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THE MEASUREMENT AND DIVISION OF WATER.

FORT COLLINS, COLORADO.

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The Agricultural Experiment Station.

On the Measurement and Division of Water.

One of the most important as well as one of the most difficult problems of irrigation is that of making a just distribution of water. Therefore, in passing over the lines of ditches with superintendents, from time to time, I have made it the object of special inquiry to find the methods used in measuring or dividing water among the consumers. In many cases, even on important enterprises, there was no attempt, save by the eye; in others the methods varied, from the crudest to others which gave some approach to accuracy. Where water has been plentiful in the streams, or where the ditches had more water than was needed for the consumers under the ditch, there has been no necessity for any close division or measurement, for there has been water to supply the demands of all. But with the greater demand for water, pressure is being brought upon the canal organizations, and many are being led to consider more economical means of distribution and more efficient means of measurement.

The prevention of waste is a matter of public importance. With more land than water, the agricultural future of Colorado will depend on the use of her existing water supply to its fullest capacity. The building of storage reservoirs, the stopping of waste, improved methods in irrigation, together with the changes consequent on irrigation, which makes less water necessary, will increase our water supply in effect, if not in amount.

It is safe to say that a good system of measurement will save a large amount of water, just as a close account of expenditures will make money go farther without wronging any one. Without measurement the practice is necessarily to give the consumer enough to stop complaint. The tendency to improvidence runs to the last consumer, for, if the water is not valuable enough to measure carefully from the canal, what inducement is there for the consumer to prevent waste. With water plentiful, the system—or lack of system—works without much friction. But in time of scarcity it is of great moment that each has no more than he is entitled to. If one man gets more than his share, some one else gets less. And this often means ruin to his crops.

This bulletin is the result of the study of the measuring devices as seen in Colorado and of those used in Italy. It cannot be said that any are free from objection, but some are noticeably better than others. On this subject the experience of Italy is useful. She has the accumulated experience of 600 years of irrigation ; we of thirty. While the progress made here in this time by a people dependent practically upon native wit for their knowledge of irrigation has been marvelous, it is unquestionably true that we may learn much from the experience of other countries. The laws governing the flow of water, the principles involved in distribution and division, are the same here as there. We are finding from our experience the necessity of laws and regulations which they have long had in practice. In other ways our experience is likely to be parallel to theirs. The Italian modules have been various, but most of them based upon one principle, which has been introduced into Colorado under the form of the statute inch. The need for modules being felt before the rise of hydraulic science, these boxes were based upon empirical principles, without the knowledge of the flow of water which we now have. That they have been used so long with even a fair degree of satisfaction reflects great credit upon Soldati and the magistrates of Milan who so firmly grasped the conditions of the problem. That these measures are no longer satisfactory is evidenced by the fact that none of the large modern canals have adopted them. The Cavour Canal, the Canale Casale, the Canale Villoresi have all adopted systems depending upon the weir. The insufficiency of the old measures is further evidenced by the fact that the Italian Government required in one of its acts of concession a proposition for a new module for the measure and sale of water.

The one proposed and adopted by this canal—the Canale Villoresi—will be especially described, because it seems to dispose of some of the difficulties which have made the weir system objectionable.

In the measurement of water there are two distinct classes of measuring boxes, different in their object. One is the dividing box, whose object is to give to each consumer some definite portion of the water flowing in the ditch. This box is found especially in the laterals owned in common by two or three neighbors, or in the smaller canals owned and operated by the stockholders. The other class is the measuring box which has in general for an object to give the consumer a certain definite quantity of water, as one cubic foot per second. These need to be adjustable, so that in times of scarcity the amount may be reduced proportionately as the quantity in the canal decreases. To this last class the Italians give the name of *module*. The French writers on irrigation, and to a limited extent the English, have adopted the word, and, as such a word is needed in our irrigation vocabulary, the term is here used. *Module* will therefore be used to designate those boxes or devices, whatever their form, whose object it is to measure the quantity of water delivered, or to give a constant flow. The word *divisor* will be restricted to the first class, whose only object it is to divide the water. A module may evidently serve as a divisor, for if the amount to be divided is known it is a simple mattter to determine the quantity to which each is entitled and to regulate the module accordingly. There will always be cases where divisors will be by all means the most convenient, but these cases will be mostly in the small ditches from which few take water. In all other cases modules of one kind or another will be found the better.

DIVISORS.

As ordinarily constructed, the division can rarely be exact, but frequently the convenience of an approximate division more than counterbalances any inaccuracy there may be. The larger ditches rarely have occasion to use divisors, for, even if the ditch has to pro rate the water, a better distribution can be effected by means of modules. If the water is to be divided into two equal portions, by placing the two lateral ditches in identical relations to the main ditch, in a straight and uniform channel, the division is exact. Emphasis should be laid on the *identical* relation, for many divisions are seen where the conditions are not the same, as, *e. g.*, one man's ditch may continue straight, the other may make an abrupt turn, one may pass through a covered box, etc. In these cases some advantage will be given to the party having the freer discharge. The effect of these differences is greater than is generally supposed. It is, however, generally easy to fill these conditions if the parties desire. In the same way the water may be subdivided into four, eight or sixteen equal parts. But where it is required to divide the water into two unequal, or into three or more portions, equal or not, the division becomes one of approximation only. The difficulty arises from the fact that the water has not uniform velocity; that near the center has greater velocity than that near the banks. If, therefore, equal openings be made across the current, those near the center have the greater discharge. Making the central openings smaller only partially evades the difficulty, for as the relative velocities of the center and sides differ with different depths, this arrangement would still be inexact for any one depth except that for which the opening is made.

In its most common form the divisor consists of a partition dividing the channel into two portions in proportion to the respective claims. This, in effect, assumes that the velocity is uniform across the whole cross-section, which is not the case, even in a uniform channel, and much less so in one irregular or in poor repair. Such a division is to the disadvantage of the smaller consumer.

The nearer the velocity is uniform across the whole channel the better this method of division, evidently. Accordingly means are frequently taken, by weir-boards or otherwise, with this object in view, but generally with indifferent success. A screen would accomplish this one object better, but the objections to its use are too many in most places to render it practicable. One form often used

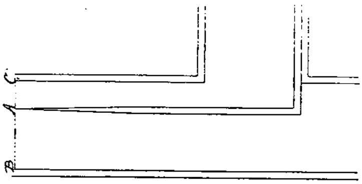

FIG. 1.—A COMMON DIVISOR.

and seen in various places has a movable partition board, A, as in the figure, so that the user who gets his water through L can move A out to some distance, according to the amount of water he needs. A cleat of some kind is generally used to prevent the board being moved beyond a certain distance. The Lariat ditch of the San Luis valley, which is broad and shallow, uses a simple truss across the ditch at the height of the division board and a depending cleat prevents more than a certain movement. In some cases at B C there is put a board, placed vertically, with the edge raised a few inches above the bottom of the channel. This then keeps the channel where the division is made of uniform depth, but it is of little benefit in equalizing the flow.

The latter idea is in some places better developed. The water is brought to a state of approximate rest by a weir-board of some height—8 inches in one seen on the Farmers' Union ditch, San Luis Valley—with a sharp crest on the up-stream side. The partition board extends lengthwise of the ditch and has its upper end sharpened. As the water falls over the weir it flows away in the respective ditches.

