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DISCHARGE CURVES AND A SLIDE-RULE.

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Synopsis.

The paper shows how far it is permissible to assume that discharges vary as the five-thirds power of depths, in Panjab channels, that is cross-section trapezoidal with $\frac{1}{2}$: 1 side-slopes (*diagrams and paragraphs* 4 *to* 10); after discussing some other methods of framing discharge tables (*paragraphs* 12 *to* 15), it describes a better method based on the above variation (*paragraphs* 16 *to* 18), giving a standard discharge table which is applicable to all these channels (*paragraph* 19).

It is argued (*paragraph* 20) that for periodical adjustment of the discharge table, the present method of percentage correction of tabular discharges is both less correct and less simple than to make a deduction from the gauge-reading before entering the table. This deduction shows directly how the channel silts and scours (*paragraph* 21). It is further shown (*paragraph* 22) how a gauge can be fitted in the channel to read cusecs direct.

Extending the examination of discharge curves, a formula is arrived at which makes it possible for a single straight-line diagram to give the information of a set like Kennedy's Diagrams, plus more diagrams for further slopes and other values of Kutter's N (*paragraphs* 23 *and* 24). Reference is made to an occasion during the war, when this was useful (*paragraph* 3), especially as the diagram does not take long to draw.

The same formula makes a handy slide-rule possible, which is described (*paragraphs* 25 *to* 27 *and* 36 *to* 39) with a full set of examples of its working.

To make this of full utility not only involves provision for working according to Kennedy's law of critical velocities, but calls for evolving a similar law for widths of channels. Accepted Panjab practice is reduced to a formula, with provision for departure from the normal (*paragraphs* 28 *to* 35), and is put on to the slide-rule.

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1. For distributing the water in their canals, Panjab irrigation engineers have to frame discharge tables for their many channels, and to keep them up to date as the channels silt or scour or otherwise change in condition. Some of them have developed methods which save labour, increase accuracy, and avoid errors often committed in unthinking routine working. This paper places some of these on record, for wider use.

2. The first formulæ for calculating the flow of water in channels, based on relatively few data, were simple in form, like the Chezy formula. As data increased and showed that a simple formula was not accurate, the formulæ became more complicated-like the Kutter formula. Later came a movement again towards more simple formulæ, of exponential form. This paper goes a step further in simplification. Dealing only with channels that nature forms to similar shapes, it connects the discharge directly with the essential dimensions of the channel, eliminating calculations of area, hydraulic mean radius, and velocity : the formula is further of a form that lends itself to the construction of a slide-rule which can be carried in the pocket in the field ; or of one simple diagram to take the place of the complete set (*e. g.*, Kennedy's) now required, that can be drawn complete in a few hours, without need for calculating a dozen or two of discharges to fix each curve drawn ordinarily.

3. An occasion occurred on which the last point was useful. In the spring of 1918 Sir Thomas Ward wrote from Mesopotamia, that the canal engineers there could not use their Kennedy's diagrams because of the flat slopes and the metric units ; there were no other diagrams or tables available. By chance, the author the day before getting this letter, hit the solution he had been seeking for many years : in camp and single-handed he made the diagram wanted that same day ; more time was spent in thinking out the probable most useful ranges of depth, width slope and discharge, than in actually making the diagram : the next mail took back a supply of the diagram, a single sheet of foolscap size. As far as the author knows, few of the engineers for whom it was intended were able to use the diagram : it was different from those they knew.

4. The channels dealt with are originally dug to a trapezoidal cross-section ; after running they are assumed to be still of trapezoidal cross-section with $\frac{1}{2}$: 1 side-slopes ; this assumption is general and accepted.

5. An assumption that is now not uncommon for use in making discharge tables, is that discharge varies as the five-thirds power of supply depth. The theoretical accuracy of that assumption can be judged from the curves plotted on Plates I (*a*) and I (*b*).

