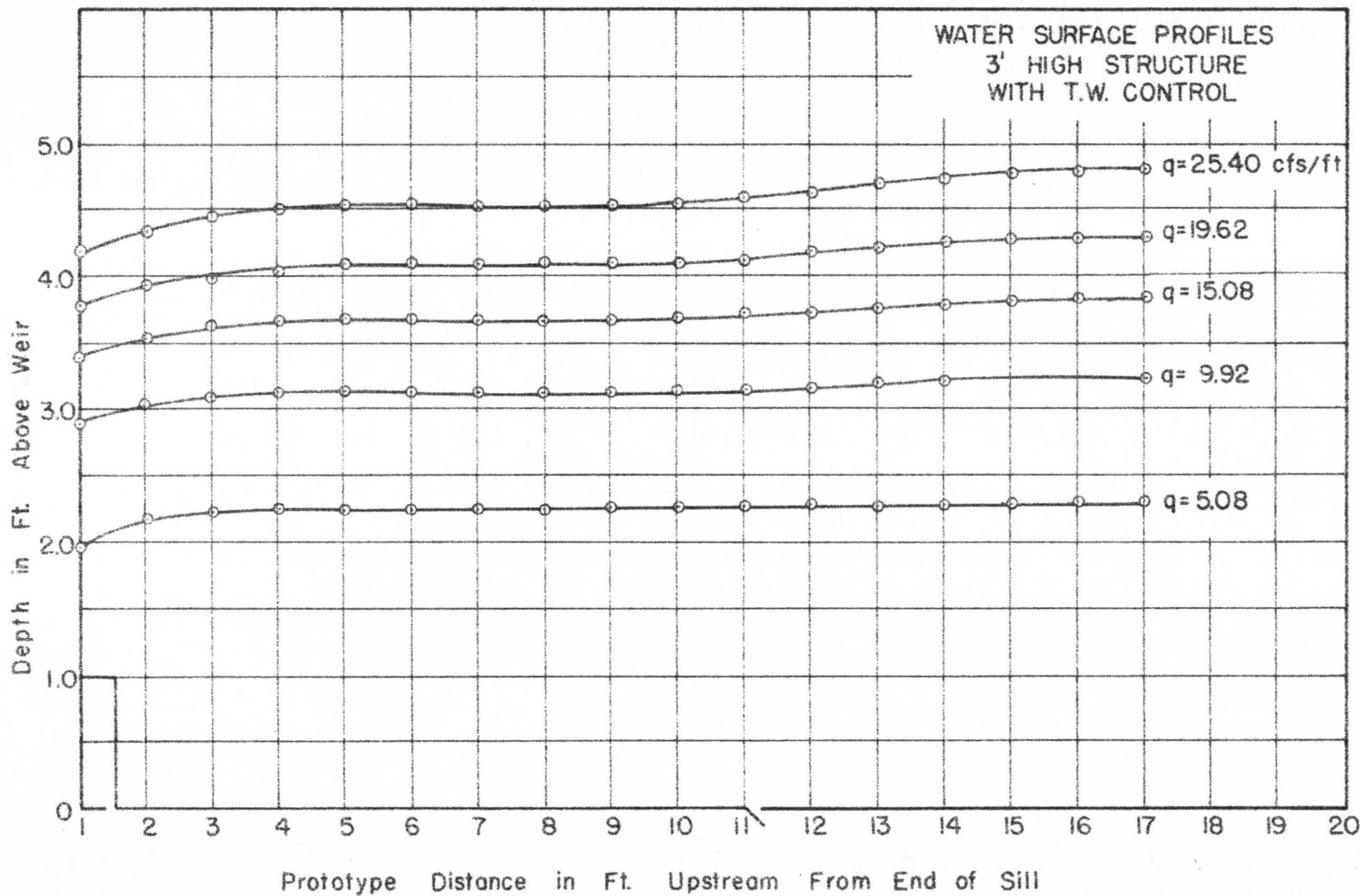


Fig. 16

crest width. In establishing a stage-discharge curve, measurements of discharge and flow depth should be made within this middle third. Measurements closer to the sill or the upstream end of the crest will encounter extreme curvatures in the streamlines and should be avoided.