If water is brought to a complete state of rest, or very nearly so, and if the water flows over the weir without lateral contraction, this method will give as satisfactory results as any divisors with which I am acquainted. An increase in the size of the ditch just at the division box will aid in bringing the water to rest.

Boxes of this kind were used by Hon. B. S. LaGrange near Greeley as early as 1871.

Since the above was written Aymard's "Irrigation du Midi du l'Espagne" has been received, in which he describes a divisor used at Elche, based on the same principles. It is due to the Moors, and has been in use on this canal since their expulsion from Spain some hundreds of years ago. It differs from the one last described in having two drops instead of one, and in taking more pains with the canal of approach. For 150 or 200 feet above the divisor the canal has a very slight fall, in order that the water may have almost no velocity of approach. The canal is paved for about 10 feet above the divisor. There are two drops about three feet apart, the upper one of 10 inches, the lower one slightly more. The division is made at the upper drop by a movable beak of wood, which may vary the width of the opening or entirely close it. The second drop is for the purpose of producing a constant current away from the point of division.

MODULES.

It is not possible to secure a module satisfactory in every respect. Some may be available in some localities where there is a heavy fall, and not in others where there is no fall to spare.

If a module fulfills the following conditions it may be reputed perfect. All the conditions not marked are essentially the same as those given by Buffon in his "Des Canaux d'Irrigation de l'Italie Septentrionale," Vol. I., p. 445–6 :

*1. Its discharge should be easily converted into absolute measure, *e. g.*, cubic feet per second.

2. Modules intended to give equal discharges should always discharge the same quantities of water in a given time wherever placed.

*3. The ratio indicated by the module to the discharges from two outlets should be the actual ratio.

4. The flow should remain sensibly unaffected by variations in the level of the supplying canal.

5. It should be as reliable with large as with small quantities of water.

6. Any attempt to alter its discharge should leave traces easy to recognize.

7. It should require but a moderate degree of intelligence to use it.

8. Calculation ought not to be necessary to regulate the discharge of different modules or to determine how much they are discharging.

9. It should occupy but small space.

*10. It should require but little fall or expense.

These conditions are evidently not of equal importance, and under different circumstances the weight given to each condition may vary. As water becomes more scarce those relating to accuracy become relatively more important. A module which has been satisfactory may become unsuited when these conditions become more important.

The old Italian modules are mostly based on an orifice of determinate size, with a constant pressure. Our statute inch is such a module. Some are circular, as the *acqua Paola*, but most are rectangular, of various dimensions. Those of the same kind had the same height of orifice and the same pressure. Different amounts were given by giving greater horizontal lenght to the orifice. The *Milanese module*, due to the engineer Soldati, is the most celebrated. The canals of that province having fallen into great disorder, the magistracy of Milan attempted to regulate them, and gave twelve conditions which a module should satisfy.† In response to these, Soldati proposed the module which has ever since been known as

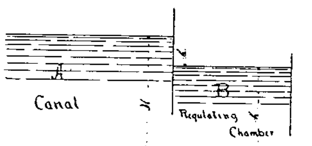

FIG. 2.

the Milanese module. The first thing he considered important was to insure that the water should flow with uniform pressure. This he attempted to do by the following principle:

† NOTE—The history of this event and the trouble is given in Bruschelti's "Storia del Irrigazioni del Milanese," in his collected works, Vol. II., pp. 118-135, condensed in Buffon. The conditions are all included in those given above.

If two chambers are connected, as in the diagram, the water in the second chamber will be lower than that in the first by an amount depending on the size of the orifices. But the amount the water in the first is above that in the second bears a constant ratio to the depth in the second. Thus, if the depth in B is 6 inches and the water in A is 12 inches deeper, if the water in B becomes 6 inches deeper the excess of A over B would increase by twice 12, or 24 inches. Its depth would then be 36, while before it was 18 inches. Under these circumstances an increase of depth of 18 inches in A causes one-third as much in B.

By means of such a regulating chamber, therefore, the variations in the height of the water in the canal are lessened in the regulating chamber, which is intended to furnish the water under constant pressure. While apparently avoiding the difficulty, this really does not do so. As a matter of fact, the flow *will increase in the same ratio for a given increase in depth of the main channel, whether the orifice comes direct from the main channel or from the regulating chamber, provided it be at the same level.*

The reason is this; The velocity of water flowing from an orifice varies with the square root of the depth, and consequently the discharge for the same opening will vary with the square root of the depth or pressure. While the variation in the regulating chamber is less by considerable than in the main canal, the head is less than it would be if the orifice were pierced at the same level in the canal, in the same ratio. As in the numerical example given, while the pressure in the regulating box doubles, or changes from 6 to 12 inches, that in the canal changes from 18 to 36 inches. In consequence, an orifice in the main canal, at the same level, would change its discharge in the same ratio as one at the lower end of a regulating box.

It follows from this that if such a module is not adjusted from time to time it is of no value as a regulator.

This, however, does not take away from its value if properly attended, for it affords a ready means of arranging that the pressure shall be a certain amount. But it should be kept clearly in mind *that unless regulated with every variation in the level of the supplying canal it does not assure a constant flow*, which has been its supposed principal merit. This module consisted essentially of two parts, that already described for attempting to maintain a constant pressure, and other apparatus, so that the water should reach the outlet without velocity. For this purpose a variety of means has been adopted, mostly by varying the chambers in length and breadth, but, according to Baird Smith, the object is very imperfectly accomplished.

This method was used in various Italian units, with openings of different size and shape under different pressures. The units were called "Oncia." No less than ten, some of them circular, are given in Carton and Marcolongo's "Manuale del Ingegnere Agronomo," 1888.

In this State the same principle has been extensively used in the Max Clark box, as it is called, named from its introducer. The box has been extensively used in the older portions of the State, and has fulfilled a useful purpose. It has the same faults as the Milanese module added to the fact that the shortness of the box is such that the movement of the water is imperfectly stopped and cannot but have a great influence on the discharge.

As the term oncia was given to the Italian unit, so the term inch has been used throughout this western country for the corresponding unit. The statutes of Colorado prescribe that water shall be measured through an orifice 6 inches in height, with a pressure of water of 5 inches above the opening, and that the number of inches shall be the same as the number of square inches in the orifice. But the term is not confined to the statute inch. On some ditches water is measured with a pressure of only two inches, on others without any, but the same term is used in all.

An inconvenience which was soon discovered was that the discharge through the Milanese module was not in proportion to the nominal discharge. A person, for instance, drawing 100 inches receives more than ten times one who draws 10. This was so noticeable that it was not long before the discharge from any one orifice was restricted to a certain number of oncia, generally six. The oncia varies from 33 to 47 litres per second, according as the orifice discharges one or six, according to Herrison. The same thing is true of the statute inch of this State—the advantage is entirely in favor of those who draw the large quantities. The reason for this difference comes from the different ratio which the perimeters of the openings bear to the areas in the different cases. For example, one drawing 24 inches has an orifice 4x6 inches, the perimeter is 20 inches. The orifice discharging 96 inches is 16x6 inches, with a perimeter 44. The ratio is less than ½ in the last case, nearly 1 in the first, and friction affects the smaller opening much more than the larger.

There are other causes of variation, as in the distance the opening is above the bottom of the regulating box, in the thickness of the sides, in the manner of its discharge. All of which render this module, excellent as its service has been in the past, inaccurate and unreliable and is leading to its abandonment.