6. On those plates are plotted data of channels of bed-widths from 2 feet to 200 feet ; for each bed-width a range of depths is taken from rather above the normal downward ; each channel is calculated by Kutter's formula with three values of N and three gradients ; a few calculations are also made by the Bazin, the Manning, and the Barnes formulæ. Vertically are plotted depths, to the logarithmic scales marked on the plots. Discharges are divided by width and by the five-thirds power of the depth, and the

logarithm of the result is plotted horizontally. To keep the separate curves distinct without unnecessary waste of space, each curve is plotted from a separate (vertical) base-line whose position and value are marked, and the scale for measuring from these base-lines is shown at the top of the plate.

7. It is the nature of such logarithmic plotting, that any purely exponential relation between discharge and depth, is represented by a straight line whose slope is a measure of the exponent ; thus in these plottings vertical lines represent an exponent of five-thirds ; a triangular scale shows the slopes for lines representing formulæ with other exponents a little above and below this. If this triangular scale were sufficiently extended to the left, it would show the slope for the exponent 0 ; that is, lines of constant discharge are inclined at a very small angle to those for constant depth, dipping down a little to the right. This means that if, instead of plotting in the ordinary way with the axes of co-ordinates at right-angles, we make them at a suitably inclined angle, we greatly magnify differences ; the " percentage scale " marked on the plate shows how legible small differences are on this plotting.

8. As an example of what can be seen from these curves, take the plot for a 200 feet wide channel graded 0·15 per thousand with Kutter's N=0·0225. The " normal " depth (explained below) will be 8·3 feet, so a vertical line is drawn through that point on the curve to test the five-thirds power relation ; with lower depths the curve passes to the right of the line, meaning that Kutter discharges are greater than those according to the five-third power relation with a co-efficient giving correct result at 8·3 feet depth, but the maximum error is only 0·4 per cent. ; at 4·3 feet depth the error becomes zero ; we can go up to 9·3 feet and down to 3·6 feet depth without the minus error becoming greater than the same 0·4 per cent. As these depths mean respectively 120 per cent. and 25 per cent. of the full supply discharge at 8·3 feet depth, this is even better agreement than practical considerations call for or make possible.

9. At the other extreme, consider the 2 feet channel ; the discharge actually varies as the 1·75 power of the depth ; but if the five-thirds power be taken and a co-efficient selected to give the correct result at full supply, then at half that depth and a third of that supply the error is only 5 per cent. ; 5 per cent. of less than one cusec is less than matters in practice.

10. In fact, with larger channels the error keeps below 1 per cent. or so, and where it begins to become a greater percentage it is still of no account in cusecs.

11. The graphs can be used to yield other information of interest, but it is not proposed to pursue such points here. We will proceed to practical application of the fact that, for all practical

purposes the discharge varies as the five-third power of the depth. It will be seen later that finally, a power very slightly different from that has been taken, but this does not affect the argument or explanation.

12. If the beds of the channels with which we deal, were truly horizontal and straight in cross-section, and straight with a uniform gradient longitudinally, and unchanging, it would save some complication in applying any discharge curves. First, the bed is not unchanging, and so a varying correction is needed. Second, the longitudinal section of the bed is in waves ; even if the bed were carefully levelled for some distance and a uniform mean gradient drawn, the gauge-reading on this gradient-line would not necessarily be the correct zero point. Third, the cross-section is also waved, but that does not really matter, as within the practical range of discharges this will make less difference than matters.

13. A common way of arriving at a discharge curve, is to plot all observations taken for some time, and by eye to plot the curve that lies best among them. Easier would be to plot the three-fifths power of discharges against gauges, when the "curve" would become a straight line, saving the need to guess the varying curvature that fitted best. But this would in most cases ignore the fact that successive observations are actually on different curves, depending on the degree of silting and scouring, and the position of bed humps and hollows, at the times of observation.