Stable Rating Curve - Studies were made to determine the effect of changing upstream bed level. The stage-discharge curves for various values of p are shown in Fig. 17. The tailwater curve used during these studies is also shown on the same figure. The data shows that there is no appreciable difference in stage with changing upstream bed level, where stage is measured 5 feet upstream from the upstream face of the sill and if the tailwater curve remains unchanged. If however, the tailwater rating curve changes, there will be an effect on the stage-discharge curve, unless the structure is sufficiently high to be out of its influence. An extreme case of change in tailwater and the subsequent change in stage is shown in Fig. 18. Since the proposed Rio Grande control structures are to have stable stage-discharge curves for discharges from 100 to 10,000 cfs, it would be necessary to set the sill elevations of the weirs in favorable positions relative to the tailwater expected at the highest design discharges so that changes in the tailwater rating curves could not affect the stage-discharge curves.

Figure 19 shows the relationship between upstream depth of water above the sill and tailwater elevation relative to the top of sill for Weir G, for various unit discharges. If the submergence is less than 60 percent, stage will be independent of tailwater level. This chart applies only to the configuration of the structure shown. By use of Fig. 19 and

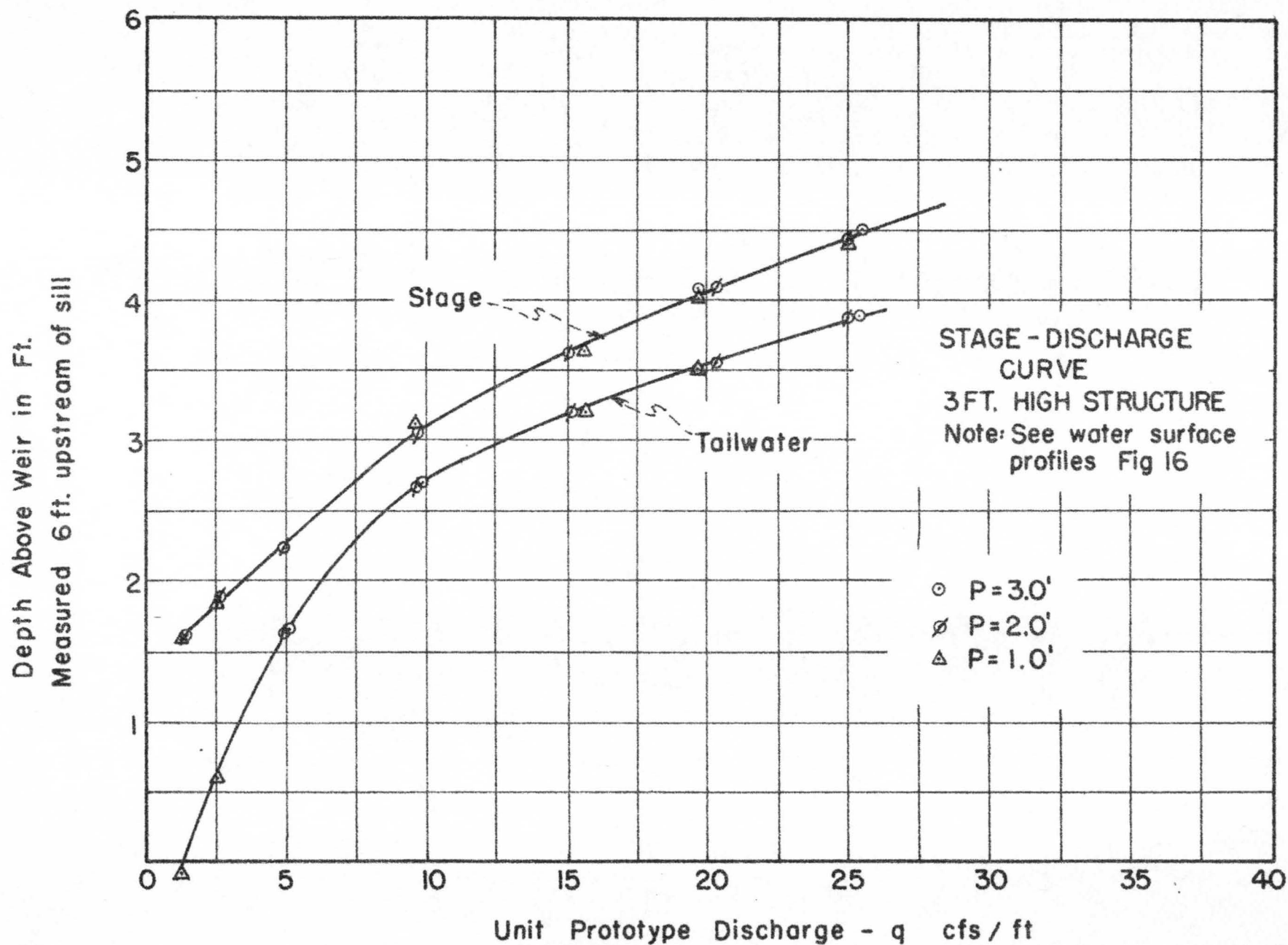


Fig. 17

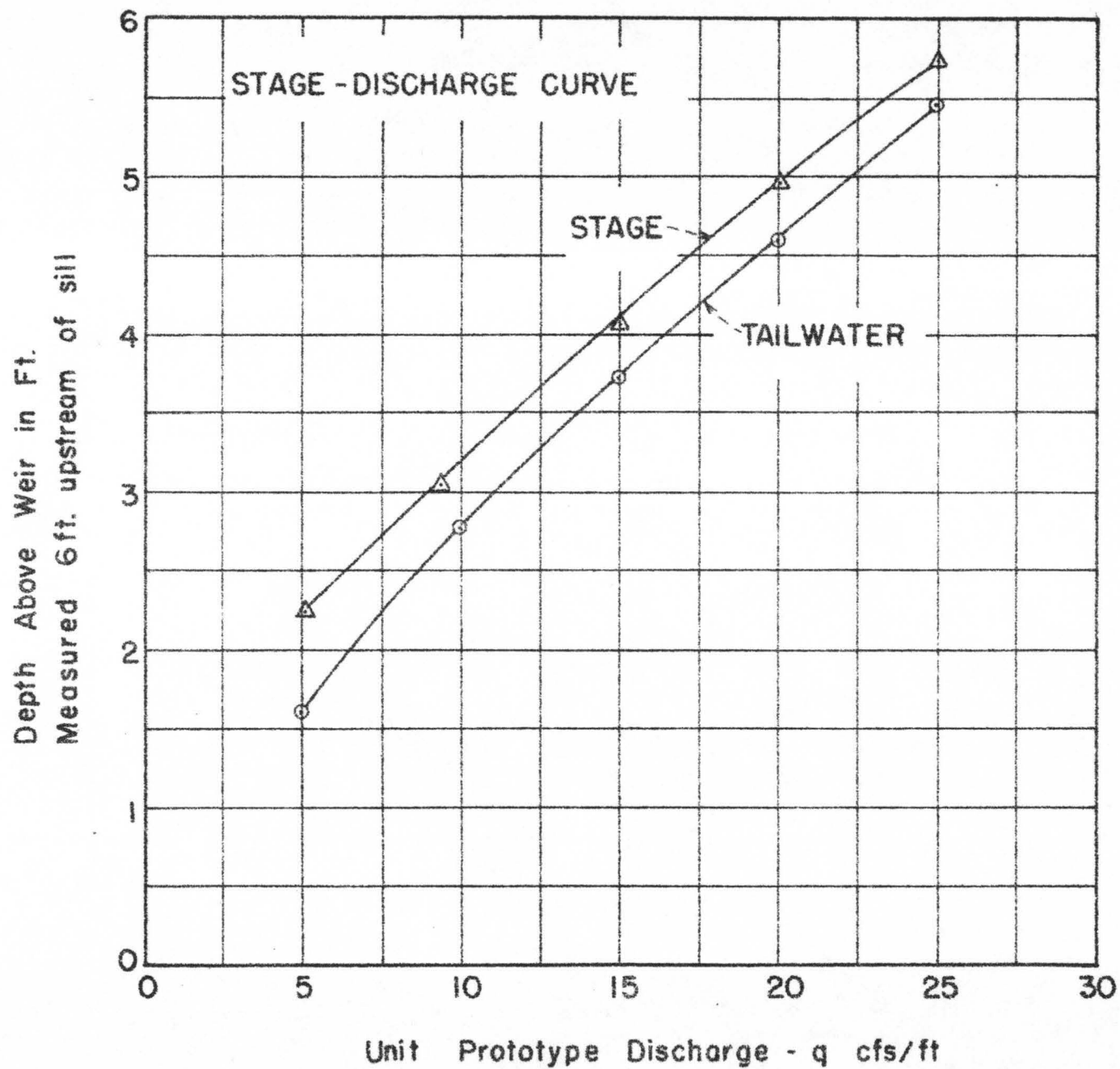
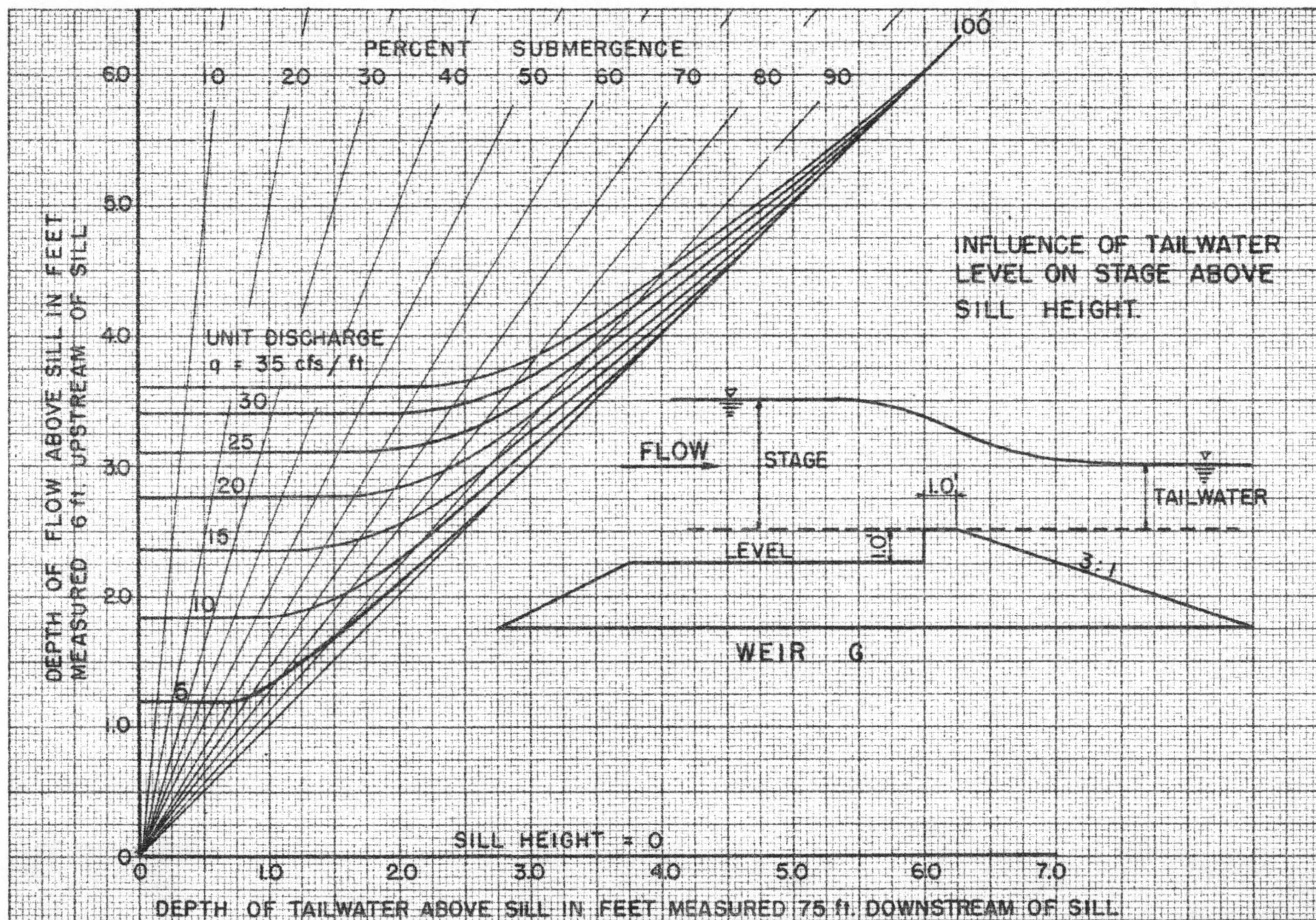