A module based on an entirely different principle is that of the Marseilles canal, one of the most costly in the world, considering the amount of water it carries. The device adopted by them is therefore of some interest, irrespective of the novelty of the plan.

In their module the water enters a hollow vertical cylinder whose upper edge is kept at a constant distance below the surface of the water. The water then flows in with constant pressure. As the level of the water rises or falls the cylinder likewise rises or falls vertically, passing through a water-tight packing. It would seem that the packing required to make the joint water-tight would interfere with its free movement up and down, and thus render the module insensitive. It seems to be used with satisfaction, however. The amount given to different users is regulated by the depth the cylinder is below the water. A simpler device for keeping the orifice a certain distance below the surface was tried on the Montrose canal, in the western part of the State. The orifice rose or fell with the water of the canal, being supported by a float, and was connected with the lateral by a pipe and a flexible joint. The trouble in such an apparatus is to make a joint which shall be water-tight and at the same time flexible enough to be moved by a moderate-sized float when the water rises or falls. If this can be done it would satisfactorily solve the problem of giving a constant flow.

On the Isabella I. canal, of Spain, another form of module has been proposed. Instead of having an orifice at a constant depth as on the Marseilles canal, the orifice varies in size as the head of water changes. With a small depth of water the orifice is large, with a large head it is small. The orifice is made larger or smaller by the water itself. In a circular hole in the bottom of the head of the lateral is a plug of iron, supported by a float. This is roughly conical in shape, with the largest diameter at the bottom. As the water rises in the canal the plug is lifted, partially stopping the orifice by the large diameter. As the water falls the orifice is opened. If the diameters of the plug are properly proportioned—and it is easy to calculate them—this module ought to be a very satisfactory one. It has the disadvantage of requiring a considerable fall, but it avoids the friction which must interfere with the action of the Marseilles module. For a discharge of 1.44 cubic feet per second, generally estimated enough for 80 acres, with a hole 12 inches in diameter, the following would be the diameters for the given depths from the top of the plug:

	Diameter in feet.
3 inches	0.53
6 "	0.70
12 "	0.80
2 feet	0.87
4 "	0.91
9 "	0.94

THE SPILL-BOX OR EXCESS WEIR.

Another means of procuring a constant head is one due to A. D. Foote, of Idaho, recently in charge of the Snake River Division of the Irrigation Survey, a cut of which is given in the *Engineering News* of November, 1886, and more fully described in the transactions of the American Society of Civil Engineers, Vol. XVI.

In fig. 3, A is the main ditch, with a gate forcing a portion of the water through box B. This has a board on the side towards the main ditch, with its upper edge at such a height as to give the required pressure at the orifice. Then if water be forced through B, the amount in excess of this pressure will spill back into the ditch. If the box B is made long enough and the spill-board be sharp edged, nearly all the excess will spill back into the ditch, thus leaving a constant head at the orifice. Mr. Foote gives this the name of excess weir. He constructed one for trial purposes. To Mr. W. H. Graves, of Monte Vista, is due its introduction into use on the large canals, with the necessary modifications. He terms it the spill-box, a more suggestive name than that proposed by Mr. Foote. In use, Mr. Graves constructs a weir in the canal and places the box at one side, always using two if possible, one at each side, to save fall and expense. The spill-box is about 16 feet long, 14 inches wide, set perfectly level. The crest next the canal is brought to a sharp edge, and

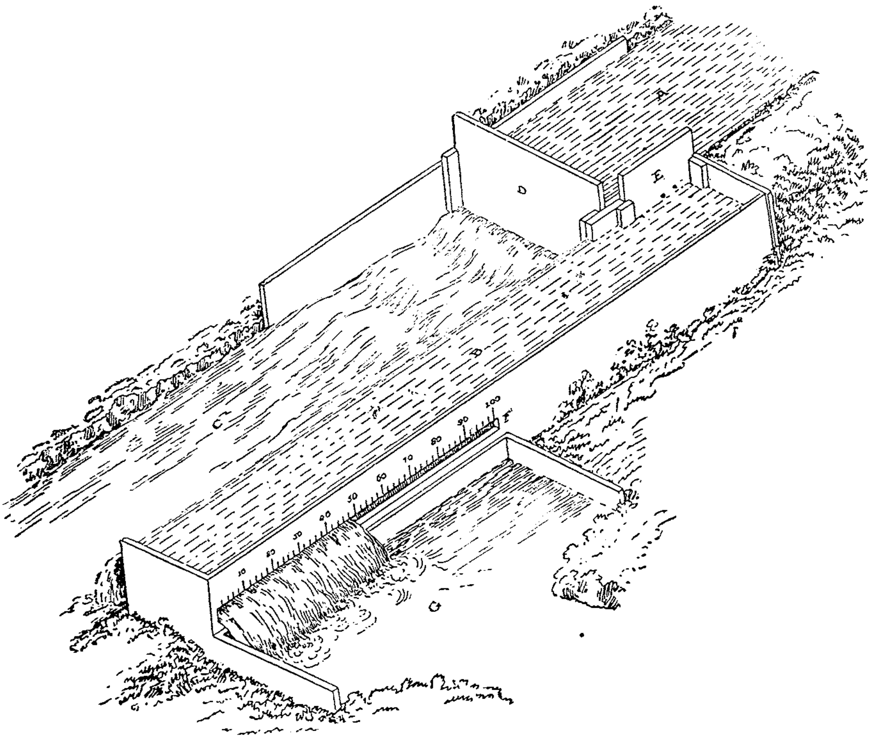

FIG. 3.

so are the 2x4 pieces on that side of the box. The gate for opening the orifice is of galvanized iron, worked by a rod and wing nut from the end of the box, so that it may be adjusted to any desired opening and locked. The side of the opening is protected by strips of galvanized iron, with the double purpose of protecting the orifice from surreptitious enlargement and furnishing a groove for the gate to slide in. Mr. Foote thinks that the main ditch need not lose more than a few inches fall—enough to have the excess spill back. Mr. Graves prefers at least a foot.

These have been introduced on the canals of which Mr. Graves is the Chief Engineer—the Monte Vista or Citizens' canal, the Rio Grande or Del Norte, the Grand River and the Montrose, which include the largest canals in the State. The farmers whom I questioned in the San Luis Valley expressed themselves as perfectly satisfied with its fairness.

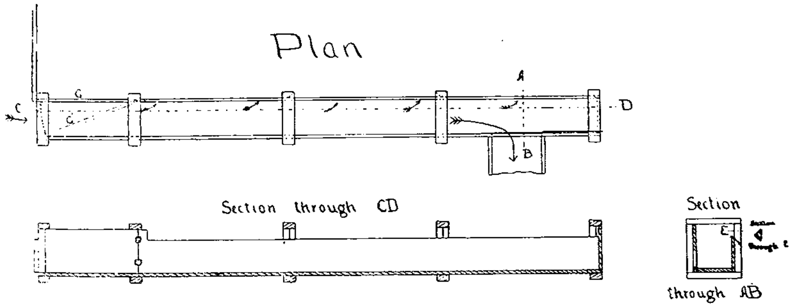

FIG. 4.—PLANS OF THE SPILL-BOX.