14. A second method is to calculate Kutter's N from a few observations taken nearly at the same time, and from this and the cross-section, to calculate discharges for a series of gauges. Apart from its laboriousness, the error in this method can be realised by considering two states of the same channel, one with a uniform high bed, and the other with low bed and a considerable silt-hump a little down-stream of the gauge ; in the former case the surface slope will remain constant as depth varies with supply, while in the other the surface slope will grow flatter as gauge reduces, and finally zero discharge will occur not with zero water-depth at the gauge but with water level with the top of the hump : Kutter's N, too, may vary as varying depth makes the side-slopes form a greater or less proportion of the perimeter.

15. A third method is to plot all observations to logarithmic scales and draw the best straight line through them : the error in this is the tacit assumption that the gauge-zero coincides with the zero of depths for the curve required.

16. The best course is to make a group of observations in succession at full supply ; and as soon after as possible to make a group at a low supply, if possible between a third and half of full supply ; plot the three-fifth powers of discharges against depths,

and the required discharge curve is the straight line through them. Or apply the following simple method of calculation :—

17. The basic formula is

$$D = k \times (g - s)^n$$

in which D is the discharge,

g ,, gauge-reading,

s ,, gauge-reading for zero discharge,

k ,, co-efficient,

n ,, exponent.

Of the three unknowns, s, k and n, the exponent n is taken at the value we have selected ; to determine the two others, the two groups of observations mentioned are sufficient : true, a third similar group of observations would enable us to calculate n as well, but this is not worth while.

18. A table is appended of the values of the nth power of numbers over the necessary range : this is a standard discharge table applicable to all channels of the kind dealt with ; to fit it to any channel we need only " s ", the gauge-reading for zero discharge, and " k " the co-efficient. The author keeps in his note-book a table of these two factors for all channels in his charge; this with the slide-rule arrived at in this paper enables him at any moment to give any discharge figures that may be wanted.

EXAMPLE.—The averages of the said groups of observations on a channel give 3,790 cusecs at 9·3 feet gauge and 1,430 cusecs at 5·3 feet. Call the depths, (g—s) in these two cases d_1 and d_2.

$d_1 - d_2$ is also the difference between the gauges = 4·0

d_1/d_2 is the $\frac{1}{n}$th power of the ratio of the discharges.

4790/1430=2·65. From the standard discharge table applied we can find that 2·65 is the nth power of 1·80.

So $1{\cdot}80\, d_2 - d_2 = 4{\cdot}0$, or $d_2 = 5{\cdot}0$.

As the gauge reading for this was 5·3, the value of s is 0·30.

From the table, $5{\cdot}00^n = 14{\cdot}486$ so $k = 1430/14{\cdot}486 = 98{\cdot}6$.

19. It should be, but actually is not, out of place to draw attention to the form of this table, and to contrast it with the tables made and used in most Panjab offices. It is a table, while the latter are merely lists. By making the parting lines at regular intervals heavier than the others, as on squared paper, the eye is helped to find the right point at once ; the steps on the table being tenths, successive differences for use in interpolating hundredths are shown as small figures.

With these values a clerk can draw up the discharge table for a channel from the standard table ; this is not beyond the capacity of departmental clerks, as the author has had several doing it for him. The above calculation of constants, and the making of the table can also be done with the slide-rule, as will be explained below in example 7.

20. As a channel silts or scours, the discharge for a given gauge (or the gauge-reading for a given discharge) varies. To allow for this, it is customary to apply a percentage correction factor to the tabular discharges, to make them agree with the last periodical observation made. This is in effect to vary " k " in the above basic formula. But as a channel silts or scours, it is " s " that varies much more than " k ", because in almost all cases slope and bed-width are hardly affected ; " k " may be changed by berm-trimming, but on the whole much less error is involved in keeping " k " constant (till a new discharge table is called for) and using " s " for the periodical variation. Cases are not unknown of the use of antique discharge tables with correction factors of 30 per cent. or even 50 per cent. ; the sort of person who is capable of committing such absurdities by the unthinking application of routine methods cannot go as badly wrong under the system described. The author's practice has been to have the discharge tables with his revenue clerks calculated for s=0, and clerks have found the system of gauge corrections simpler to apply than the older system of correction factors : of course one should avoid gauge-corrections to two places of decimals on channels on which it is not necessary to read the gauge finer than tenths of feet.

