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The Venturi Flume

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This bulletin is based on experiments conducted in the hydraulic laboratory at Fort Collins, Colo., at Cornell University, and at the field laboratory at Bellvue, Colo., under co-operative agreement between the Irrigation Division of the Bureau of Public Roads, U. S. Department of Agriculture, and the Colorado Agricultural Experiment Station.

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THE VENTURI FLUME

By

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A preliminary report on the Venturi flume was prepared by V. M. Cone and published in the Journal of Agricultural Research, Vol. IX, No. 4, April 23, 1917. This report was not intended to cover the whole subject, but rather to present the possibilities of this device as a practical means of measuring flowing water for irrigation purposes. The original investigations were made at the hydraulic laboratory at Fort Collins, Colorado, but, due to the inadequate facilities, it was not possible to carry the experiments to the point most desirable from an irrigation standpoint. Under a co-operative agreement between this Bureau and Cornell University, experiments were conducted at the Cornell hydraulic laboratory under the supervision of Dr. Schoder and the late Professor Turner on the larger sized flumes, where flows of 300 to 400 second feet were used. Additional experiments were performed at the field laboratory on the Cache la Poudre river at Bellvue, near Fort Collins, Colorado, in order to properly correlate all the tests previously made. All these data were not available at the time of the first published report, and in our subsequent study, various characteristics of the flume have become apparent which were not evident when the original experiments were made.

This bulletin is intended to present a more complete statement as to the law of flow through the Venturi flume and also to define more clearly its limitations and advantages.

Many devices have been developed for the measurement of water for irrigation, but, due to the great variation of the conditions as found in practice, no individual type has yet been found which exactly meets all of the requirements. The standard methods of measuring flowing water are all more or less affected by the ever-changing condition of the channel, either immdiately above or below the structure, or else the capacity of the device limits the discharge.

The overpour, sharp-crested weir is the most accurate method of determining the quantity of flow, but certain requirements as to contractions and velocity of approach must be maintained in order to keep the weir standard. The accuracy of measurement is only possible at the expense of considerable loss in head or grade of the channel, and in many cases the installation of the standard weir is impossible on account of the lack of fall. This is especially true where large quantities are to be measured. Where the water carries considerable silt, there is a tendency to fill the weir basin with sediment, which affects both the contractions and the velocity of approach. The submerged orifice and weir are limited to practically the same requirements, in so far as contractions and velocity of approach are concerned, but permit of operation under conditions where a small loss of head is important.

The rating flume, which is nothing more than a constant section through which the water passes, is the accepted standard for the measurement of the comparatively large flows. This method of measurement is subject to various effects, and is only rarely found to maintain a constant condition. Experience indicates that, in the majority of cases, the rating flume is wholly unreliable, due to the change of velocity of approach, silting conditions in the flume and the accumulation of vegetation in the channel, as well as along its banks. It is not uncommon to find the rating flume affected by check boards, placed in the channel below the flume, for the purpose of raising the water sufficiently to permit the irrigation of higher lands.

The Venturi flume has been developed to meet these various conditions; however, it is not claimed that this device is accurate to the last degree, but under ordinary conditions it is believed to be very much more dependable than our present accepted methods. A number of these Venturi flumes have been installed and are in actual use, and it has been found that this new device possesses the following desirable features: *

1—It is moderately inexpensive and simple to construct.
2—It is simple in its operation.
3—It requires little maintenance.
4—It is free from working parts.
5—It is sufficiently accurate to meet practical needs.
6—It is unaffected by sand, silt or floating trash.
7—It requires but little loss of head in its operation.
8—It possesses a very wide range in its capacity of discharge.

Altho the Venturi flume possesses many very desirable features, there still remain certain defects in the present design that work to its disadvantage. It is believed, however, with further

*(Journal of Agricultural Research, Vol. IX, No. 4, V. M. Cone)

experimentation, that some of the undesirable features can be very greatly modified, if not entirely eliminated. In order to completely correct these defects, it may be necessary to change the design of the present flume in some respects in order that a more uniform or stabilized condition will exist in the down stream or diverging section. In view of the fact that considerable work had already been done on the present type of flume, and further, since a number of these flumes are now in operation, it was thought advisable to complete the investigation along the original lines, and later to continue with the idea of attempting the improvement of the present flume.

The present type of Venturi flume (Plate 1) consists of a contracted section through which the water passes, or essentially, a flume with a converging and diverging section, with a short "throat" section between them. The effect of passing liquids through con-

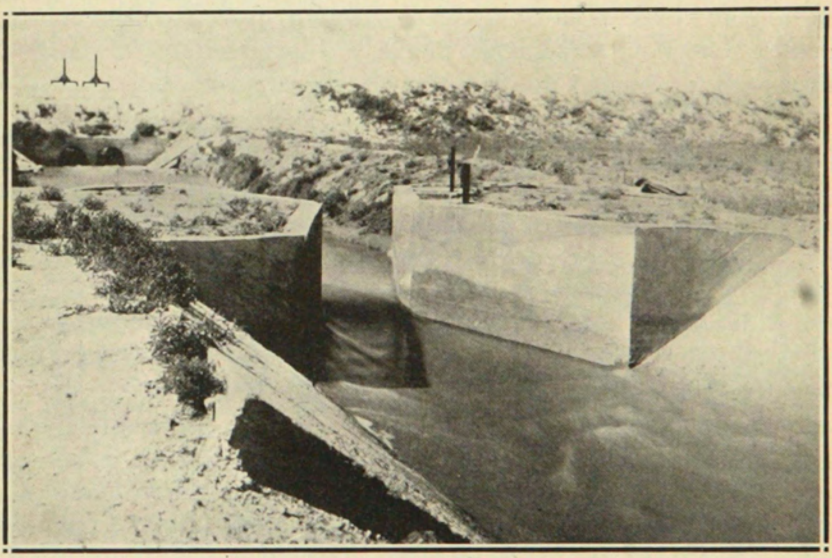

PLATE I.—Field Installation of Three Foot Concrete Venturi Flume of Rectangular Cross Section.

verging and diverging tubes was known to the Romans, and later, in 1797, Prof. Giovanni Battista Venturi, an Italian philosopher, studied this phenomenon and after many careful experiments performed at the University of Modena, stated the law in definite form. Nearly 100 years later, Clemens Herschel made the practical application of the Venturi principle to the measurement of water flowing through pipes. The Venturi flume is an adaptation of the

Venturi principle, but the water passes the contracted section without pressure; that is, exposed to atmospheric pressure only. The Venturi principle, as applied to an open flume, manifests the same characteristics as when the flow is confined in a tube; namely, there is a reduction in the head at the contracted section.

The floor of the Venturi flume is level and placed at the elevation of the grade of the channel. The short throat section forming the contraction has been arbitrarily taken as 1 foot long for the various sizes calibrated, and midway along the axis of the throat the head is observed. The head in the converging section is observed at a point on the side of the flume. This point is twice the width of the throat from the upper edge of the throat, and this distance is measured along the longitudinal axis of the flume. This distance was arbitrarily taken so as to give a point well within the converging section, and to be so situated as to correctly register the head at that point. The flow through the flume will be a certain function of these two heads, and the width of the throat.

In the preliminary investigation of the Venturi flume, various slopes of the converging and diverging sections were tried out, and from the standpoint of economy and the general behavior, it was decided to base all the calibrations of the various sizes of rectangular flumes on the general plan that the total length of the flume would be six times the width of the throat, plus 1 foot, and that the width of the flume at either end would be three times the width of the throat, but more recent observations prompted the suggestion that this originally assumed plan should be somewhat modified.

Our investigation so far has been confined very largely to the rectangular flumes; that is, those where the throat section is defined by two vertical faces, each 1 foot in length, measured along the axis of the flume and placed parallel to and equidistant from this axis. The V-notch and trapezoidal flumes; that is, those where the throat sections are defined by two sloping faces, have been tested, but the inadequate facilities for making the tests prevented calibrating the flumes of this type for large discharges.

Field calibrations of trapezoidal flumes have been attempted but with little success. As a usual thing, the field installation provides little or no regulation for the purpose of extending the observations over any considerable range. It is hoped that more complete information may be obtained on a series of trapezoidal sections which would permit of establishing the law of flow through this type of structure. At present the only data available for the trapezoidal flume are found in the Journal of Agricultural Research, Vol. IX, No. 4, Apr. 23, 1917.

The Venturi flume is very simple in operation, altho two heads must be observed to determine the rate of discharge. It is recommended that the observations of head or depth be made in still boxes or gage wells, so placed that the water level in the throat, and also the point indicated in the converging section can be communicated to these boxes or wells by means of short lengths of pipe. The observations of head or depth can best be determined by means of a hook gage located in each well. However, a plumb bob or a weight of special design, to be referred to later, suspended on a graduated tape may be used in lieu of the hook gage. Investigations, as well as observations under practical conditions, seem to indicate that heads determined by means of graduated scales fastened to the inside surface of the flume, countersunk until flush

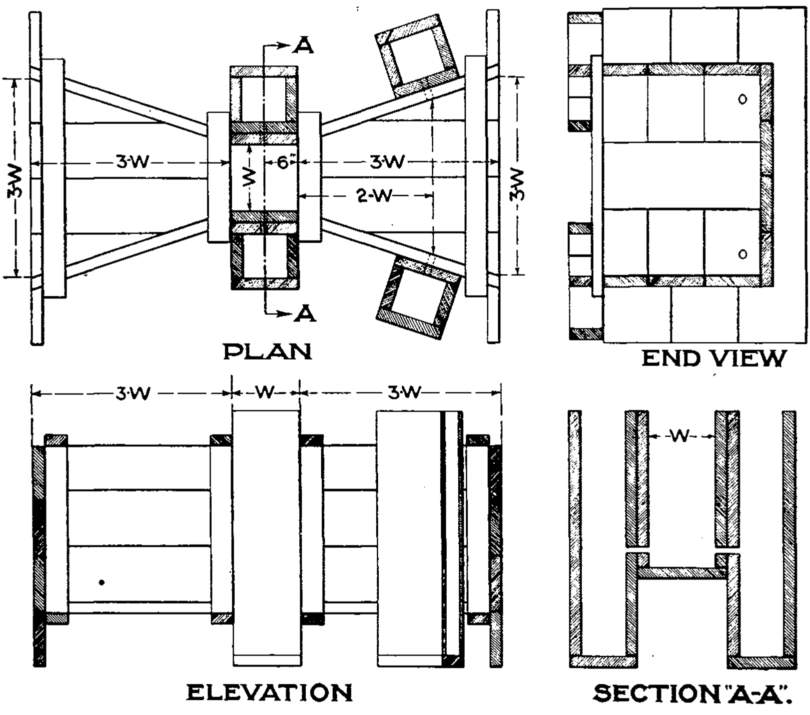

FIGURE 1.—Standard Plan for Venturi Flume with Rectangular Cross Section.

with the surface, do not give the best results. It was first thought that two points of observing the heads would be sufficient to definitely establish the conditions of flow for rectangular flumes, but due to the switching of the current in the diverging section, it was found necessary to observe the head at identical points on each side of the flume. The introduction of additional points of observing the head is not a desirable feature, but is necessary to insure the dependability and accuracy of the device. Table 1 gives the errors introduced into the discharge by determining the heads from one set of gage wells which register the depths on one side of the flume only. To avoid the possibility of uncertainty in the readings and to obtain a more correct determination, it is suggested that the arrangement of wells and connections be made as shown in Figure 1.