C is the entrance of water from the ditch; G a gate which serves to admit as much water as is desired; B the outlet furnishing water to the user.

The success of the device for maintaining the head constant is nearly perfect. Under circumstances purposely made unfavorable—when there was a strong head of water in the canal, no regulation of the gate B, and with obstructions so placed on the weir as to force nearly all the water into the upper end of the box—the depth flowing over opposite the orifice was less than two inches. Under normal conditions the variations in head in the box will be very slight and the flow practically constant. When the flow from openings of different sizes are compared, however, besides the difference in favor of the larger user from causes already spoken of, there must be a velocity of approach which being greater as the discharge is greater would again be to the advantage of the large consumer. On a delivery of 100 inches the effect of this velocity would be to increase the amount by some 5 per cent. over that due to the head proper. This could be lessened by proportioning the size of the box to the amount it is expected to discharge.

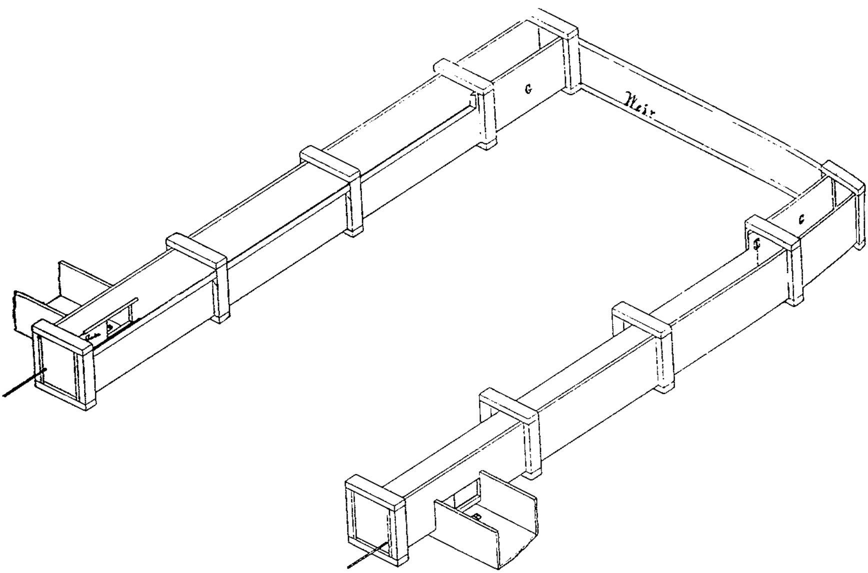

FIG. 5.—THE SPILL-BOX.

(As usually placed, in pairs.)

The weir is placed across the ditch, making the ditch lower below than above, giving opportunity for the water to spill back into the ditch. G is a movable gate to regulate the amount of water admitted at different stages of water in the canal.

Though used on these canals to measure in statute inches, there is no reason why the device should not be used with the weir system, especially of the Villoresi form, shown in fig. 7, and have the superior advantages of the weir.

THE WEIR MODULES.

The form of module which best satisfies the conditions of accuracy is that of the overfall or sharp-crested weir. Other forms might be as accurate, but no other has been subjected to such exhaustive experimental investigation. Besides, its conditions are easily met, so that one may place weirs satisfying these conditions and feel confident that the actual discharge will be close to the calculated.

Because of these facts and the growing importance of accuracy, the coming module will be based upon the weir. It is gradually displacing other types. Australia is using it, exclusively, we think; India, and even in Italy, the originator of most of our measures, the newer canals are using it to the exclusion of the Milanese module. The old canals will probably continue the use of the old module, for rights have become vested in measurement by them, and consumers are jealous of change. A large proportion of the newer canals in Colorado provide that measurement shall be made over a weir. So far as learned no canal has abandoned its use. Cippoletti, who was commissioned by the Canale Villoresi to propose a new module in obedience to the requirement of the Italian Government, says in regard to the weir:

"It is indisputably demonstrated that in weirs with complete contraction, constructed and observed with the necessary accuracy, the *coefficient of contraction remains constant*, and Francis' formula guarantees the exactness of the discharge with an error not greater than *one-half of one per cent.* for depths of water from 3 to 24 inches; providing the length of the weir is not less than three—or better yet, four—times the depth of water flowing over the weir." (Cippoletti, Canale Villoresi Module per la dispensa delle acqua, Milano, 1886, p. 35.)

Cippoletti would, however, use a slightly different coefficient.

The weir is worthy of special attention. Two forms will be considered and tables given for their discharge—the rectangular weir, whose sides are vertical, which is the one ordinarily meant when weir is spoken of, and the one which has been the subject of experiment; and the trapezoidal weir proposed by Cippoletti, after a thorough investigation. Its sides are inclined at a slope of one-fourth horizontal to one vertical.

WEIRS.

The most complete experimental investigation of the flow of water over weirs was made by an American, J. B. Francis, of Lowell, Mass. At that point were located a number of manufacturing enterprises drawing their water from the Merrimac River, with a combined capital of over thirteen millions of dollars. It became necessary to determine more definite measurement of the water, and Francis' experiments were instituted for this purpose. Carried on with all the appliances and conveniences which the capital interested would warrant, the experiments were performed with such care and such attention to minute sources of error that they are above criticism.

One difficulty in such experiments is to obtain a suitable basin in which to measure the water. In this case Francis was fortunate in having one suitable in the Lower Locks, into which the water could be deflected at will after passing the weir. The lock was carefully prepared. Cracks were filled, leaks stopped, even the depressions about nail heads cemented up. The remaining leakage was ascertained by experiment. The slight increase in capacity due to bulging when full was ascertained. The total capacity of the basin when 9½ feet deep was over 12,000 cubic feet.

A preliminary set of experiments was made for determining the proper form of the equation, and after this was determined the main experiments were devoted to finding the value of the coefficient of the formula. The formula indicated by his experiments has since been standard within the limits indicated by him. If one observes the flow of water through an orifice he will observe that the stream becomes narrower, or is subject to lateral contraction. If over a weir, the sheet of water becomes thinner immediately below the crest, as in fig. 6, or is subject to a vertical contraction. By taking separate account of these two contractions Francis succeeded better than previous experimenters in producing a formula which represented the discharge. The form of the equa-

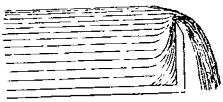

FIG. 6.

tion indicated by theory and agreeing closely with Francis' experiments is of the form,

$$Q = a \, L \, H^{\frac{3}{2}}$$

Where Q = the quantity of water flowing in cubic feet per second, L = the effective length of the weir in feet. This is not necessarily the same as the actual length of the weir.

H = the depth of water flowing over the weir in feet. Because of the contraction shown in fig. 6, this must be measured far enough from the weir to be free from its influence. If the water approaches with a current this depth needs to be increased by a correction indicated by theory. This correction is troublesome to make. In practice it is better to so reduce the velocity of the current that the correction may be neglected.

a is a numerical coefficient which is needed to multiply the result obtained by the indicated operations in the measured quantities, in order to give Q the discharge.

From his experiments Francis adopted for this coefficient the value, $a = 3.33$; though 10-3 would agree more closely with his results, and it seems to the writer to be more convenient for calculation.

The formula of Francis then becomes

$$Q = 3.33\ L\ H^{\frac{3}{2}}$$

where the letters mean the same as in the formula on the previous page, and with the same restrictions.