Fig. 18



knowledge of flow depths in the river at different discharges, the sill elevation for the structure can be determined.

Sill Height and Shape - It is desirable that the water depth over the crest of the structure be greater than critical depth so that flow measurements can be made on the crest of the structure. The height of sill at the downstream end of the weir relative to the crest, should therefore be sufficient to maintain control through the desired range of discharges, yet not be too high so that velocities at the lower flows would be too small for measurement by current meter. A sill height of one foot was found to be adequate to maintain control and was used throughout the studies of Weir G.

Consideration was given to the possibility of sloping the sill and crest of the structure laterally across the channel to provide a low point for flow measurement at low discharges. Unless the angle of the V so-formed is fairly small, considerable variation in the water surface over the sill could result at low discharges. Visualize a lateral slope in the sill of 6 inches in 200 feet. (0.0025). Similar difficulties would result at high discharges because of cross flow and resulting non-uniformity of flow over the weir.

Sand Bars - The results of studies in the 2-ft flume showed that aggradation of the upstream bed to the crest of the weir does not affect the stage-discharge curve. Therefore, sand bars at or below this level will not affect the flow distribution or lateral water surface profile over the weir.

The studies were concentrated on sand bars that extended above the crest of the weir. Various widths and locations of the bars relative to the structure were investigated. To facilitate the laboratory procedure,

concrete blocks were used to simulate stationary sand bars. Studies were also made to a limited extent with moving bars in the upstream channel.

Sand bar lengths were first investigated. Successive increase in lengths of the bars from 2 ft to 12 ft (model dimensions) did not effect a difference in the flow distribution. The increases in length were always parallel to the flow. Thereafter, bars of about 3-1/2 ft in length were used.

The sand bars were enlarged laterally in the flume at various positions upstream of the structure. For the case of sand bars extending above the water surface, the effect of its presence in the channel was noticeable on the water surface profile if the bars were close to the structure. When the bar extended about 25 percent of the width from one side of the flume, its presence within 300 ft of the flume at a unit discharge of 29 cfs per ft (prototype) affected the water surface slightly. When the bar was placed further upstream the effect was not noticeable and was greater when located closer to the structure.

The effect of sand bars was also dependent upon the discharge. For the same size bar and location within the channel, lower discharges did not affect the water surface profile in the same manner. In principle, the bars must be sufficiently far upstream from the structure so that the flow beyond the bar can fully diverge across the entire width of the channel.