It has been suggested that a narrower diverging section might so modify the downstream conditions as to permit of reliable results from reading one side only; however, this restriction would no doubt greatly increase the mean velocity at the exit of the flume, thus causing a scouring action in the channel immediately below the structure which would require the installation of protection against this action.

The velocity of approach to the Venturi flume has no effect upon the accuracy of this device. When a certain quantity is flowing through the flume, drawing its supply from a still water basin, there will be a definite head at the gage connection in the converging section and in the throat, also a definite difference in head. If this same discharge were to approach the flume with a velocity, the upper gage reading would be less as would also the throat reading, and the difference in head would be greater. Since the upper head is less, the difference must be greater to permit of the same discharge, and because of the increased velocity, the head at the throat section is automatically decreased to balance the change in the velocity of approach.

In the Venturi flume the loss of head, due to the structure, is small except when the difference in head is great. Under normal conditions met with in practice, the velocity head is recovered when the water leaves the lower edge of the flume. However, when the difference in head is large, the water will maintain its high velocity through the flume and will not become normal until some obstruction, as an irregularity in the downstream channel, causes the formation of standing waves and the change from a high to a low velocity.

The fact that obstructions might occur in the flume is of considerable importance, and actual tests have been made to ascertain the effect of placing such obstructions in the flume in both the converging and diverging sections. The preliminary investigations made in 1915 on the V-notch flume brought out the fact that placing a 2-by 4-inch timber on edge, nailed to the floor of the flume at a point 3 feet above the throat section, did not increase the discharge by more than one per cent for any depth. Similar tests on a V-notch flume installed at the field laboratory at Bellvue, Colorado, showed the same result. In addition, it was found that placing the 2-by 4-inch timber on the downstream end of the flume had no appreciable effect.

Recent tests on a 3-foot rectangular flume show that 2-by 4-inch timbers nailed vertically to the sides of the converging sections, above the upper gage connections with 2-inch projection, had no effect; also the 2-by 4-inch timber on edge on the floor of the flume at a distance one foot above this gage connection had no effect, but when the timber was placed one foot below, or downstream from the connection, the effect was to increase the upper head so as to indicate approximately 4 per cent increase in the discharge when flowing 10½ second feet. Small strips placed transversely on the floor, projecting one-half inch, both in the converging and diverging sections, had no effect on the discharge. The deposit of sand and silt upon the floor of the flume has been found to be of small consequence, due to the fact that, as the converging section decreases in area, the velocity increases and the tendency for settlement or deposit is eliminated. Large floating masses would no doubt lodge in the throat section if the rectangular flume were installed, but this trouble could be effectively met by the installation of the trapezoidal section which would pass the lodging mass by the increased or accumulated head above the structure.

Requests have been made for information and data relative to Venturi flumes having capacities for more than one thousand second feet, but facilities and equipment are not available at present for undertaking the calibration of flumes of more than 30 second feet capacity. The law of flow, as has been determined from our experimental data, is applicable to sizes up to and including the five foot throat, but only approximations can be made for larger sized flumes by the application of the known law of flow. It is thought that the present range of calibration of flumes will meet the ordinary demand, and special cases requiring exceptional capacity will necessitate individual rating or calibration.

The Venturi flume is gaining in favor as a practical device, and the fact that it possesses many desirable features and few objectionable points bids fair to establish it as one of the standard measuring devices for practical irrigation purposes. The present design is not free from all objection, and is not claimed to be absolute in its operation, but when compared with other means of measurement it is found to be within reasonable limits of accuracy.

RECTANGULAR VENTURI FLUME

Since the publication of the first report on the Venturi flume, there has been a great number of these flumes built and installed for use in the measurement of water to irrigators. So far the greater per cent has been the rectangular type, and it appears to be somewhat more popular than the trapezoidal flume; however, there has been a number of the trapezoidal Venturi flumes installed, the calibration having been made by the interested parties.

The preliminary investigations of the Venturi flume resulted in a selection of certain ratios and dimensions applicable to a standard plan for the rectangular type. The assumptions as to dimensions were based on conclusions made evident by the behavior of model flumes of various ratios, and for uniformity the length of throat for all the sizes tested has been made one foot. The angle of convergence and divergence is equal and constant for the various sized flumes calibrated. The dimensions for the rectangular Venturi flume are shown in Figure 1. The calibration of this flume has covered a great many individual tests and includes the 1-, 1½-, 2-, 3-, and 5-foot sizes. The measured discharge has ranged from less than 1 to nearly 400 second feet in the calibration of this type of flume.

The diagrams and tables pertaining to the rectangular flume contained in this bulletin are based on the data collected at Cornell, our original data, and the more recent calibrations made at our field laboratory at Bellvue, Colorado.

As previously stated, our recent investigations indicate the desirability of providing the flume with four gage wells, two on each side of the flume. Tests were made to determine the per cent of error resulting from taking the readings in only one set of gage wells. Table 1 gives the results of these tests. In this table, the deviation from the true amount is either plus or minus, depending upon which side of the flume the observation wells are located; or in other words, which side the current is flowing in the diverging section with reference to the gage wells. If the current is flowing in the diverging section on the side of the observation wells, then the amount recorded will be more than the actual discharge; if the observations are taken on the opposite side from the current in the diverging section, then the reverse is true. Mean readings of simultaneous observations taken in four wells, as shown in Figure 1, will, under ordinary conditions, give the true gage height.

The derivation of the expression for computing the discharge through rectangular Venturi flumes is somewhat involved, and no attempt will be made to go into detail. As a general statement, it may be said that the basis of deduction is Bernoulli's theorem, which results in the following for the theoretic discharge:

$$Q = C\ W\ H_b \sqrt{\frac{2g\ H_d}{1 - \frac{9}{49}\left(\frac{H_b}{H_a}\right)^2}}$$

Where Q=discharge in second feet,
W=width of throat in feet,
H_b=head at the throat in feet,
H_a=Head in converging section in feet,
$H_d = (H_a - H_b)$=difference in the two heads,
C=constant.

The value C, is really not a constant but varies with the width of the throat and also with the upper head, H_a, and the difference in head H_d. This variation is expressed by the following formula:

$$C = (0.9975 - 0.0175W) + \frac{(H_d - 0.163\ H_a^{1/2})^2}{\left(\frac{8}{20-W}\right) H_a^2}$$

which, when substituted for C in the theoretical equation, gives:

$$Q = \left[(0.9975 - 0.0175\ W) + \frac{(H_d - 0.163\ H_a^{1/2})^2}{\left(\frac{8}{20-W}\right) H_a^2}\right] W H_b \sqrt{\frac{2g\ H_d}{1 - \frac{9}{49}\left(\frac{H_b}{H_a}\right)^2}}$$

The discharge diagrams, Figures 13, 14, 15, 16, 17 and 18 appended to this report, are based upon calculated values as determined by this expression. These curves are plotted on a logarithmic scale which presents the data in such a form as to be readily understood and applied. The use of the diagram can best be illustrated by an example. Assume a 2-foot Venturi flume with an upper gage height of 1.26 feet and a difference in head of 0.21 feet. In Figure 15, find the difference in head, 0.21, in the column on the left of the diagram, midway between the two horizontal lines, follow across the diagram horizontally until the 1.20 upper gage height curve is reached; estimate the fractional part and then read the discharge of 8.0 cubic feet per second at the bottom of the diagram vertically beneath this point. In determining the discharge, care should be observed in noting the change in the scale dimension in the different parts of the diagram.

It will be observed that for each upper head there is a limiting point, beyond which the curve does not extend. This limit is represented in the diagram by the curve designated as "free flow." This results from the fundamental theory of flow through contractions in channels. For every upper head as the difference in head increases, a point is finally reached beyond which the difference in head can no longer be increased. This is the point at which the maximum discharge occurs. This condition has been observed experimentally and it was found that it occurred when the throat gage registered from 50 to 60 per cent of the upper gage. This percentage varies with the size of flume and the upper head, increasing as the size of the flume increases and decreasing as the upper head increases. After the free flow condition has been reached, the depth of water in the diverging section may continue to drop without affecting the discharge or the gage heights.

Some idea as to the accuracy of the rectangular Venturi flume may be gained by inspecting the diagram, Figure 2, which is based upon comparisons of actual discharge with the quantity determined by computation, the basis of the computed values being the empirical expression developed from the experimental data. It will be noted that the per cent of deviation of the observed discharge from the computed quantity is largely confined to errors of less than 5 per cent; however, it is apparent that an occasional point is considerably more in error. This diagram is based upon 453 individual observations covering the calibration of the 1-, 1½-, 2-, 3-, and 5-foot rectangular flumes. The distribution of observations is quite uniform over the various sizes of flumes, and the compilation of the data for the comparison was made without selection or elimination.

The number of tests and the variety of conditions under which they were performed, seems to warrant the conclusion that with proper precaution quite dependable results may be expected.

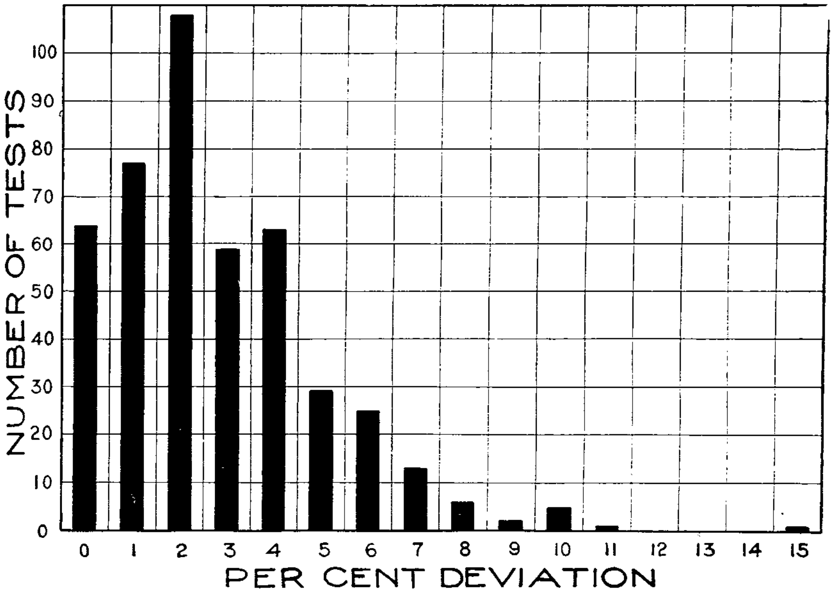

FIGURE 2.—Plot showing the Deviation of the Computed Data from the Experimental Data for all the Sizes of Rectangular Venturi Flumes Calibrated.