END CONTRACTION.

An additional word needs to be said regarding L, the effective length of the weir. The contraction of the stream passing over the weir has already been mentioned. The contraction is said to be complete when the sides and walls are so far away as not to affect it; incomplete when so affected, or no contraction, as when the weir is in the lower end of the flume and extends the whole width.

The contraction should be complete or none at all.

If no contraction the full measured length of the weir is used.

If complete, the length of the weir is diminished by one-tenth of the depth for each contraction. The contractions usually occur in pairs, one on each side of the opening. If the opening be broken into two parts or bays there may be four contractions. Thus, in Series A of Francis' experiments, given on page 24, the length of the weir being 10 feet and the depth 1.56 feet, the two contractions reduce the length by 2-10 of 1.56 feet, the depth, or 0.31 feet. L, the effective length to be used in the calculation, is then 9.69 instead of 10 feet.

It is best to have complete contraction, the conditions of securing which are given in Nos. 4 and 5 of the following conditions. While it is generally believed that this formula is accurate, it is not so generally understood that it is safe to apply it only within the conditions of the experiments on which it is based.

CONDITIONS OF THE RECTANGULAR WEIR.

If the weir be placed so as to meet the following conditions, the formula above given and the tables attached to this bulletin, may be used with confidence that the result is correct within 1 per cent:

First—That the water shall not exceed 24 nor be less than 6 inches in depth. Experiments subsequent show that it is practically safe to 3 inches.

Second—That the depth of water on the crest shall not be more than one-third the length of the weir.

Third—The crest of the weir itself should be horizontal; the sides vertical; with both crest and sides brought to a sharp edge on the up-stream face. The least rounding increases the discharge. The up-stream face should be vertical.

It is also necessary to secure:

Complete contraction.
Free discharge.
And the approach of water to the weir without perceptible velocity, cross currents or eddies.

Hence the following additional conditions:

Fourth—The distance from the side walls to the crest should be at least equal to the depth on the weir, in order to secure contraction.

Fifth—The distance of the crest above the bottom of the channel should be at least twice the depth of the water flowing over it, in order to avoid the effect of the bottom on the crest contraction.

Sixth—The air must have free access under the falling sheet.

Seventh—The approaching channel should be made much larger than the weir opening, to bring the velocity of approach within low limits.

A fuller consideration of the proper conditions and the effects of their neglect is given with the Villoresi module on page 27. These apply equally well to the rectangular weir. The experimental foundation of the formula is shown in the following

ABSTRACT OF FRANCIS' EXPERIMENTS ON WEIRS.

[Depth has in all cases been corrected for velocity. Supply canal 14 feet wide.]

Serial No.	Depth of Water on Weir in Feet.	Coefficient for the Experiments.	Length of Weir, ft.	No. Contractions.	COMMENTS.
1-4	1.56	3.318	10	2	SERIES A.
5-10	1.25	3.334	10	2	Crest of weir is 5 feet above bottom of channel of approach.
11-33	1.00	3.322	10	2	
56-61	0.80	3.325	10	2	
72-78	0.62	3.328	10	2	
36-43	1.06	3.353	10	2	SERIES B.
62-66	0.83	3.340	10	2	Same as A except that crest is only 2 feet above bottom of channel.
79-84	0.65	3.326	10	2	
44-50	0.98	3.341	10	0	SERIES C. Canal made same width as weir, suppressing contraction, otherwise as in A.
67-71	0.80	3.339	10	0	
51-5	1.00	3.327	10	0	SERIES D. Water cannot expand after passing weir.
34-5	1.02	3.360	8	4	SERIES E. Water 5′ deep.
85-8	0.68	3.337	8	4	Water 2′ deep. Two bays, separated by partition 2′ wide, giving 4 contractions.

Series C and D correspond to weirs erected in flumes, C at the lower end, D in the middle, each of full width of flume.

As a general thing, the coefficients increase slightly as the depth decreases, so that for small depths, less than three inches, the discharge will generally exceed the computed amount by one or two per cent.

A table giving the discharge for different depths over weirs of various lengths is given in the appendix, which will be useful to those already using this system.

THE CIPPOLETTI OR CANALE VILLORESI MODULE.

A module based on the same principles and experiments, but differing in shape, is the module of the Canale Villoresi. The Canale Villoresi—so named from the engineer who projected it—is the latest great Italian canal. Constructed in 1881–4, it waters some 65,000 ettare, or 160,000 acres, between the Ticino and Adda rivers. So important a public benefit did the project seem to be, that the Provincial Council of Milan voted the money to construct it. Its cost was fully one fourth as much as all the canals in Colorado to-day. The various modules in use had long been unsatisfactory, principally, according to Herrisson, for the reason that they favored the large users.

In the act of concession, the government imposed the condition of proposing a module for the measurement and sale of water. The government required that it should be founded on the theory of the weir with free fall, and that it should give ample guarantees of security and accuracy. The problem was put in the able hands of Cesare Cippoletti, the director of the works. Much of the following is condensed from his work: "Canale Villoresi; Modulo per la Dispensa delle Acqua, etc., Milan, 1886," published by the direction of the Societa Italiana per Condotte d'Acqua. The problem Cippoletti proposed to himself was, while preserving the simple and convenient form of the formula of Francis, and a constant coefficient, to determine the form and conditions of a weir such that no single cause would produce more than one half of one per cent. error between the actual discharge and that given by the formula.

His investigations were based principally upon the experiments of Francis, supplemented in certain directions by some of his own.

His work is interesting and valuable, from the thorough study he has given to the various disturbing causes, and the means of lessening their effect.

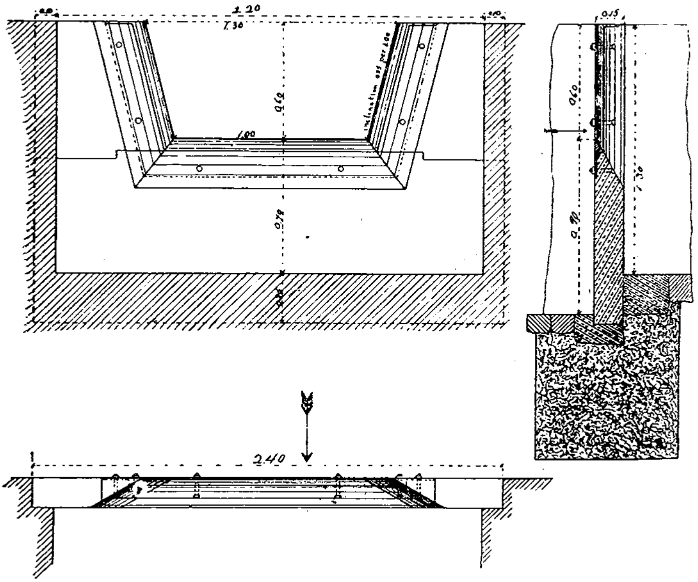

FIG. 7.—THE VILLORESI OR CIPPOLETTI TRAPEZOIDAL MODULE.
The dimensions are given in decimals, with the length of the sill as the unit.

The effective length of the rectangular weir, as already noted, becomes less as the depth of water becomes greater. Also, the effective length of two weirs is not in the ratio of their lengths. These facts form objections to the rectangular weir.