21. Incidentally, the record of successive values of " s " yielded by periodical discharge observations, serves as a record of the varying depth of silt in the channel.

22. Another possible development to which this leads ; where the referring gauge of a channel is above a work such that the discharge-curve does not change, the author has the gauge graduated to read cusecs direct ; similar gauges can be made for ordinary channels, arranged to be fixed with their zero points at the reading " s " on the ordinary gauge, and secured from unauthorised interference.

23. For small variations, it is already accepted as sufficiently correct to consider that velocity (and therefore discharge) of a channel varies as the square root of the gradient, and inversely as Kutter's N. Above, we have found that discharge can be taken as varying with a power of depth ; if only the variation of discharge with bed-width can also be reduced to exponential form without too much loss of accuracy, it will be most useful. That has been done, but it is not proposed to add to the length of the theoretical part of this paper by describing it. One point only.

When $n = 5/3$, $4^n = 10{\cdot}079$; a very slight change is sufficient to make $4^n = 10$ exactly, and this rounding off has useful properties; it is justified by theoretical considerations it is not proposed to describe here. The result can be tested by comparison with discharges calculated or taken from Kennedy's Diagrams.

24. Reference was made before to a discharge diagram in metric units that was furnished to Mesopotamia. It can now be realised that with the exponential formula, the diagram for any slope and value of N, plotted to logarithmic scales, is of straight lines without any curves. By calculating the discharges and fixing the points for three channels with widths and depths $w_1 \times d_1$, $w_1 \times d_2$, and $w_2 \times d_1$, we fix both the relative inclination and spacing of the lines for equal depths, widths, and discharges. Discharges for any depth and bed-width (for the slope and value of N used) are read as in Kennedy's and other similar diagrams: for any other pair of values of slope and N, the distance from the intersection of bed-width and depth to the line for discharge is the same on any part of the diagram; a scale of slope and N is provided to give the said distance; instead therefore of a number of separate diagrams, this one diagram suffices for all values of slope and of N. It is not considered worth while to print this Mesopotamian diagram in these proceedings, but it will be shown at the Congress meeting.

25. The exponential formula also lends itself to construction of a nomogram: but anyone who has specialised in methods of graphic calculation will realise that the most generally useful device in this case is a slide-rule: this has been made, and is illustrated in Plate II. At the Congress meeting it is hoped to have a number of rules ready, to lend for testing to those with the best opportunities and most likely to be able to suggest improvements.

26. The scales of an ordinary slide-rule are marked with 1 at the left end, rising numbers to the right till we come to 9, and then the right end again 1: that is to say the scale gives significant figures only, leaving the user to place the decimal point correctly. That does not apply on this discharge slide-rule. The scales should be used only with the values marked on them, except in the manner shown in the examples, or where the user knows that this does not involve error, or has tested whether the change makes any difference.

27. The front of the rule has, above, a scale of bed-widths with one of depths sliding against it; below, a scale of discharges with one of fall per thousand sliding against it; (the primary scale of fall is the right hand one of the pair actually marked). These are the four calculating scales; two more scales along the middle of the slide, for guidance only, will be explained later. These scales

are graduated and placed so as to give results practically agreeing with Kennedy's Diagrams, for trapezoidal channels of $\frac{1}{2}$: 1 side-slopes with Kutter's N=0·0225. Those who do not understand slide-rules will most simply see how they give these results, from the examples given later. When the left-hand scale of fall is used, the values on the discharge scale require multiplying by 10. Using the right-hand scale of fall, the slide-rule is directly usable from 10 to 400 cusecs ; using the left-hand scale of fall it is directly usable up to 100 feet bed-width : this range probably covers about 95 per cent. of the work to be done. For small discharges, example 6 shows how to apply the fact that four times the depth means ten times the discharge ; this rule might also be of use for extraordinarily deep big channels. For big channels, example 5 shows how to apply the rule that ten times the bed-width means eleven times the discharge ; this rule might also be of use for extraordinarily narrow small channels.