The installation of the rectangular Venturi flume should offer no difficulty as to construction or setting. Either concrete or wood may be used, but for the larger sizes and where permanency is required, concrete is recommended.

The flume should be located in the most desirable place with reference to alignment of ditch and grade. The floor elevation should agree with the grade line or bottom of the ditch in order that there will be no tendency to deposit silt or sand at the ends of the structure. If placed below grade, for small differences in head, the velocity within the flume is relatively low and would tend to silt the floor and cause trouble by stopping the pipe connections to the observation wells. It is recommended that the floor be a little above the grade rather than too low. The floor should be level in both directions and if constructed of concrete, should be given a smooth trowel finish. The most important element in the construction of these flumes is the dimension of the throat section. If concrete, it is recommended that the forms be set so that the distance between the two vertical faces will be from ¾ to 1 inch over size. After the forms have been removed, a finish coat of the required thickness should be put on to bring the width of throat to the correct dimension. The finished length of the throat measured along the axis of the flume is to be one foot, and if a plaster coat is added after forms are removed it will be necessary to make the cast face from 2 to 3 inches longer. This method of constructing the throat will insure a greater degree of accuracy in obtaining the true size. A trowel finish on the sides or walls of the flume is not absolutely necessary, but in most cases will add to the appearance and general utility of the structure. For wooden structures, see description of method given for V-notch flumes on page 23.

The observation wells should be cast in place and made a part of the structure. The tubes leading to these wells should be one-inch pipe, a single tube being sufficient, and should be placed two or three inches above the floor. These inlet tubes should be set flush with the inside surface of the flume, and it is important that they be normal or at right angles to this surface. The depth of the well should be sufficient to permit sand or silt to deposit and only require cleaning at long intervals. The well should extend somewhat above the general ground line, thus avoiding storm water washing trash into the well. Covers for the wells are recommended as a protection against foreign matter being deposited within them. At least one of the inside faces of the well should be made vertical and be provided with stud bolts for the purpose of anchoring a plank to support a hook gage or other measuring device.

Experience indicates that a graduated scale fastened to the inside face of the Venturi flume is not sufficiently accurate to determine the correct elevation of the water surface. The size of the wells would need to be comparatively large in cross section to permit of accurate reading of the scale if placed in the still wells. For the determination of the depth of water in the still wells above the floor of the flume, a depth scale, Figure 3, has been proposed which is simple in construction and operation, and when set will give the upper gage reading and the difference in head. The design of this scale is such as to eliminate the possibility of erroneous reading and also the chance of miscalculating the difference in the height of the two water surfaces. After the slides are once set, the readings may be read at leisure.

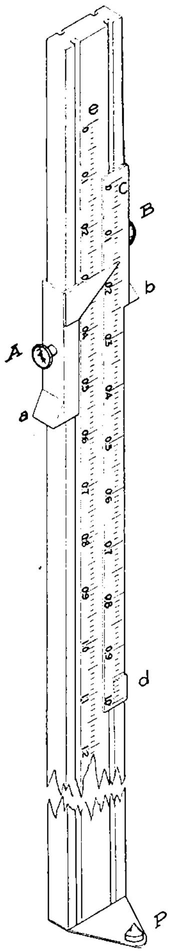

FIGURE 3 — Adjustable Scale for Determining the Upper Head and Difference in Head for Venturi Flumes.

At each gage well, fixed surfaces or supports are required which have the same elevation above the floor of the flume. It is thought advisable to have these surfaces protected by a metal plate to insure permanency. These supports should be provided with notches of sufficient length and depth to keep the rod vertical while observing the heads. To use this adjustable scale, set the slide (A) for the water surface in the upper gage well, and the slide (B) for the water surface in the throat gage well. It is immaterial which slide is first set. It is only necessary to move the whole rod vertically and at the same time to see that it is firmly held in the notch with one hand until the point (P) exactly coincides with the water surface. Securing this position, move the slide (A) or (B), as the case may be, downward until the stop (a) or (b) rests firmly against the plate mentioned above. The reading is similarly observed in the other gage well. The upper edge of the pointer on the slide (A) will indicate the head (H_a) on the scale (e) and the difference in head or (H_d) on the scale (c). These adjustable scales may be made of sufficient length to permit their use on moderately deep wells; however, care must be exercised in keeping the rod or scale vertical.

To locate the zero point of the scale (e) it is only necessary to measure vertically from the point (P) a distance equal to the difference in elevation between the floor and the top of the supports or notches on the wells. To locate the zero point of the scale (c), place the points (a) and (b) at the same elevation and adjust the scale to read zero as determined by the pointer on slide (A). Where one rod is to be used for a number of flumes, it will be necessary to have the fixed surfaces or supports on the wells at the same distances from the floor of the flume in all cases, or otherwise each flume will require a correction for the upper head reading.

Another practical way of determining the readings is by means of a tape and plumb bob, or special weight with a hook attached to the side, as shown at (a) Plate II. The steel tape should be reversed in direction; that is, the zero end attached to the case. A small sliding clamp is attached to the tape and when the point of the plumb bob, or hook of the special weight, just touches the water

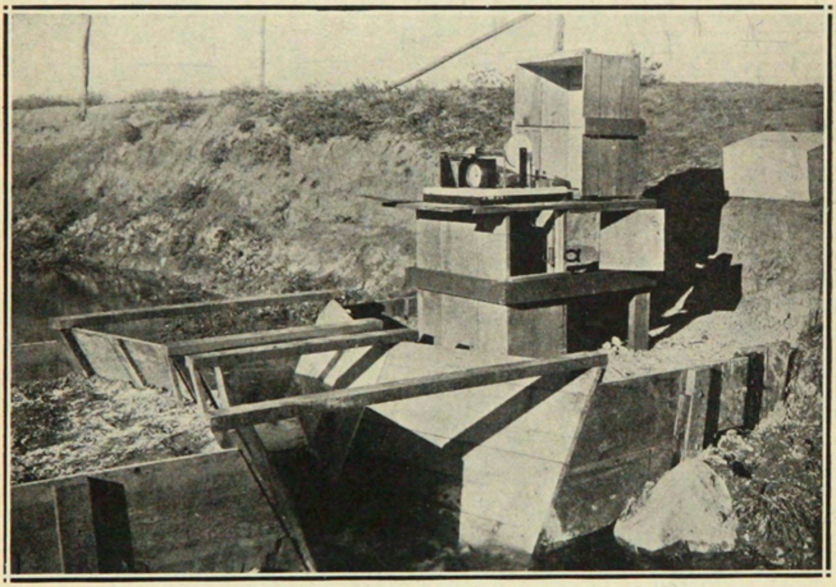

PLATE II.—Field Installation of V-Notch Venturi Flume and Automatic Gage Height Recorder.

surface, this clamp is then moved downward against a stop, which should be located at a point above the floor of the flume equal to the distance between the point of the plumb bob or hook, and the zero of the tape. The reading indicated on the tape by the clamp will be the value of the upper head. To determine the difference in head, it is necessary to provide a fixed scale for the throat gage well, reading downward, with the zero at the same elevation as the stop for the upper gage well. By means of the tape, with the clamp reading the upper head, adjust the point of the plumb bob, or hook, to the water surface in the throat well. The index of the clamp will then give the difference in head as read on the fixed scale. This means of determining the readings is very advantageous as the tape and plumb bob can be carried about in one's pocket.

In order to have a continuous record of the depths of water passing through the flume, some type of recording instrument is required. The need of an instrument of this kind has been felt for some time, but not until recently has one been designed and built. This model instrument, built at the hydraulic laboratory at Fort Collins, is, in its general form, similar to the usual single stage recording instruments, but in addition to recording a single gage height, it also records the difference between two gage heights. An eight day chart is used where the depth scale is two inches to the foot, which permits the readings to be made to hundredths of a foot. The installation of such an instrument to record the gage heights is a simple and inexpensive operation. The gage wells should be large enough to accommodate a ten inch float, and the upper and throat gage wells should be placed side by side. The instrument should be mounted on a suitable support, in such a position as to permit the floats to freely actuate the recorder, and at such a height as to be convenient and easy to manipulate. A wooden box, hinged at one side and provided with hasp and lock, should be provided for field installation to protect the instrument.

Plate II shows the installation of this type of register in conjunction with the V-notch Venturi flume. If it is intended that a recording instrument be installed, special arrangement of the position of wells is necessary. The present design of the Venturi flume recording instrument requires that the two wells be in close proximity and separated by a thin partition wall, common to both wells. To successfully install this instrument will further require that some means of communicating the heads from the opposite side of the flume to the float wells be provided. A pipe of moderate dimension should be placed beneath the floor of the flume and connected to each pair of wells. As a practical means of testing the pipe connections, or tubes, it is suggested that the wells be filled with water by means of a bucket and the rate of drop in the water surface observed.

It is of considerable practical importance to know what conditions will obtain after the Venturi flume has been installed in the canal. The loss of head or difference in the elevation of the water surfaces above and below the structure, when the flume is in operation, has been observed for a considerable range of discharges for the various sizes of rectangular flumes. These data have been prepared in the form of diagrams as shown in Figures 4, 5, 6, 7, 8 and 9.

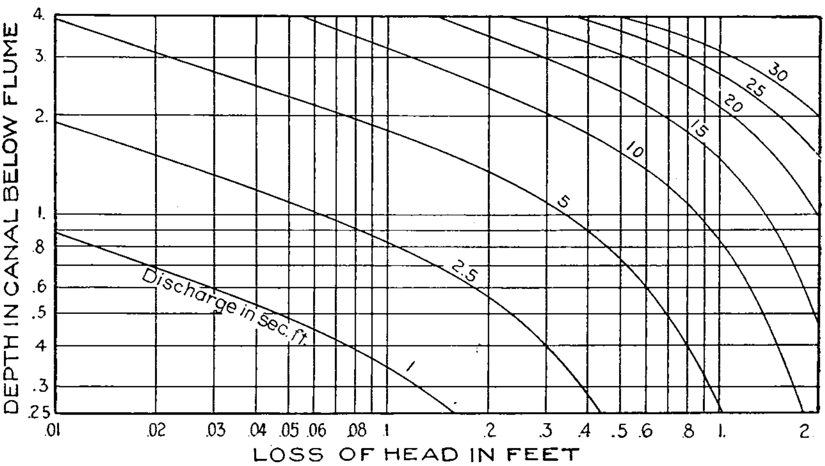

FIGURE 4.—Curves Showing the Loss of Head in Feet in a One Foot Rectangular Venturi Flume for Different Depths and Discharges.