Cippoletti's improvement consists principally in automatically overcoming, by the shape of the opening, this contraction, so that the effective length of the same weir remains the same, and the discharge from two weirs for the same depth will be in the ratio of their lengths—one twice as long discharging twice as much.

The weir which he adopted is of the trapezoidal shape, the sides being inclined at one-fourth horizontal to one vertical, as shown in fig. 7. This inclination was adopted from theoretical and experimental considerations, so that with complete contraction the added area of the triangles would just make up for the contraction; consequently the discharge through the weir would be the same as through the rectangular weir of the same length, but without contraction. The actual length of the weir is therefore used, and simplifies calculations very much.

The conditions Cippoletti attempted to meet, then, were:

1. To place the weir in such condition that all causes affecting its discharge shall not cause an error greater than one-half per cent.

2. To eliminate automatically the lateral contraction, so as to preserve the simple formula:

$$Q = a \, L \, H^{\frac{3}{2}}.$$

(*a*) with the coefficient *a*, constant for all depths
(*b*) and so that the discharge shall be rigorously proportioned to the length of the weir.

In order that no cause shall produce an error greater than one-half per cent., it is necessary:

1. That the weir be preceded by a straight channel of constant cross-section, with its axis passing through the middle of the weir, and perpendicular to it; this straight reach to be of such length that the water goes

with uniform velocity without internal agitation or eddies. In ordinary cases fifty or sixty feet is sufficient.

2. Only by making the contraction complete in the whole perimeter can a definite value of the numerical coefficient not subject to doubt be attained, and for this it is necessary,

(*a*) that the opening of the weir be made in a plane surface, perpendicular to the course of the water;

(*b*) that the opening itself have a sharp edge on the up-stream face, and the walls cut away so that their thickness at the point of discharge shall not be above 1-10 the depth for depths below 5 inches, nor above $\frac{1}{4}$ the depth for depths from 5 to 24 inches;

(*c*) that the distance of the sill of the weir from the bottom of the canal be at least three times the depth on the weir, and at least twice the depth on the weir from the sides;

(*d*) that the lateral contraction remaining undisturbed, the length of the weir shall be three, or better four, times the depth of the water;

(*e*) that the depth of water flowing over the weir shall not be less than 3 inches.

3. The velocity of approach must be very small; for weirs one meter (40 in.) long and depth of 12 inches it ought not to be greater than 6 inches per second; for weirs of two meters ($6\frac{1}{2}$ ft.) long and depth of 24 inches it ought not to be above 8 inches per second. In all these cases the cross-section of the canal of approach ought to be at least seven times that of the weir: For the other conditions, if *c* and *d* of No. 2 be fulfilled, they are also in the present case.

4. The layer of falling water should be perfectly free from the walls below the weir, in order that air may freely circulate underneath. For short weirs it is sufficient that the lateral walls of the lower canal be free

from the sides of the weir. The level of the water in the lower canal has no influence on the discharge of the weir, unless it may reach the plane of the sill.

5. The depth of the water should be measured with accuracy where the suction of the flow does not affect the height and where it is free from influences which can affect the true level of the water, as the wind or the movement of the water. The height should be read to within 1-300 of the depth in order that the error may be within ½ per cent.

6. The weir ought to be constructed with care and carefully located. It should not vary more than 4° from being perpendicular to the channel. Its sill should be horizontal.

Effect of Disturbing Causes.

All the disturbing causes may be divided into three categories: First—Those which may increase or decrease the discharge. Second—Those which always tend to increase the discharge. Third—Those which always tend to decrease the discharge.

The height of water measured may be too great or small, and, as it is as likely to be one as the other, the errors due to this may be neglected.

The effect of obliquity of the weir, or eddies, is to decrease the flow.

Velocity of approach, nearness of sides and bottom to the crest, of incomplete contraction, of a crest not perfectly sharp, of air not having free access beneath the sheet of falling water, etc.—the effect of each of these is to increase the discharge.

The causes tending to increase the discharge evidently outnumber those decreasing it, and are, all things being taken into account, more difficult to overcome. The combined effect of all taken together is evidently to increase the discharge; Cippoletti therefore increases Francis' coefficient by 1 per cent. to allow for the preponderance of accidental causes increasing the discharge, thus making the equation become

$$Q = 3.36\tfrac{2}{3}\ L\ H^{\frac{3}{2}}$$

where Q, L, H, represent the same quantities as on page 21, except that L is here the actual length of the weir.

This form seems to possess some very advantageous qualities, rendering it much more simple in use than the rectangular weir and dispensing with some of the objections which have not rendered the weir popular. The effective length to be used in calculation is the same for all depths, while in the rectangular weir, with complete contraction, every change in depth alters the effective length and makes the calculation inconvenient and laborious. The discharge also being in proportion to the length, very nearly, makes it convenient for application with such a device as the spill-box, where the opening may be made of this form instead of that used by Graves. Then, if one person is entitled to one-half as much as another, the sill may be made half as long, or a moveable gate may reduce the width with an error probably very small, and if any error it is in favor of the smaller user.

The amount ot water available and our apparatus at present available for testing the flow of water is not sufficient to test this to any great extent. The flow over 6-inch and 12-inch weirs has been measured. These seem to indicate that the correction to Francis' formula for these lengths would be nearer 2 than 1 per cent. It would be less for larger weirs. The experiments are sufficient to show that the Cippoletti weir may be used under the conditions stated, with confidence that the error will not be likely to exceed 1 per cent.

One difficulty which arises in the use of the Cippoletti form, as well as the rectangular weir, in muddy waters, is the sediment which may deposit in the still water in front of the weir-board, but this in most places will not be a serious difficulty.

While this module cannot be said to be free from objection or disadvantages, it seems to possess the most merits of any known to the writer at present.

A table follows giving the discharges over various weirs of the Cippoletti form. It will be noticed that the discharge over the two-foot weir is twice that over the one-foot for the same depth, and that in general the discharge is in proportion to the length.

TABLES OF DISCHARGE.

In the following tables of discharge over rectangular weirs and over trapezoidal weirs of the Cippoletti form, the tables hold true, with but small error, for weirs placed so as to satisfy the conditions given on page 27.

For that portion of the table printed in bold-faced type, the difference between the actual and calculated discharges will not be likely to exceed 1 per cent.

For small depths the actual discharge may exceed the amount here given by 2 to 5 per cent.