28. For designing channels to dimensions as close as possible to those that nature in the Panjab is likely to accept at the balance between silting and scouring, the most suitable guidance is at present found in two rules.

29. It is well-known that Kennedy for certain conditions found the empiric formula connecting depth and Vo (the " critical velocity " at which the bed will neither silt or scour).

$$V_o = 0{\cdot}84 \times d^{0{\cdot}64}.$$

His suggested and the accepted way of allowing for other conditions is to specify a Critical Velocity Ratio, V/Vo. (For this ratio a symbol is very necessary, and in this paper it will be denoted R_v).

30. The above rule does not touch widths. Kennedy also gave a very rough guide to widths, in the form of proportion of width to depth suggested at various discharges. In a note dated July 1917 Woods filled this in, in greater detail ; his dimensions were based on observation of channels in the Jhang Division of the Lower Chenab Canal, mostly of less than 300 cusecs discharge, but including a few up to 1,200 cusecs ; above that limit the " tabular data are based partly on records of natural channels of the Western Jumna Canal " (that is up to about 4,000 cusecs,) " and partly on conjecture." The present writer tried to improve on this set of figures, not conforming to any formula or suggested law. In a paper (" Regime Channels," Panjab Engineering Congress, 1919) he deduced from averages of a vast body of data an empiric formula connecting velocities with widths as well as depths : when he managed to collect data of bigger channels, they were all appreciably wider than the figures given by his formula, showing that its form is incorrect. No constructive suggestions having been brought forward, Woods' table is still the best guidance.

31. This table is given in the printed departmental pamphlet of 1920, "Normal data of design for Kennedy Channels." That pamphlet also reproduces Plate 10 of Kennedy's Diagrams, giving the slope width and depth of channels to flow at velocities of V_o: on that diagram Kennedy has plotted a fair curve through Woods' dimensions. It will be more useful if an empiric formula of approximately correct form can be fitted to this table of data; this will further make it possible to suggest a rule for conditions that are not suited by Woods' normal sections. This is a constructive suggestion that can be tested in practice and may lead to advances. It is worked out here because it adds to the utility of the slide-rule, which also gives an easy means of testing it.

32. Inspection of the said curve shows that it is of what may be described as parabolic form, but flattens out so as to keep below a limiting depth. Part of the conjecture on which it is based is Kennedy's suggestion that if the velocity in a channel exceeds 3·5 it will erode the berms; such erosion, by increasing the width, decreases the depth and the velocity, till the velocity comes down to his suggested limit of 3·5. As V_o is insisted upon, and 3·5 is the critical velocity for 9·3 depth, that depth should be the said upper limiting depth.

33. Kennedy's curve for Woods' normal proportions is very nearly fitted by the formula

$$d_n = 9{\cdot}3 \times \left(\frac{W}{22 \times w}\right)$$

writing d_n for the normal depth for a given width. It is not likely that anyone will assert that the 8·16 depth for 150 feet width and the 3·59 depth for 15 feet width given by the curve are more correct than the 8·10 and 3·77 depths given by the formula, these being the greatest divergences: in fact the exactness of the data does not call for trying to fit them more exactly by a more complicated formula. Plotting shows that the value 9·3 is as good as any; and the value 22 is that deduced by plotting, to give the best agreement.

34. To suit conditions where d_n does not obtain (just as V_o does not obtain everywhere) it is suggested that depths can be specified by their relation to d_n: thus a set of channels may have normal depths which are all $0{\cdot}9 \times d_n$.