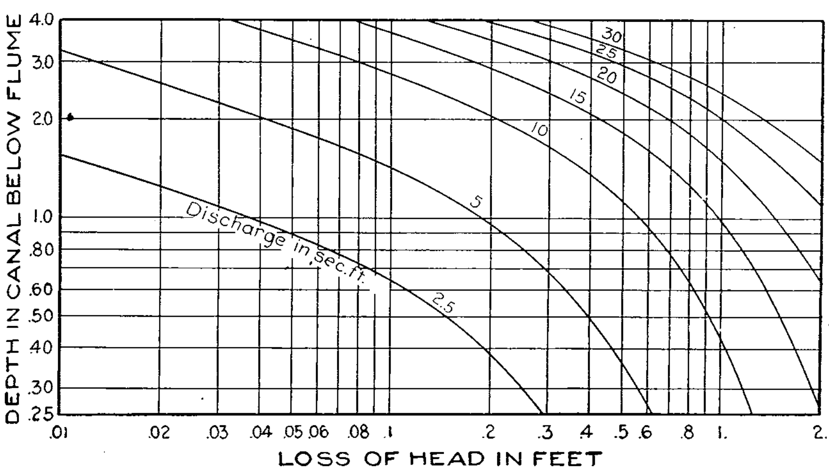

FIGURE 5.—Curves showing the Loss of Head in Feet in a One and One-Half Foot Rectangular Venturi Flume for Different Depths and Discharges.

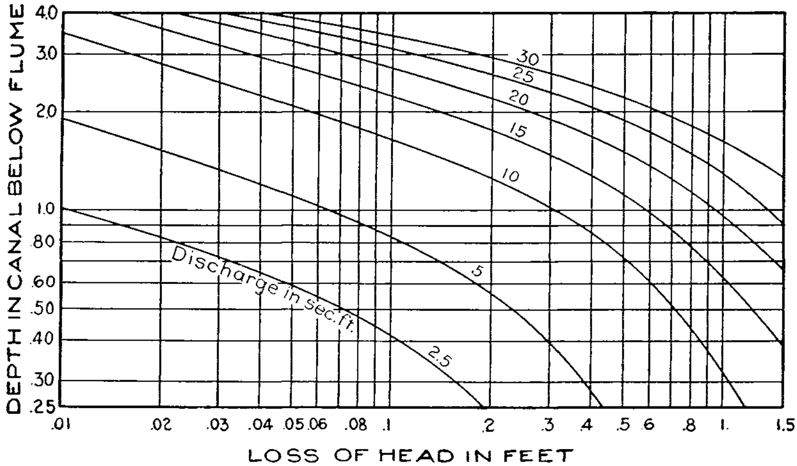

FIGURE 6.—Curves Showing the Loss of Head in Feet in a Two Foot Rectangular Venturi Flume for Different Depths and Discharges.

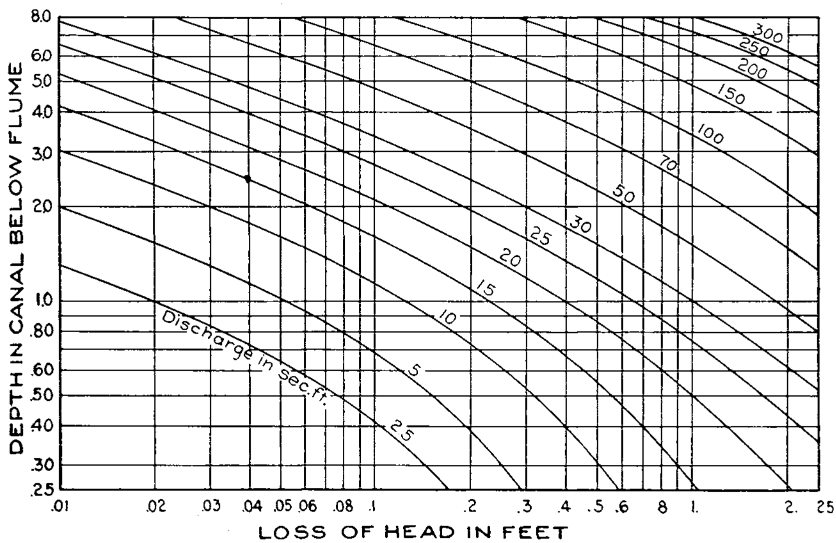

FIGURE 7.—Curves Showing the Loss of Head in Feet in a Three Foot Rectangular Venturi Flume for Different Depths and Discharges.

The use of these diagrams is in approximating the increase in depth of water in the canal above the flume due to the obstruction caused by the throat section. As an example of the application, let it be assumed that the canal is 12 feet wide on the bottom with a normal carrying capacity of 50 second feet. Since the 4-foot Venturi flume has a width of 12 feet at the ends of the structure, it is evident that this size should be installed. As the condition exists before installing this flume, it is observed that the depth of water is approximately 2½ feet. Figure 8 shows the loss of head through this size flume, and for a depth of 2½ feet it is observed from this

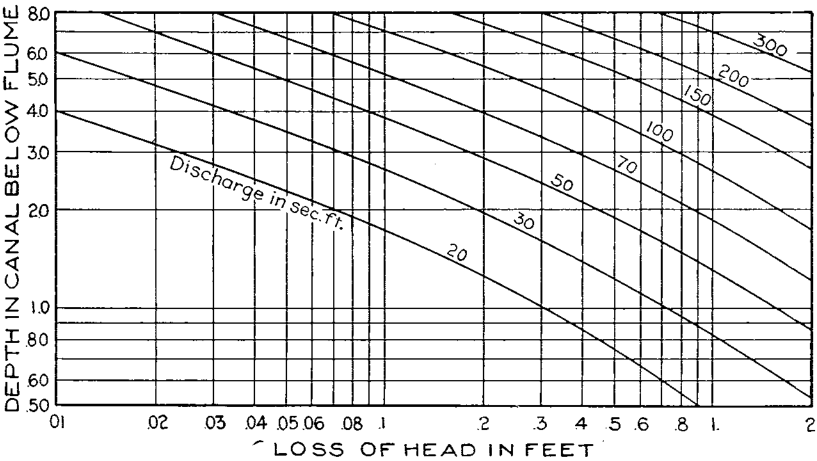

FIGURE 8.—Curves Showing the Loss of Head in Feet in a Four Foot Rectangular Venturi Flume for Different Depths and Discharges.

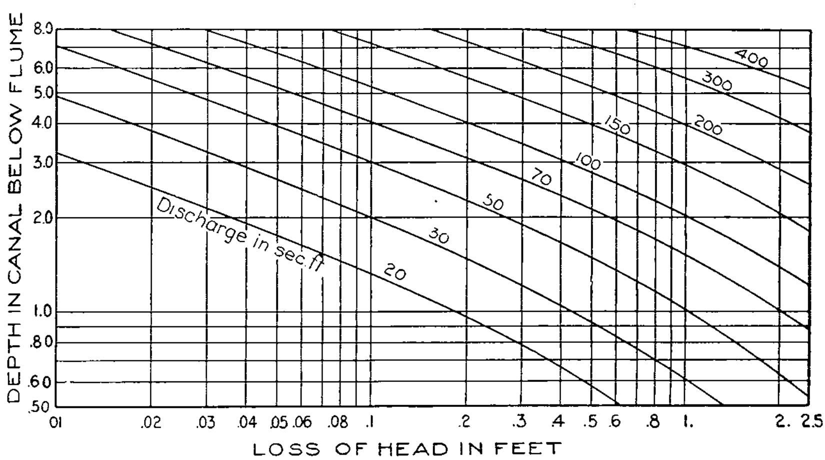

FIGURE 9.—Curves Showing the Loss of Head in Feet in a Five Foot Rectangular Venturi Flume for Different Depths and Discharges.

diagram that a loss of head of 0.3 feet would occur. This amount, added to the downstream depth, will be approximately 2.8 feet, or the depth above the flume when discharging 50 second feet.

V-NOTCH VENTURI FLUME

For a number of years there has been a demand for a measuring device that would accommodate comparatively small flows with a minimum loss of head through the structure. To meet this need, a V-notch Venturi flume has been calibrated for flows from 0.1 to 10 second feet. In this flume, the throat is formed by two plane surfaces, one foot wide and intersecting at the floor line at an angle of approximately 53°, or with a side slope of ½ to 1. The sides of the converging and diverging sections also have this same side slope, measured in the plane normal to the axis of the flume. Plate II shows a V-notch flume and automatic gage height recorder, installed in a small stream. The standard dimensions of this special type flume are given in Figure 10.

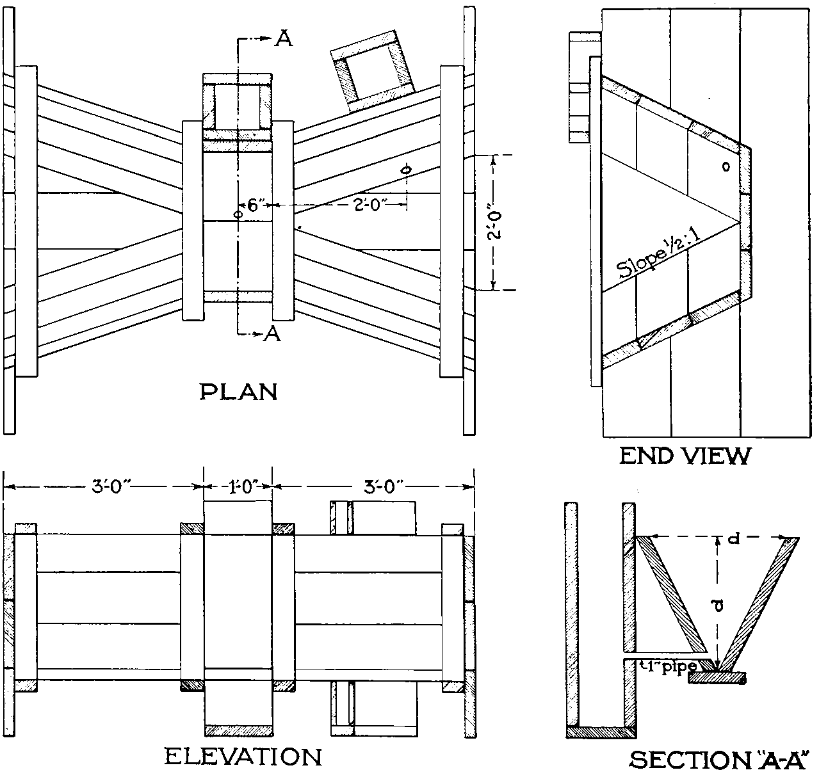

FIGURE 10.—Standard Plans for V-Notch Venturi Flume with Side Slopes ½ to 1.