L. G. CARPENTER.

DISCHARGE OVER CIPOLETTI'S TRAPEZOIDAL WEIRS OF VARIOUS LENGTHS AND WITH VARIOUS DEPTHS.

$$\text{Formula, } D = 3.3\tfrac{2}{3}\ L\ H^{\frac{3}{2}}.$$

Depth of water on crest.		DISCHARGE IN CUBIC FEET PER SECOND OVER WEIR.						
In Ins.	In Feet.	1 ft. Long.	1½ ft. Long.	2 ft. Long.	3 ft. Long.	4 ft. Long.	5 ft. Long.	10 ft. Long.
.3	.025	.0135	.0202	.0269	.0404	.0539	.0673	.1347
.6	.05	.0377	.0566	.0754	.1131	.1508	.1885	.3771
.9	.075	.0690	.1035	.1280	.2071	.2761	.3451	.6902
1.2	.10	.1064	.1596	.2128	.3192	.4256	.5319	1.0639
1.5	.125	.1488	.2232	.2976	.4464	.5952	.7440	1.4881
1.8	.15	.1956	.2934	.3912	.5868	.7824	.9780	1.9560
2.1	.175	.2464	.3697	.4929	.7393	.9858	1.2322	2.4644
2.4	.20	.3010	.4515	.6020	.9029	1.2039	1.5049	3.0098
2.7	.225	.3592	.5388	.7184	1.0777	1.4369	1.7961	3.5922
3.0	.25	.4208	.6312	.8417	1.2625	1.6833	2.1041	4.2083
3.3	.275	.4855	.7282	.9709	1.4564	1.9419	2.4273	4.8547
3.6	.30	.5531	.8297	1.1063	1.6594	2.2126	2.7657	5.5314
3.9	.325	.6238	.9358	1.2477	1.8715	2.4954	3.1192	6.2384
4.2	.35	.6972	1.0459	1.3945	2.0917	2.7890	3.4862	6.9724
4.5	.375	.7730	1.1595	1.5460	2.3190	3.0920	3.8649	7.7299
4.8	.40	....	1.2777	1.7035	2.5553	3.4071	4.2588	8.5177
5.1	.425	....	1.3993	1.8658	2.7987	3.7316	4.6645	9.3290
5.4	.45	....	1.5246	2.0328	3.0492	4.0656	5.0820	10.1640
5.7	.475	....	1.6534	2.2045	3.3067	4.4089	5.5112	11.0225
6.0	.50	....	1.7854	2.3805	3.5708	4.7610	5.9512	11.9025
6.3	.525	....	1.9210	2.5614	3.8420	5.1227	6.4034	12.8068
6.6	.55	....	2.0599	2.7465	4.1198	5.4930	6.8663	13.7326
6.9	.575	....	2.2018	2.9357	4.4036	5.8715	7.3393	14.6787
7.2	.60	....	2.3472	3.1293	4.6939	6.2585	7.8231	15.6463
7.5	.625	....	2.4955	3.3274	4.9911	6.6548	8.3185	16.6370
7.8	.65	....	2.6462	3.5283	5.2924	7.0565	8.8206	17.6413
8.1	.675	....	2.8007	3.7343	5.6014	7.4686	9.3357	18.6715

DISCHARGE OVER TRAPEZOIDAL WEIRS—Continued.

Depth of water on crest.		DISCHARGE IN CUBIC FEET PER SECOND OVER WEIR.					
In Ins.	In Feet.	2 ft. Long.	3 ft. Long.	4 ft. Long.	5 ft. Long.	7 ft. Long.	10 ft. Long.
8.4	.70	3.9437	5.9156	7.8874	9.8593	13.8030	19.7186
8.7	.725	4.1565	6.2347	8.2930	10.3912	14.5477	20.7824
9.0	.75	4.3733	6.5599	8.7466	10.9332	15.3065	21.8665
9.3	.775	4.5942	6.8912	9.1883	11.4854	16.0796	22.9708
9.6	.80	4.8177	7.2265	9.6354	12.0442	16.8619	24.0885
9.9	.825	5.0453	7.5679	10.0906	12.6132	17.6585	25.2264
10.2	.85	......	7.9154	10.5538	13.1923	18.4692	26.3846
10.5	.875	......	8.2669	11.0225	13.7781	19.2893	27.5562
10.8	.90	......	8.6234	11.4978	14.3723	20.1212	28.7446
11.1	.925	......	8.9850	11.9800	14.9749	20.9649	29.9499
11.4	.95	......	9.3516	12.4688	15.5860	21.8204	31.1720
11.7	.975	......	9.7233	12.9644	16.2054	22.6876	32.4019
12.0	1.00	......	10.1000	13.5667	16.8353	23.5667	33.6667
12.3	1.025	......	10.4808	13.9744	17.4679	24.4551	34.9359
12.6	1.05	......	10.8666	14.4888	18.1110	25.3554	36.2220
12.9	1.075	......	11.2575	15.0100	18.7624	26.2674	37.5249
13.2	1.10	......	11.6524	15.5365	19.4206	27.1888	38.8412
13.5	1.125	......	12.0513	16.0684	20.0855	28.1198	40.1711
13.8	1.115	......	12.4553	16.6071	20.7588	29.0624	41.5177
14.1	1.175	......	12.8644	17.1525	21.4406	30.0168	42.8812
14.4	1.2	......	13.2764	17.7019	22.1274	30.9784	44.2548
14.7	1.225	......	13.6936	18.2581	22.8226	31.9517	45.6453
15.0	1.25	......	14.1148	18.8197	23.5246	32.9344	47.0492
15.3	1.275	......	14.5410	19.3880	24.2349	33.9289	48.4699
15.6	1.3	......	......	19.9603	24.9503	34.9305	49.9007
15.9	1.325	......	......	20.5394	25.6742	35.9439	51.3484
16.2	1.35	......	......	21.1238	26.4047	36.9666	52.8095
16.5	1.375	......	......	21.7123	27.1404	37.9966	54.2808
16.8	1.4	......	......	22.3075	27.8844	39.0382	55.7688
17.1	1.425	......	......	22.9082	28.6352	40.0898	57.2704
17.4	1.45	......	......	23.5128	29.3910	41.1474	58.7820
17.7	1.475	......	......	24.1242	30.1552	42.2178	60.3105

DISCHARGE OVER TRAPEZOIDAL WEIRS.—Continued.

Depth of water on crest.		DISCHARGE IN CUBIC FEET PER SECOND OVER WEIR.			
In Inches.	In Feet.	4 ft. Long.	5 ft. Long.	7 ft. Long.	10 ft. Long.
18.0	1.5	24.7396	30.9245	43.2943	61.8490
18.3	1.525	25.3604	31.7005	44.3808	63.4011
18 6	1.55	25.9866	32.4833	45.4766	64.9666
18.9	1.575	26.6182	33.2727	46.5818	66.5455
19.2	1.6	....	34.0685	47.6959	68.1370
19.5	1.625	....	34.8702	48.8183	69.7405
19.8	1.65	....	35.6782	49.9495	71.3565
20.1	1.675	....	36.4913	51.0878	72.9826
20.4	1.7	....	37.3111	52.2355	74.6222
20.7	1.725	....	38.1376	53.3926	76.2752
21.0	1.75	....	38.9691	54.5568	77.9383
21.3	1.775	....	39.8074	55.7304	79.6149
21.6	1.8	....	40.6515	56.9121	81.3030
21.9	1.825	....	41.5009	58.1013	83.0018
22.2	1.85	....	42.3577	59.3008	84.7154
22.5	1.875	....	43.2179	60.5031	86.4358
22.8	1.9	....	....	61.7211	88.1730
23.1	1.925	....	....	62.9442	89.9203
23.4	1.95	....	....	64.1720	91.6743
23.7	1.975	....	....	65.4116	93.4452
24.0	2.0	....	....	66.6560	95.2228
25.5	2.125	....	....	72.999	104.285
27.0	2.25	....	....	79.541	113.63
28.8	2.4	....	....	87.619	125.17
30.0	2.5	....	....	93.156	133.08

DISCHARGE OVER RECTANGULAR WEIRS OF VARIOUS LENGTHS AND WITH VARIOUS DEPTHS OF WATER, WITH COMPLETE CONTRACTION.