35. There is the further possibility that the limiting depth for any such set of normal depths, lying on a curve similar to that described, may also be fixed by the limiting velocity that has been taken as 3·5 and the critical velocity ratio. The value $R_v = 1{\cdot}0$ gave the limiting depth 9·3; more generally, normal depth $= 9{\cdot}3/R_v^{1{\cdot}61}$

$$\text{or } R_d = d/d_n = 1/R_v^{1{\cdot}61}$$

These possibilities are all covered by the slide-rule, and it is hoped

that designing to correct widths will now be reduced to law and order, at least to a degree equal to that of designing to correct velocities.

36. Along the middle of the slide is an upper scale of normal widths, placed with regard to the scale of depths just over it so that widths lie under the correct values of d_n. Under this again is a scale of normal discharges, such that these are what are carried by channels of normal proportions flowing with velocity V_o. The use of these, too, is most simply explained by means of examples.

37. The back of the rule is for calculating critical velocity ratios ; here too the step of first calculating velocities is eliminated, and the calculation is made directly from discharge width and depth. It is very like the front, with the following differences. The scale of widths above is not of bed-widths for $\frac{1}{2}:1$ channels, but of mean widths ; this side of the rule can therefore be used for any trapezoidal channel with one step of mental calculation, which is unavoidable. For $\frac{1}{2}:1$ channels, in designing with bed-widths, the reading on this scale is bed-width plus half depth ; in dealing with observations of water-surface width, the reading on this scale is that width minus half the depth. No guiding scales are needed on this side. In place of the scale of fall on the front, there is a scale of Critical Velocity Ratio. The scales of depth and discharge are as on the front. Example 12 is sufficient to show the use of these four scales together, whichever of the four quantities is the unknown. On the scales of width, R_v, and discharge on this side, the decimal point *can* be shifted.

38. The plate shows at the right-hand side below, scales of N and fall, whose use is exemplified in Example 10 : in the rule actually being made, the scale of R_v and N has been made continuous ; this makes it possible to do any ordinary multiplication and division by using this scale and the discharge scale as an ordinary slide-rule ; this scale can also be used with the scale of fall as an ordinary slide-rule for squares and square roots ; the scale of fall is so placed that if repeated once to the left its end would come at the marked graduation of the discharge scale.

39. When, if ever, this slide-rule is made up more elaborately, with a cursor such as would be useful when using the guiding scales on the front, the middle of the slide on the back will probably be used for scales by which to calculate with the 1·5 and 2·5 powers of depths, for weirs, rectangular, triangular and trapezoidal notches.

40. The examples that follow are fairly complete but not exhaustive ; they attempt to cater for the man who has at least a notion of the subject ; those who know more will find more uses of the rule possible ; those who know less are left to find elementary structinion in the proper place.

41. Before formulating an opinion that the working shown by some of the examples is complicated, it should be considered what the slide-rule is primarily meant and made to do, and what it merely can also do if necessary : the rule can be made to do what is wanted, if only that is specified. For example, if the slide-rule were wanted as it stands but modified only for another set of conditions on the lines suggested in paragraphs 34 and 35 above, no more is involved than printing with the guiding scales moved by the correct amounts.

42. The author made himself a paper slide-rule more or less on these lines, six years ago : trade has suffered so from slumps and booms, that he could not find a manufacturer ready to take it up and make it properly, and there the matter rested. He has now to express his obligation to L. Ishar Dass who showed that local resources were capable of producing the rule in a form in which it would be useful. Though in a technical paper, advertisement is out of place, it is considered justifiable to mention that Sheikh Ghulam Mohi-ud-Din, Managing Proprietor of the Imperial Photo-engraving Company of Lahore, has prepared the plate and printed the rules which will be produced at the Congress meeting.

Examples.

NOTE.—Unless otherwise specified, "width" is the bed-width of a trapezoidal channel with ½ : 1 side-slopes : and Kutter's N=0·0225 unless otherwise specified or of no account.