The results of the calibration of the V-notch flume show that the loss of head is small for the usual conditions of operation, and that for any discharge the loss in head increases as the depth decreases. For convenience in determining the loss of head caused by the installation of the V-notch flume in a channel, the results are given in graphical form in Figure 11. To find the loss of head when the discharge and average depth are known, find the depth in the column on the left of the diagram, follow the horizontal line at

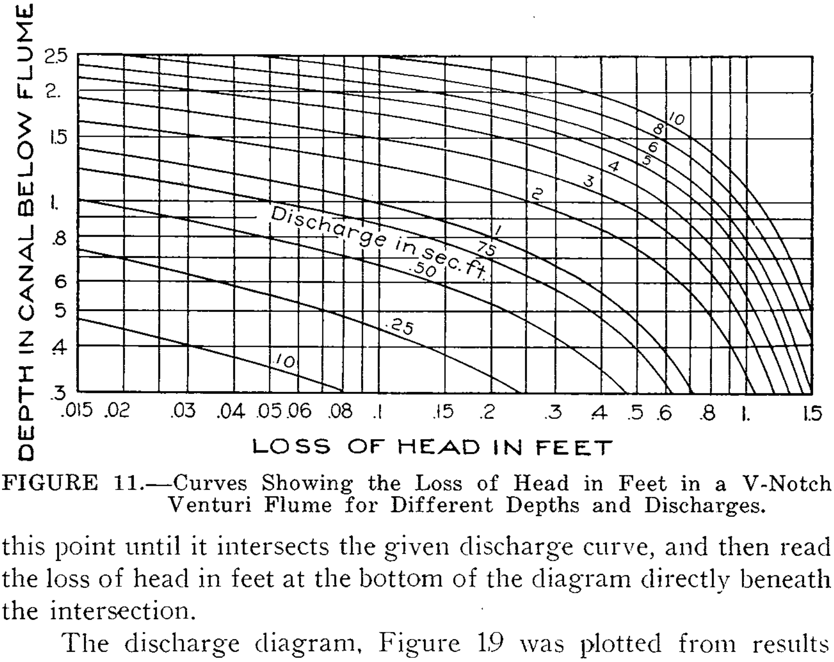

FIGURE 11.—Curves Showing the Loss of Head in Feet in a V-Notch Venturi Flume for Different Depths and Discharges.

this point until it intersects the given discharge curve, and then read the loss of head in feet at the bottom of the diagram directly beneath the intersection.

The discharge diagram, Figure 19 was plotted from results computed from the formula:

$$Q = C\,\frac{H_b^{\,2}}{2}\sqrt{\frac{2g\,H_d}{1-\dfrac{H_b^{\,4}}{(2\tfrac{2}{3}+H_a)^2\,H_a^{\,2}}}}$$

Where Q=discharge in second feet,

$$C = 0.930 + (4.07 - 1.4\,H_a)\,(H_d - 0.05\,H_a - 0.04)^2 - \frac{0.362}{e^{80 H_d}},$$

H_a =upper head in feet,
H_b =throat head in feet,
$H_d = (H_a - H_b)$ = difference in head in feet,
e =2.7183.

This formula is based on the results of the experiments made at the hydraulic laboratory at Fort Collins, Colorado, and the field laboratory at Bellvue, Colorado. To find the discharge from the diagram when the upper head, H_a, and the difference in head, H_d, are given, find the point where the horizontal line, thru the given difference in head on the left of the diagram, intersects the upper head curve, and read the discharge in second feet at the bottom of the diagram directly beneath this point.

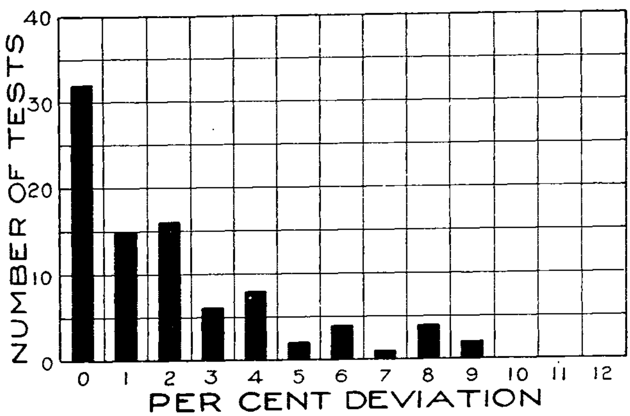

FIGURE 12.—Plot Showing the Deviation of the Computed Data from the Experimental Data for the V-Notch Venturi Flume.

The agreement of the results from the diagram with the experimental data is shown in Figure 12 which is similar to Figure 2 for the rectangular flumes.

The installation of the V-notch Venturi flume should not offer any practical difficulties. Either concrete or timber may be used. For concrete structures, see description of method given for rectangular flumes on page 14. If built of timber, it is recommended that commercial 2-inch plank be used. These planks should be surfaced on one side and so placed that this smooth surface would form the inside of the flume. Care should be exercised in properly fitting the sides to the throat section so as to make the edge of the two surfaces or joint smooth and regular. The pipe connection to the throat gage well should be made as shown in drawing, and approximately 2 inches above the bottom point of the throat. The pipe connection for the upstream or upper gage well should be placed horizontally and at right angles to the edge of the plank, also approximately 2 inches above the floor. These pipes should not extend beyond the inside surface of the sides of the structure. The floor of the flume should be level in both directions and placed so that the floor line will be on the grade of the channel. The size of the gage wells is not important; however they should be of sufficient size for cleaning purposes. If made of 2-by 12-inch plank and built as shown in the plan, the opening will be approximately 8 by 10 inches. The depth should be sufficient to reach at least one-half foot below the floor of the flume and a bottom should be provided for both wells. When set in position, they should be vertical and close to the structure, with the tops of the wells at the same elevation. Covers for the wells may be provided if found necessary.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and cooperation of the Jackson Ditch Company of La Porte, Colorado, in permitting the use of their diversion dam and head works in connection with the experiments conducted at the Bellvue laboratory.

SUMMARY

The Venturi flume is intended to meet those conditions for which the standard weir or other measuring devices are not suited, the most important application being where sufficient head is not available for other types of measuring devices.

The accuracy of the Venturi flume is sufficient to meet ordinary requirements and by actual computation it has been shown that, for all sizes of rectangular flumes investigated with discharges ranging from less than 1 second foot to nearly 400 second feet, 94 per cent of all tests show an error in discharge of 5 per cent or less.

A similar comparison for the V-notch flume shows that for discharges ranging from 0.1 to 10 second feet, 70 per cent of all the tests show an error of 2 per cent or less.

In order to obtain the best results from the rectangular Venturi flume, it is recommended that four gage wells be installed, and that the mean reading be used in determining the discharge.

Where the installation of a flume is made with the intention of using a recording instrument, a special arrangement of float wells is necessary, and also provision must be made for connecting these two wells with those on the opposite side of the flume.

Frequent testing of the sensitiveness of the gage wells is advisable. Cleaning of the wells of silt or sand should be done when found necessary, and this can best be accomplished by a false bottomed bucket or can, rigidly fixed to a long rod or wooden handle.

Scales or gages attached to the inside surface of the flume for determining the head are not sufficiently accurate for general purposes.

Due to the nature of the law of flow through the Venturi flume, the accuracy increases as the difference in head increases; also the per cent of error in making the reading is decreased when the difference in head is great. Consequently, it is advisable, if the head is available, to operate the flume with the greatest difference in head possible.

The application of the general discharge formulas, as given for the Venturi flume, is not recommended for determining discharges for flumes having throat widths or depths beyond the limits of those shown in the diagrams; however, if these expressions are applied, the results will be only approximations.

Concrete structures are recommended, but timber may be used if the structures are well braced to insure stability.

The logarithmic discharge diagrams are used in exactly the same manner as an ordinary co-ordinate chart; however, care must be used in picking off the values because of the fact that the intervals of equal value decrease as the quantities increase.

Changing the velocity or increasing the depth of water below the flume does not effect the utility of the device. All changes are automatically taken care of by the variation in the gage heights.

TABLE 1.—PER CENT OF ERROR FOR RECTANGULAR FLUMES, DUE TO OBSERVING HEADS ON ONE SIDE ONLY.

One Foot Throat

H_a	H_d	Standard Discharge	% Error
1.000	0.133	2.60	1.23
1.500	.041	2.60	2.77
2.000	.019	2.58	3.56
2.500	.011	2.56	5.35
3.000	.009	2.54	3.57
1.500	.208	5.06	1.64
2.000	.088	5.10	2.42
2.500	.046	5.10	2.20
3.000	.033	5.10	3.80
3.500	.026	5.11	3.96
4.000	.019	5.12	3.07
2.000	.707	10.20	0.00
2.500	.280	10.24	1.15
3.000	.166	10.21	2.39
3.500	.114	10.18	2.76
4.000	.083	10.17	2.06
3.000	.503	15.30	0.44
3.500	.318	15.30	1.25
4.000	.212	15.30	1.42

Two Foot Throat

H_a	H_d	Standard Discharge	% Error
1.000	0.127	5.07	3.35
1.500	.041	5.10	4.90
2.000	.024	5.10	5.75
2.500	.014	5.10	4.32
1.500	.252	10.35	3.06
2.000	.095	10.24	6.37
2.500	.056	10.23	5.67
3.000	.039	10.25	5.73
3.500	.028	10.26	6.36
4.000	.022	10.26	7.62
2.000	.284	15.36	3.38
2.500	.143	15.41	5.24
3.000	.095	15.43	6.25
3.500	.067	15.40	5.85
4.000	.047	15.36	4.54
2.500	.291	20.30	3.14
3.000	.166	20.30	4.79
3.500	.115	20.32	5.71
4.000	.083	20.33	6.01
2.500	.588	25.31	0.00
3.000	.299	25.31	2.94
3.500	.195	25.31	3.69
4.000	.136	25.39	3.93
3.000	.546	30.22	0.77
3.500	.345	30.22	1.66
4.000	.238	30.30	3.02

Three Foot Throat

H_a	H_d	Standard Discharge	% Error
1.000	0.052	5.12	6.64
1.500	.019	5.22	6.41
2.000	.010	5.22	7.01
2.500	.006	5.11	7.15
3.000	.004	5.11	7.83
1.500	.091	10.20	5.41
2.000	.044	10.20	7.97
2.500	.029	10.47	8.87
3.000	.020	10.20	9.62
3.500	.014	10.44	6.61
1.500	.240	15.00	4.60
2.000	.104	15.44	7.32
2.500	.063	15.35	8.20
3.000	.044	15.30	8.90
3.500	.031	15.35	9.19
4.000	.022	15.60	10.31
2.000	.200	20.37	4.92
2.500	.106	20.31	6.80
3.000	.068	20.40	8.23
3.500	.052	20.30	8.97
4.000	.038	20.20	8.86
2.000	.410	25.60	2.02
2.500	.187	25.52	5.25
3.000	.116	25.50	6.67
3.500	.080	25.50	7.02
4.000	.058	25.60	7.23
2.500	.302	30.45	3.18
3.000	.176	30.20	3.88
3.500	.118	30.50	5.32
4.000	.087	30.00	4.98
3.000	.822	50.10	0.42
3.500	.451	50.00	3.68
4.000	.300	50.00	6.82
5.000	.174	50.00	9.00
6.000	.118	50.00	9.42
7.000	.087	50.00	8.24
8.000	.064	50.00	8.12

Five Foot Throat

H_a	H_d	Standard Discharge	% Error
1.000	0.063	10.0	9.93
1.500	.025	10.0	8.85
2.000	.016	10.0	6.02
2.500	.334	50.1	8.88
3.000	.203	50.1	11.25
3.500	.142	50.2	12.43
4.000	.105	50.1	11.77
5.000	.065	50.1	11.02
6.000	.044	50.0	9.56
7.000	.032	50.0	9.10
8.000	.027	49.9	10.10
3.000	.510	70.2	6.91
3.500	.316	70.1	9.63
4.000	.223	70.2	10.30
5.000	.132	70.0	10.10
6.000	.088	70.0	10.05
7.000	.064	70.0	10.42
8.000	.049	70.0	10.15
4.500	1.308	149.2	1.64
5.000	.902	150.3	6.11
6.000	.504	150.6	9.84
7.000	.332	150.6	11.68
8.000	.242	150.4	12.66
7.000	2.090	299.0	1.02
8.000	1.312	299.0	4.39
9.000	.930	299.0	5.53

TABLE II.— CONVERSION TABLE, SECOND FEET, TO COLORADO STATUTORY INCHES, BASED ON ONE SECOND FOOT, EQUALS 38.4 MINER'S INCHES.