$$\text{Formula, } D = 3\tfrac{1}{3}\,(l - .2H)^{\frac{3}{2}}.$$

Depth of Water on Crest.		DISCHARGE IN CUBIC FEET PER SECOND.						
		With two Complete Contractions.						Correction to be *added* to each of the preceding to give discharge with *no* contraction.
In Inches.	In Feet.	1 ft. Long.	1½ ft. Long.	2 ft. Long.	3 ft. Long.	5 ft. Long.	10 ft. Long.	
0.3	.025	.0133	.0200	.0267	.0400	.0677	.133	.0000
0.6	.050	.0369	.0556	.0743	.1116	.1863	.3726	.0004
0.9	.075	.0674	.1015	.1360	.2040	.3410	.6820	.0010
1.2	.1	.1033	.1550	.2078	.3132	.5240	1.0519	.0021
1.5	.125	.1438	.2175	.2912	.4385	.7332	1.4695	.0037
1.8	.15	.1879	.2817	.3816	.5743	.9627	1.9312	.0058
2.1	.175	.2355	.3575	.4795	.7235	1.2115	2.4315	.0085
2.4	.2	.2861	.4352	.5843	.8824	1.4787	2.9690	.0119
2.7	.225	.3399	.5177	.6956	1.0513	1.7627	3.5412	.0160
3.0	.25	.3959	.6042	.9126	1.2293	2.0227	4.1462	.0208
3.3	.275	.4543	.6946	.9350	1.4157	2.3771	4.7803	.0264
3.6	.3	.5149	.7287	1.0725	1.6103	2.7057	5.4441	.0328
3.9	.325	.5775	.8863	1.1952	1.8129	3.0483	6.1368	.0401
4.2	.35	.6420	.9871	1.3423	2.0226	3.4032	6.8547	.0483
4.5	.375	.7079	1.0905	1.4732	2.2385	3.7691	7.5956	.0574
4.8	.4	....	1.1974	1.6160	2.4623	4.1489	8.3655	.0674
5.1	.425	....	1.3070	1.7689	2.6926	4.5400	9.1586	.0785
5.4	.45	....	1.4189	1.9221	2.9874	4.9410	9.9725	.0905
5.7	.475	....	1.5333	2.0790	3.1703	5.3529	10.8094	.1036
6.0	.5	....	1.6500	2.2392	3.4177	5.7748	11.6672	.1178
6.3	.525	....	1.7689	2.4029	3.6709	6.2069	12.5469	.1331
6.6	.55	....	1.8899	2.5698	3.9295	6.6489	13.4474	.1496
6.9	.575	....	2.0129	2.7395	4.1928	7.0995	14.3658	.1671
7.2	.6	....	2.1381	2.9128	4.4621	7.5607	15.3072	.1859
7.5	.625	....	2.2646	3.0881	4.7351	8.0291	16.2641	.2059
7.8	.65	....	2.3929	3.2663	5.0130	8.5064	17.2399	.2271
8.1	.675	....	2.5234	3.3478	5.2965	8.9939	18.2374	.2496

DISCHARGE OVER RECTANGULAR WEIRS.—Continued.

Depth of Water on Crest.		DISCHARGE IN CUBIC FEET PER SECOND.				
		With Two Complete Contractions.				Correction to be *added* to each of the preceding to give discharge with *no* contraction.
In Inches.	In Feet.	2 ft. Long.	3 ft. Long.	5 ft. Long.	10 ft. Long.	
8.4	.7	3.6313	5.5536	9.4882	19.2497	.2783
8.7	.725	3.8170	5.7747	9.9901	20.2786	.2984
9.0	.75	4.0052	6.1702	10.5002	21.3252	.3248
9.3	.775	4.1961	6.4704	11.0190	22.3905	.3525
9.6	.8	4.3884	6.7734	11.5434	23.4684	.3816
9.9	.825	4.5833	7.0810	12.0764	24.5649	.4121
10.2	.85	4.7806	7.3929	12.6175	25.6790	.4440
10.5	.875	4.9792	7.7075	13.1641	26.8056	.4774
10.8	.9	....	8.0257	13.7177	27.9477	.5123
11.1	.925	....	8.3473	14.2779	29.1044	.5485
11.4	.95	....	8.6725	14.8451	30.2766	.5864
11.7	.975	....	9.0012	15.4192	31.4642	.6258
12.	1.0	....	9.3333	16.0000	32.6667	.6657
12.3	1.025	....	9.6679	15.5859	33.8809	.7091
12.6	1.05	....	10.0058	17.1784	35.1099	.7531
12.9	1.075	....	10.3471	17.7777	36.3552	.7988
13.2	1.1	....	10.6890	18.3825	37.6110	.8460
13.5	1.125	....	11.0370	18.9916	33.9731	.8949
13.8	1.150	....	11.3865	19.5030	40.1615	.9455
14.1	1.175	....	11.7396	20.2303	41.4573	.9977
14.4	1.2	....	12.0935	20.8569	42.7654	1.0516
14.7	1.225	....	12.4507	21.4893	44.0358	1.1072
15.	1.25	....	12.8103	22.1269	45.4184	1.1645
15.3	1.275	....	13.1733	22.7713	46.7663	1.2237
15.6	1.3	....	13.5375	23.4189	48.1224	1.2846
15.9	1.325	....	13.9047	24.0727	49.4927	1.3473
16.2	1.35	....	14.2744	24.7318	50.8753	1.4117
16.5	1.375	....	14.6450	25.3936	52.2651	1.4779

DISCHARGE OVER RECTANGULAR WEIRS.—Continued.

Depth of Water on Crest.		DISCHARGE IN CUBIC FEET PER SECOND.		
		With Two Complete Contractions.		Correction to be *added* to each of the preceding to give discharge with *no* contraction.
In Inches.	In Feet.	5 ft. Long.	10 ft. Long.	
16.8	1.4	26.0625	53.6710	1.5460
17.1	1.425	26.6355	55.0870	1.6160
17.4	1.45	27.4122	56.5122	1.6878
17.7	1.475	28.0950	57.9515	1.7615
18.	1.5	28.7814	59.3999	1.8371
18.3	1.525	29.4719	60.8584	1.9146
18.6	1.55	30.1675	62.3290	1.9940
18.9	1.575	30.8681	63.8116	2.0754
19.2	1.6	31.5727	65.3042	2.1588
19.5	1.625	32.2809	66.8050	2.2441
19.8	1.650	32.9935	68.3185	2.3315
20.1	1.675	33.7093	69.8393	2.4207
20.4	1.7	34.4295	71.3710	2.5120
20.7	1.725	35.1546	72.9146	2.6054
21.0	1.75	35.8827	74.4662	2.7008
21.3	1.775	36.6151	76.0286	2.7984
21.6	1.8	37.3520	77.6020	2.8980
21.9	1.825	38.0709	79.1614	3.0196
22.2	1.85	38.8341	80.7716	3.1034
22.5	1.875	39.5812	82.3717	3.2093
22.8	1.9	40.3321	83.9816	3.3174
23.1	1.925	41.0860	85.5995	3.4275
23.4	1.95	41.8436	87.2271	3.5399
23.7	1.975	42.6045	88.8625	3.6545
24.	2.0	43.3665	90.5061	3.771
27.	2.25	....	107.44	5.06
30.	2.50	....	125.16	6.59
36.	3.00	....	162.79	10.39