1. What is the discharge of a channel 20 feet wide, 4 feet deep, and graded 0·4 per thousand ?

Move the slide so as to bring that depth against that width on the upper scales ; on the lower scales, against that fall, read the discharge 230 cusecs.

Note that with the slide in this position, on the upper scales 3 feet depth comes against 32 feet width, 5 feet depth against 14 ft. width, and so on ; any such pair of dimensions gives a channel which, with the above fall discharges the same 230 cusecs.

Note also that with the slide still in the same position, 0·3 fall comes against 200 cusecs, and so on ; this gives the discharge for any fall, of any of the above channels.

2. Design a channel to carry 200 cusecs with fall 0·4 per thousand.

On the lower scales set that fall against the discharge ; on the upper scales read off, for example 3·4 × 23, or 3·9×18½, or 4·4×15¼.

In the absence of any further specification, any of these pairs of values will do.

3. A channel has been made 15 feet wide and fall 0·4 per thousand ; calculate its discharge table.

Reverse the slide ; that is remove and reinsert it still with the front in front, but with the depth scale as the lower edge. Now on the upper edge set that fall against that width, and on the lower edge read :—

Depth	..	1·0	1·5	2·0	2·5	3·0	3·5	4·0	4·5
Discharge	..	17	33	54	77	105	135	170	205

4. Medium, big discharge. Design a channel for 1,000 cusecs with fall 0·2 per thousand.

Set that fall on the left-hand scale against 100 discharge, and on the upper scales read 5·0×78.

5. Big discharges. What is the discharge of a channel 250×8·0 feet, graded 0·3 per thousand.

On the upper scales set 8·0 against 25 feet width ; on the lower scales, using the left-hand scale of fall, against 0·4 read 80. On account of the use of the left scale of fall this must be multiplied by ten ; as the width is ten times the scale-width taken, this must again be multiplied by 11. Answer, 8800. It is of course quite simple

to multiply by 11 ; *if in finding dimensions of a channel for a big discharge we want to divide by* 11, *this can be done by using the scales made for* R_v *and discharge on the back ; move the slide to bring discharge on it over* 1·1 *on the bottom scale, and read the scale discharge to be taken, over* 1·0 *on the lower scale.*

6. Small discharges. Design a channel to carry 6 cusecs with fall 0·4 per thousand.

Set that fall on the right-hand scale against 60 *cusecs ; above, read off* $4{\cdot}0\times5\frac{1}{2}$; *answer* $1{\cdot}0\times5\frac{1}{2}$ *since four times the depth means ten times the discharge.*

7. Discharge curve from observations. Reliable observation on a channel gives 3,790 cusecs at 9·3 gauge and 1,430 cusecs at 5·3 gauge. Frame the discharge table.

Using the scales for discharge and R_v *on the back as an ordinary slide-rule, set* 3790 *on the* R_v *scale against* 1430 *on the discharge scale ; at either end of the discharge scale read* 2·65 *which is the required ratio. Turn to the front, reverse the slide, set* 1·0 *depth against* 10 *discharge ; against* 26·5 *on the discharge scale read* 1·80 *on the depth scale, meaning that* $1{\cdot}80^n=2{\cdot}65$.

$$d_1 - d_2 = 9{\cdot}3 - 5{\cdot}3 = 4{\cdot}0, \qquad \text{and } d_1 = 1{\cdot}80 \times d_2$$
$$\text{so } 0{\cdot}80 \times d_2 = 4{\cdot}0, \qquad d_2 = 5{\cdot}0$$
$$\text{and} \quad s = 5{\cdot}3 - 5{\cdot}0 = 0{\cdot}3.$$

With the slide still reversed, on the front set this 5·0 *depth against the* 1430 *discharge ; this discharge being outside the range of the scale, we may consider the values marked on it all multiplied by* 10, *both for setting and reading ; the slide is now in position for reading off the discharge table, taking for each gauge a depth* 0·3 *less. Note that* k *is the discharge for* 1 *foot depth, and the discharge for* 4 *feet depth is* $10\times k$. *In any case in which the slide is not in such a position to give all the discharges wanted, it may be moved as if shifting the decimal place in the discharge scale ; that is, bring* 4 *feet depth to where* 1 *foot was, or vice versa. The following shows how much difference is made on this fairly large channel, by a slight error in finding* s.