Second Feet	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	...	4	8	12	15	19	23	27	31	35
1	38	42	46	50	54	58	61	65	69	73
2	77	81	84	88	92	96	100	104	108	111
3	115	119	123	127	131	134	138	142	146	150
4	154	157	161	165	169	173	177	180	134	188
5	192	196	200	204	207	211	215	219	223	227
6	230	234	238	242	246	250	253	257	261	265
7	269	273	276	280	284	288	292	296	300	303
8	307	311	315	319	323	326	330	334	338	342
9	346	349	353	357	361	365	369	372	376	380
10	384	388	392	396	399	403	407	411	415	419

TABLE III.—DECIMALS OF A FOOT FOR EACH 1/16 OF AN INCH.

Inches	0	1/16	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/1	7/8	15/16
0	.000	.005	.010	.016	.021	.026	.031	.037	.042	.047	.052	.057	.063	.068	.073	.078
1	.083	.089	.094	.099	.104	.109	.115	.120	.125	.130	.135	.141	.146	.151	.156	.162
2	.167	.172	.177	.182	.188	.193	.198	.203	.208	.214	.219	.224	.229	.234	.240	.245
3	.250	.255	.260	.266	.271	.276	.281	.287	.292	.297	.302	.307	.313	.318	.323	.328
4	.333	.339	.344	.349	.354	.359	.365	.370	.375	.380	.385	.390	.396	.401	.406	.412
5	.417	.422	.427	.432	.438	.443	.448	.453	.458	.464	.469	.474	.479	.484	.490	.495
6	.500	.505	.510	.516	.521	.526	.531	.537	.542	.547	.552	.557	.563	.568	.573	.578
7	.583	.589	.594	.599	.604	.609	.615	.620	.625	.630	.635	.641	.646	.651	.656	.662
8	.667	.672	.677	.682	.688	.693	.698	.703	.708	.714	.719	.724	.729	.734	.740	.745
9	.750	.755	.760	.766	.771	.776	.781	.787	.792	.797	.802	.807	.813	.818	.823	.828
10	.833	.839	.844	.849	.854	.859	.865	.870	.875	.880	.885	.891	.896	.901	.906	.912
11	.917	.922	.927	.932	.938	.943	.948	.953	.958	.964	.969	.974	.979	.984	.990	.995

UNITS OF MEASURE

The Cubic Foot per Second, called second-foot, is a unit of measure for flowing water. When a stream discharges 1 cubic foot of water in one second, there is a second-foot flow.

The Acre-Foot, is a unit of measure for standing water, and is that volume which will cover one acre one foot deep. An acre-inch is one-twelfth of an acre-foot, or the volume which will cover one acre to a depth of one inch.

The Miner's Inch is unsatisfactory, and rapidly losing favor as a unit for measuring water, because it is not a definite quantity. It varies with the conditions under which it is used, and is therefore being replaced by the second-foot.

TABLE OF HYDRAULIC EQUIVALENTS.

One cubic foot equal 7.48 gallons, or approximately 7½ gallons.

One cubic foot of water weighs approximately 62½ pounds.

One cubic foot per second equals 448.83 gallons per minute, or approximately 450 gallons per minute.

One cubic foot per second flowing for 1 hour, equals approx-mately 1 acre-inch.

One cubic foot per second, flowing for 12 hours, equals approx-imately 1 acre-foot.

One cubic-foot per second, flowing for 24 hours, equals approx-imately 2 acre-feet.

One acre-foot equals 43,560 cubic feet, equals 325,851 gallons.

One million cubic feet equals 22.95 acre-feet.

In Colorado it has been generally assumed that 1 Miner's inch (Statutory inch) equals 1-38.4 of one cubic foot per second.

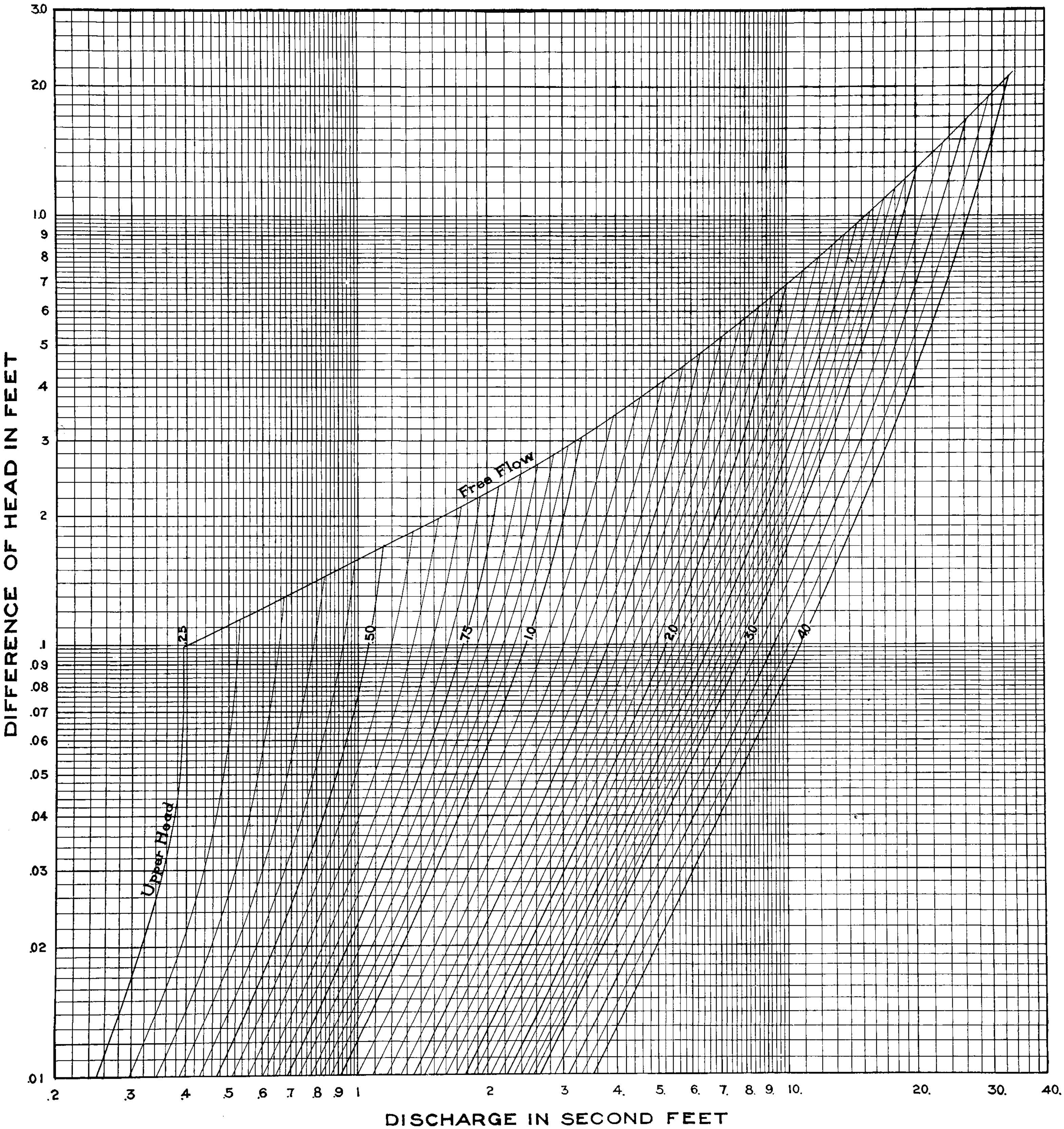

FIGURE 13.—Discharge Diagram for the One Foot Rectangular Venturi Flume, Plotted from Results Computed by the Formula Given on Page 11.