Sand bars which did not extend above the water surface were also studied. It was found that larger bars in lateral extent could be allowed for a comparable effect on the water surface profile. At a distance of 300 ft upstream from the structure, for instance, 40 percent lateral constriction

could be tolerated in a channel 360 ft wide. Various arrangements of sand bars on both sides of the channel were also tested. In general, any arrangement of sand bars which tends to increase the concentration of flow within the upstream channel will affect the flow distribution at the structure, unless as stated previously, sufficient distance is available for the flow to diverge.

Moving sand bars were studied with various arrangements of groins in an effort to alter the flow distribution and to create sufficiently high velocities in the restricted channel to accelerate the movement of the bar. No satisfactory arrangement of the groins were found.

If a bar of significant size is deposited by a flood in the proximity of the structure, the most practical and economical solution would be to mechanically level off the top of the bar.

CONCLUSIONS

Structure

The results of the model studies showed that Weir G (the cross section of which is shown in Fig. 8) would be suitable for use in the Rio Grande as a control and measuring structure. Modification of the sloping faces of the weir flatter than 2:1 and 3:1 for the upstream and downstream slopes, respectively, did not improve the hydraulic performance of the structure. The crest of the structure should be wide enough, parallel to the flow, for the establishment of a good measuring section. For unit discharges up to 25 cfs per ft, 10 ft would be sufficient, but wider structures may be used. Measurements of discharges and stages should be made within the middle third of the structure. The recommended height of sill is one foot above the crest of the weir. (See Fig. 8.) This height will allow control to be maintained at the sill and create sufficient velocities over the crest of the structure at low discharges for measurement with a current meter. The elevation of the top of the sill with respect to tailwater level must be established with adequate field information on stage discharge relations at the site. Use of Fig. 19 will assist in the establishment of the sill level.

Stage-Discharge Relation

The stage-discharge rating at the structure is unaffected by upstream channel aggradation so long as the bed does not aggrade above the crest of the structure. It is affected, however, at any unit discharge by changes in tailwater level if the submergence is greater than about 60 percent.

Sand Bars

Sand bars of sufficient height in the vicinity of the control weir can affect the distribution of flow in the channel, hence, the stage-discharge curve. Existence of such sand bars should be limited in its proximity to the structure by mechanical removal.

APPENDIX

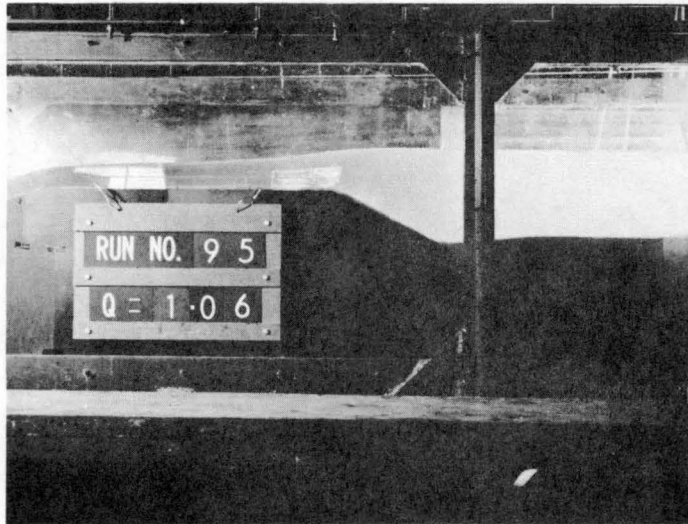


Fig. A-1. Weir A in 2-ft Flume with Sand Bed.