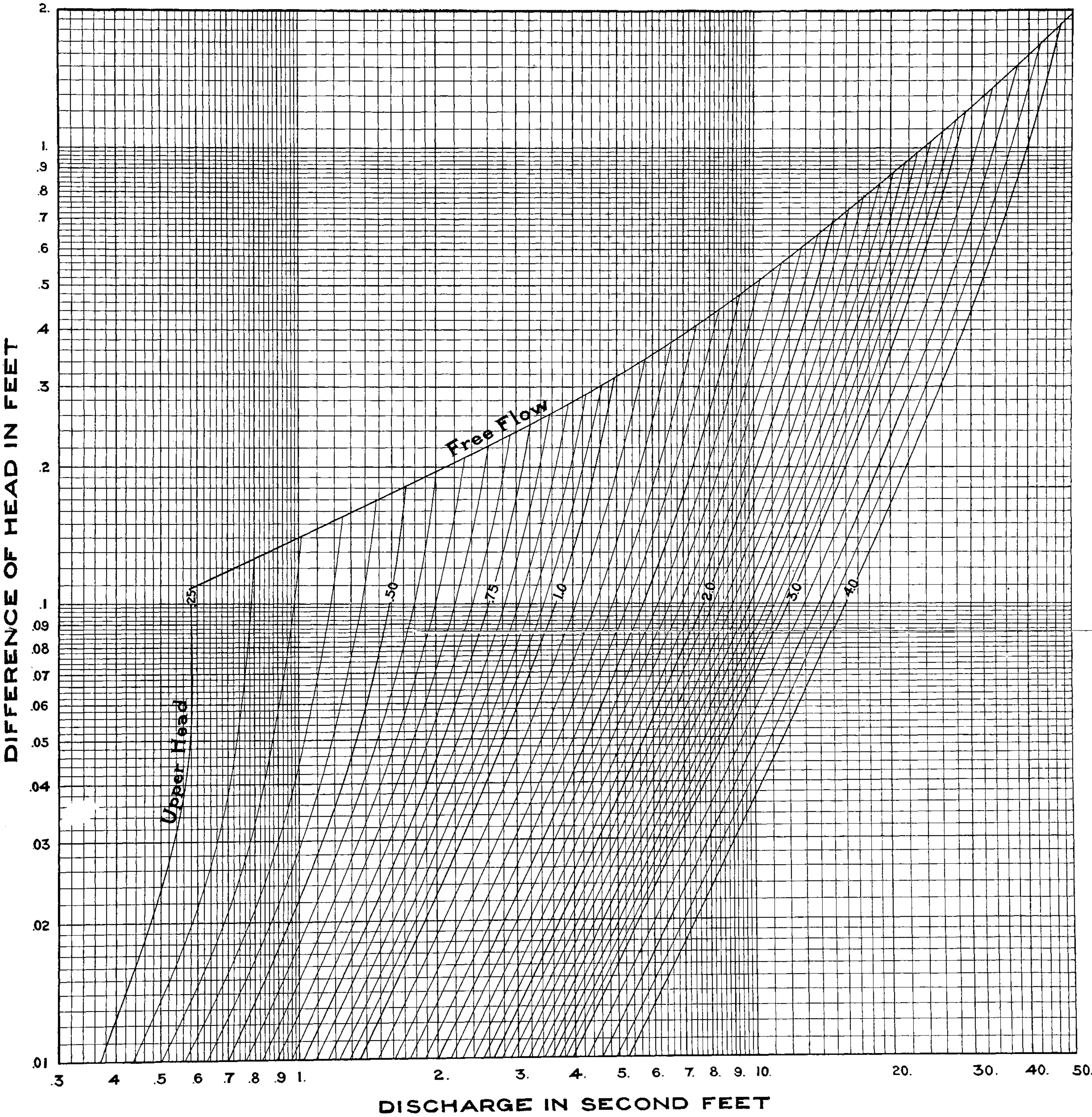

FIGURE 14.—Discharge Diagram for the One and One-Half Foot Rectangular Venturi Flume, Plotted from Results Computed by the Formula Given on page 11.

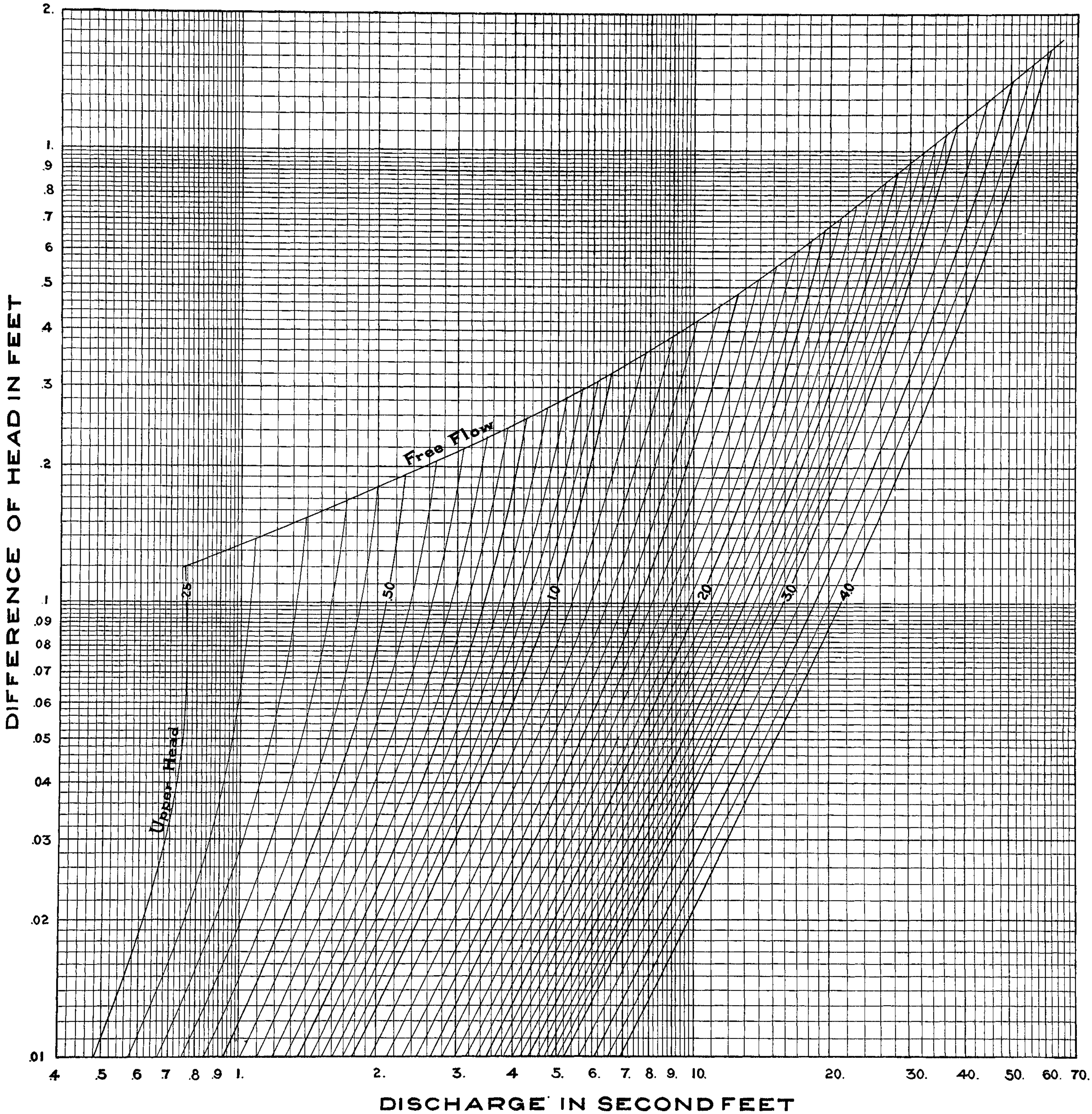

FIGURE 15.—Discharge Diagram for the Two Foot Rectangular Venturi Flume, Plotted from Results Computed by the Formula Given on Page 11.

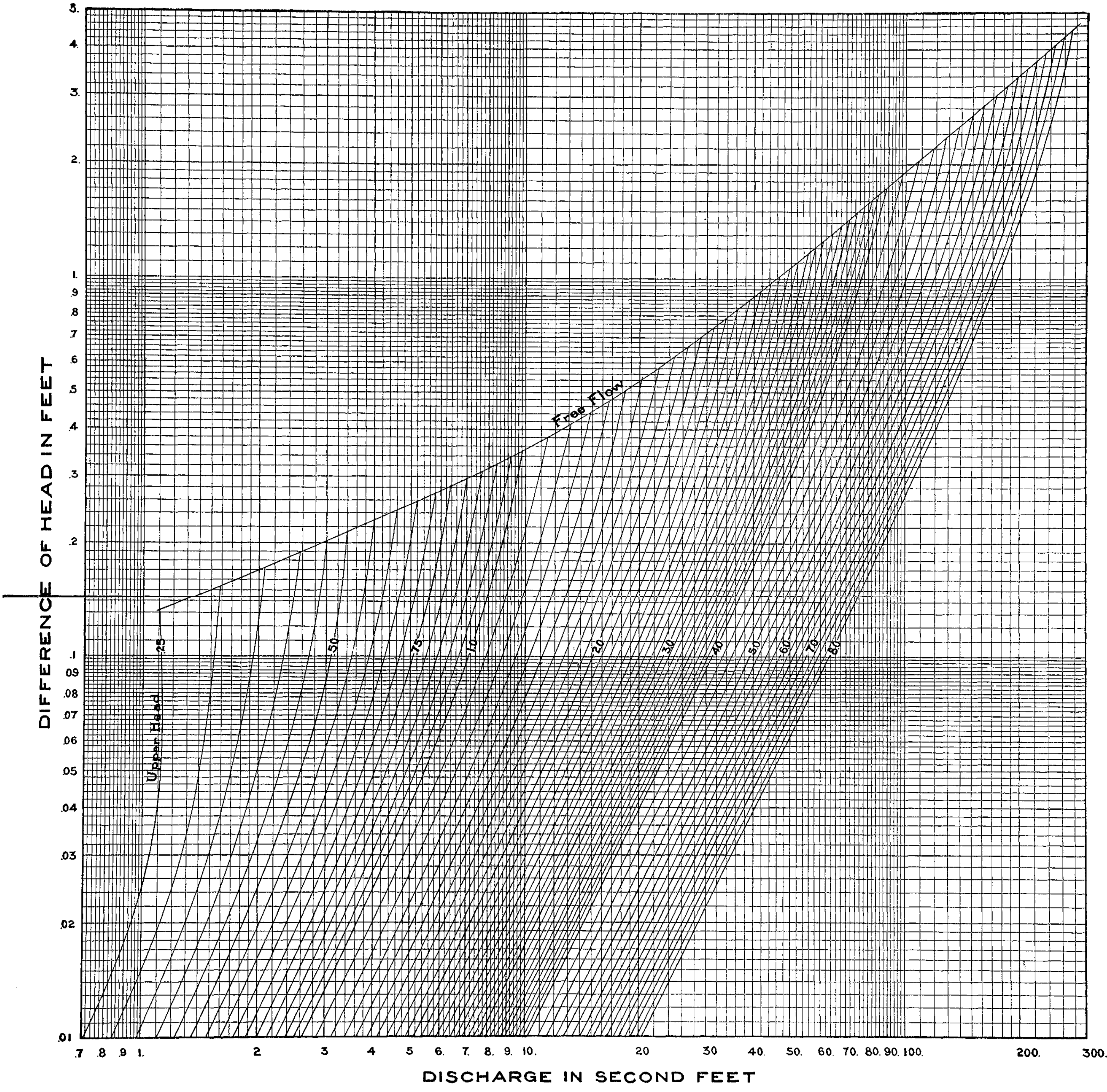

FIGURE 16.—Discharge Diagram for the Three Foot Rectangular Venturi Flume, Plotted from Results Computed by the Formula Given on Page 11.