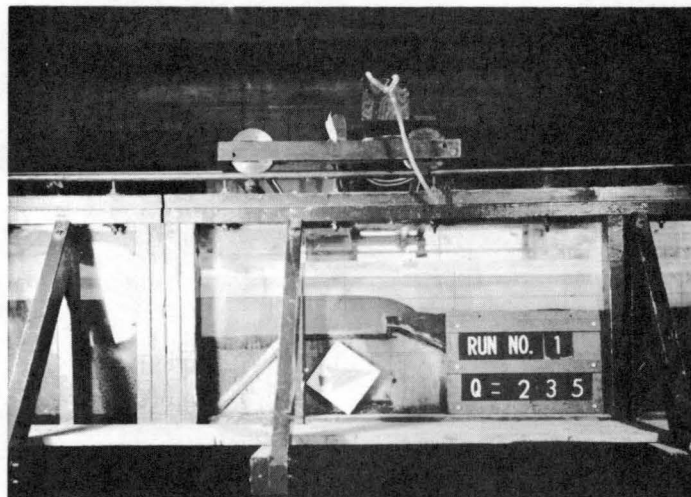


Fig. A-2. Profile View of Weir and Sand Bar Studies.

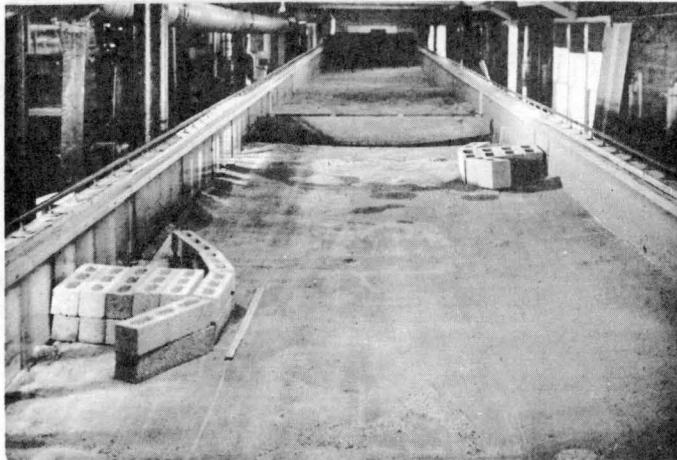


Fig. A-3. Sand Bar Studies in 8-ft Flume.
Cheese-cloth on Flume Bed with
Concrete Bar Sand Bars.

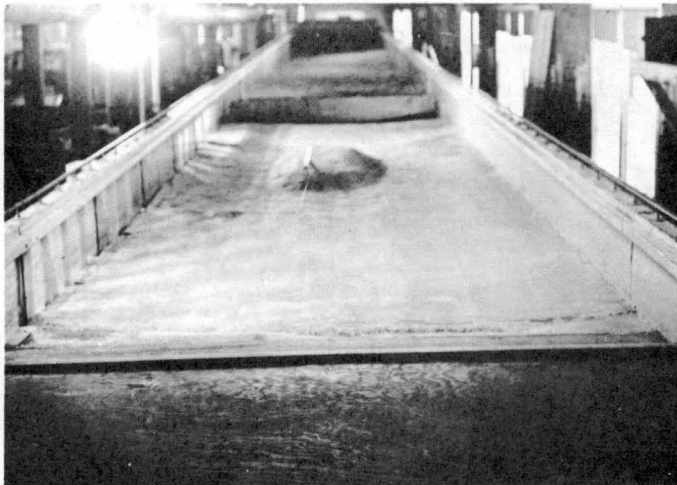
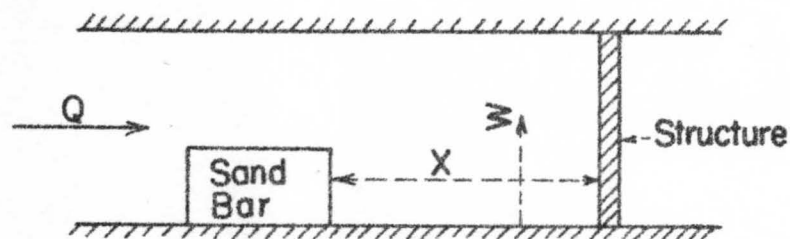


Fig. A-4. Sand Bar Studies with Sand Bar
in Center of Channel.

Fig A-5



STAGE VARIATION
AT STRUCTURE DUE
TO SAND BARS IN
UPSTREAM CHANNEL

40% Constriction
Sand bars below
water surface