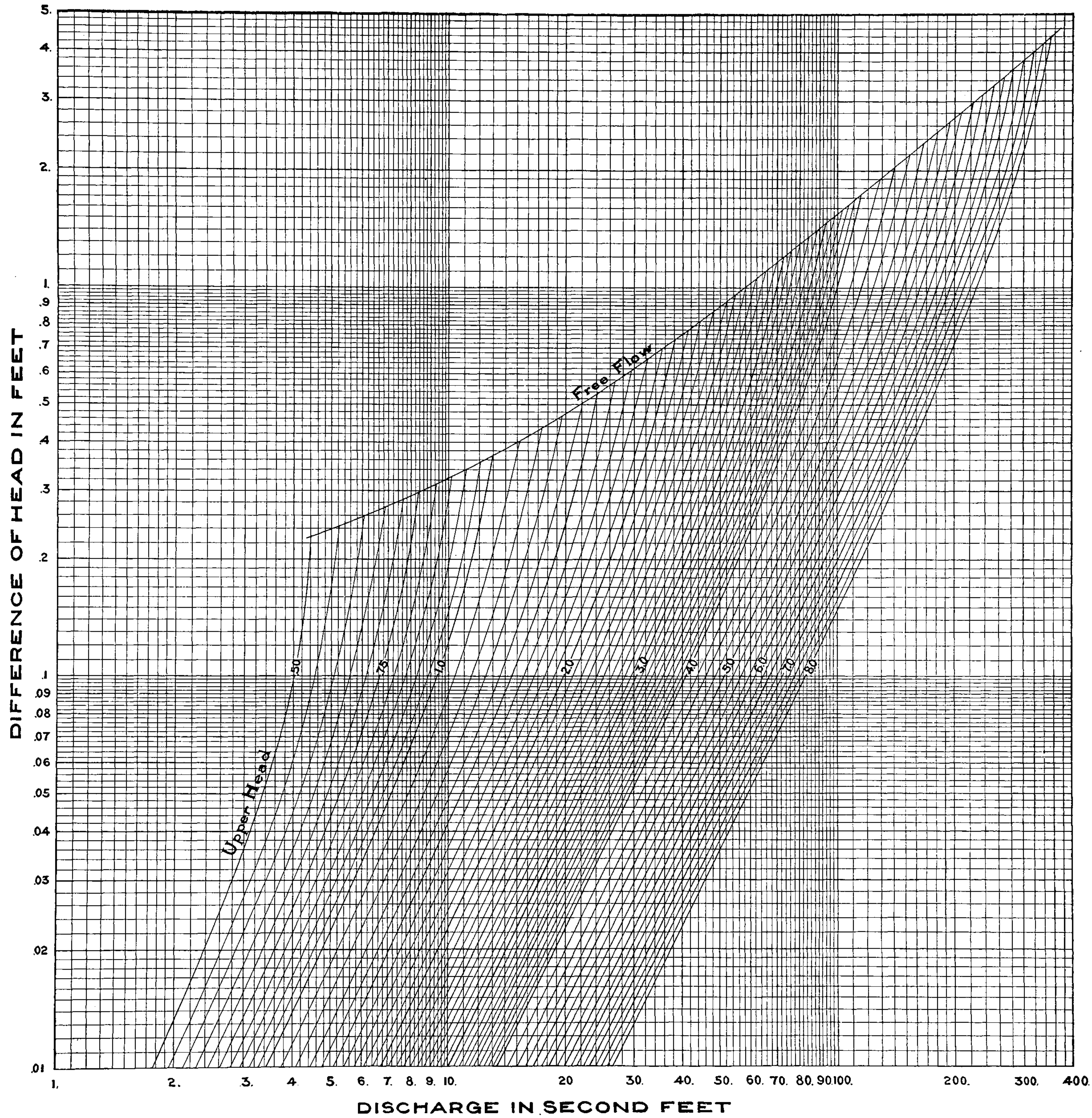

FIGURE 17.—Discharge Diagram for the Four Foot Rectangular Venturi Flume, Plotted from Results Computed by the Formula Given on Page 11.

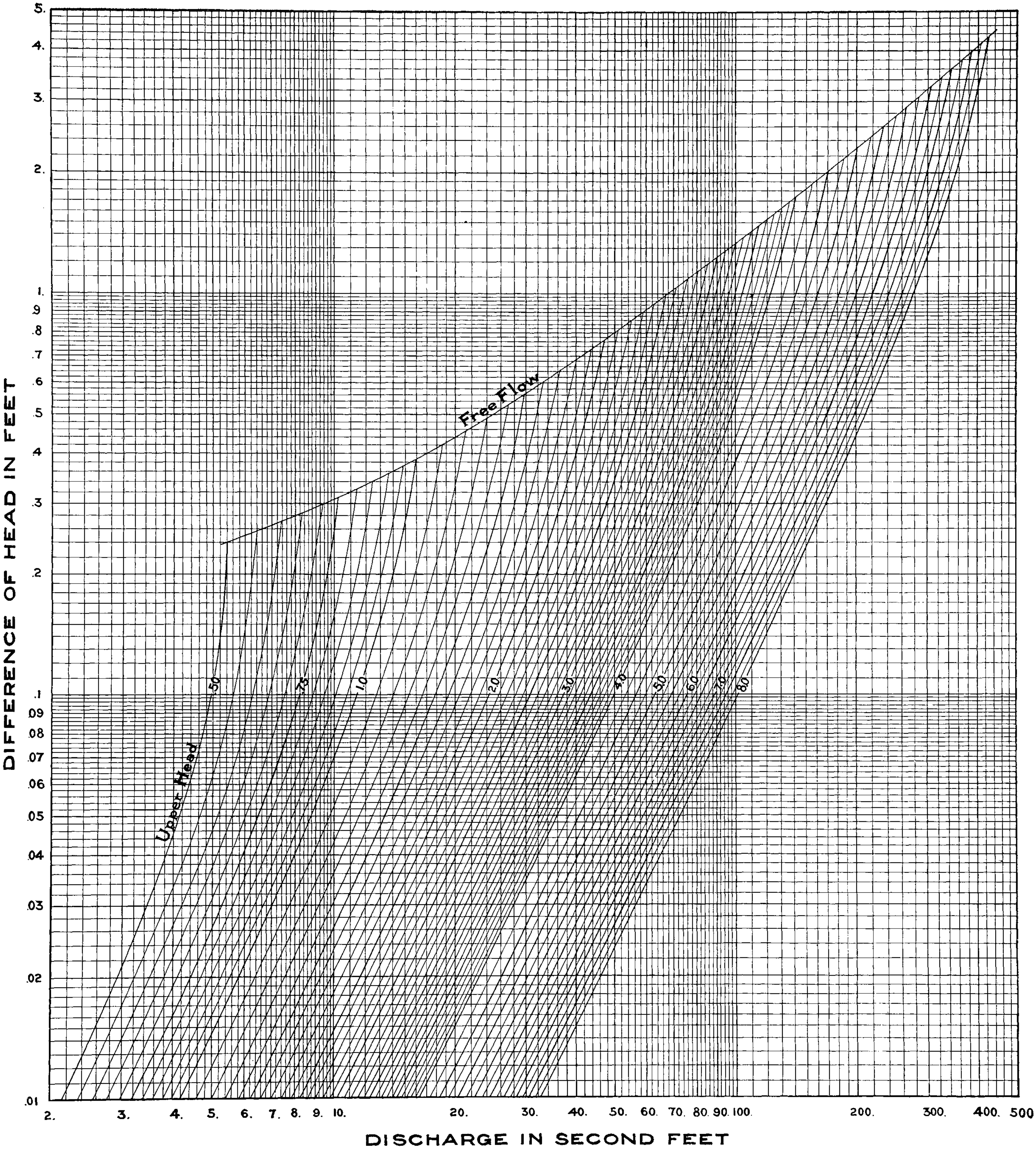

FIGURE 18.—Discharge Diagram for the Five Foot Rectangular Venturi Flume, Plotted from Results Computed by the Formula Given on Page 11.

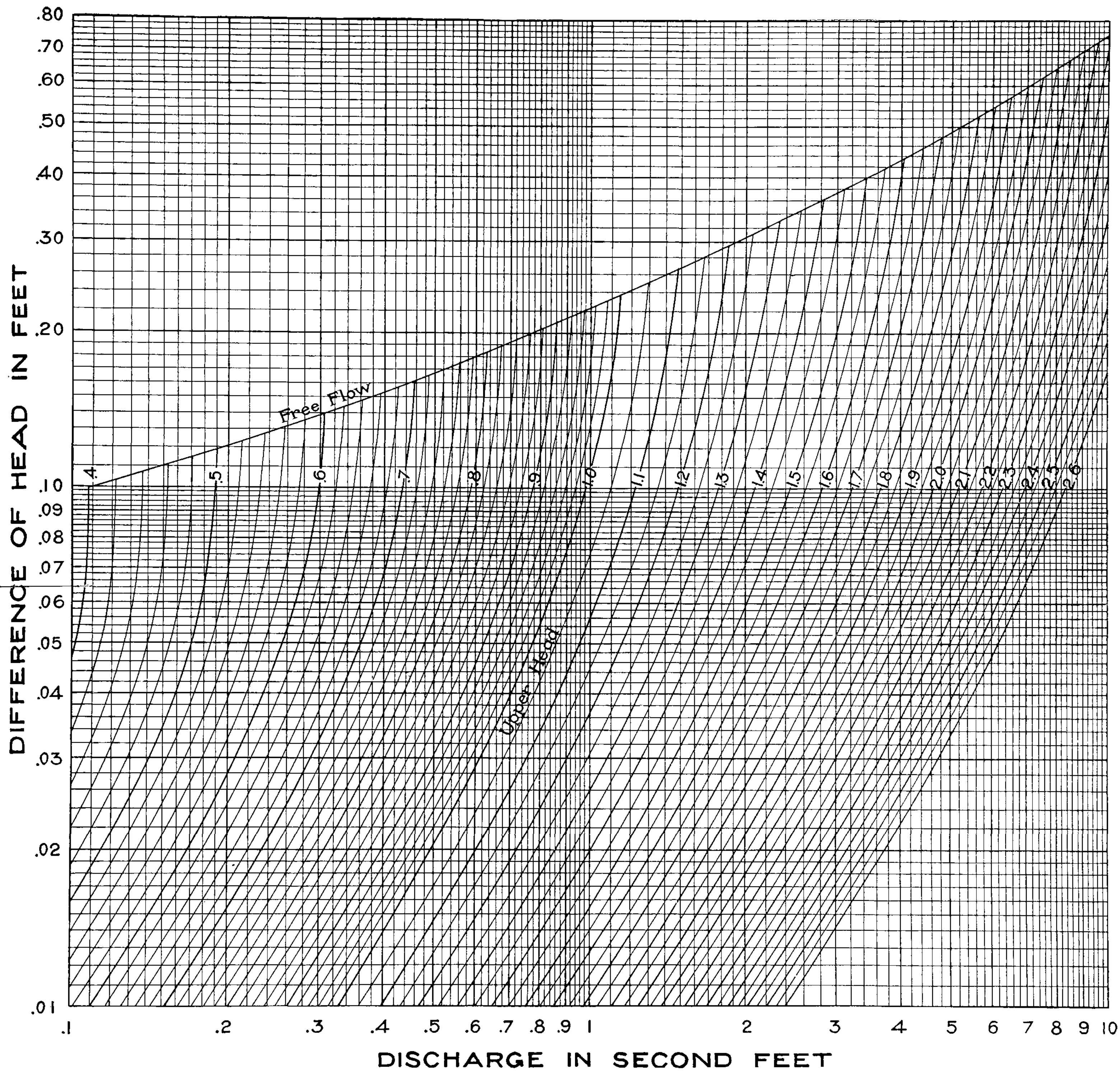

FIGURE 19.—Discharge Diagram for the V-Notch Venturi Flume, Plotted from Results Computed by the Formula Given on Page 22.