Gauge	1·0	3·0	5·0	6·0	7·0	8·0	9·0
s=0·3	98·6	513	1300	1775	2320	2922	3580
s=0·25	97·6	523	1308	1784	2327	2925	3580

Note.—Discharges for 1·0 *depth instead of gauge are entered above ; this is the same as* k.

8. Design a channel to carry 500 cusecs with Vo and d_n.

By the guiding scales, the channel for this discharge should be $32\times5{\cdot}6$. *Setting these together above, below against* 50 *discharge read* 0·22 *per thousand fall on the left.*

Note.—It can be seen by trial, that to specify a wrong fall entails sacrificing either normal depth or Vo ; this means that if the scale of normal depth wanted and the R_v wanted are really known, the fall is the last thing that should be specified.

9. Design for the same conditions as the last, but with $1{\cdot}2 \times V_o$.

$500 \div 1{\cdot}2 = 418$. *A channel* $29\frac{1}{2} \times 5{\cdot}3$ *is of correct normal proportions to discharge* 418 *cusecs with Vo ; if* 500 *cusecs be put through it, it will still be of normal proportions, and* R_v *will have been put up to* 1·2. *Set that depth against that width, and read that a fall of* 0·34 *per thousand, is needed to put the discharge up to* 500 *cusecs.*

10. Design for the conditions of example (8), but with Kutter's N=0·025.

The solution will be the same as before, except that the slope must be increased to make up for the increase of N. On the back, move the slide to bring 225 *against fall* 0·22, *and under* 250 *read the corrected fall* 0·27 *per thousand.*

11. Design a channel to carry 500 cusecs with fall 0·25 per thousand, and normal proportions.

Set fall to discharge as before ; compare the readings that come under each other on the two scales of bed-width, till you find the point where they are equal ; there read off $31 \times 5{\cdot}4$. *As with Vo that channel would discharge* 450, *with* 500 *cusecs* R_v *will be* $500 \div 450 = 1{\cdot}11$.

12. What is the critical velocity ratio in a channel of 64 feet surface width and 5 feet depth, discharging 700 ?

$64 - 5{\cdot}0 \div 2 = 61\frac{1}{2}$ *mean width ; set these above on the back, and below against* 7 *on the discharge scale read* $R_v = 0{\cdot}8$. *The scales, except that for depth, can be used with the decimal point shifted.*

13. Design a channel for a given discharge, with a given fall and given R_v.

This is the form of problem that this slide rule is probably worst at, but also the form that is probably most incorrect to specify. On the front set fall to discharge ; on the back set R_v *to discharge ; allowing for the difference between bed-width and mean width, find the channel that is given by both sides.*

14. Design a channel for 100 cusecs, for V_o and for depth $0{\cdot}8 \times d_n$.

Reverse the slide ; set depth 8·0 *against* 100 *discharge and against* 10·0 *depth read* 143 *discharge. This means that the normal channel for* 143 *cusecs will at* 0·8 *of its full supply depth discharge* 100. *So find the normal channel for* 143 *cusecs, and run it at only* 0·8 *depth.*

This is not perfectly accurate, but the difference is only that between the 1·661 *and the* 1·64 *power of* 0·8, *plus the small error of the rule, which is not enough to matter.*

15. Design a channel for 100 cusecs with 0·8 of V_o, and normal depth for that value, as suggested in the paper, (paragraph 35).

A channel discharging 100 *cusecs with* $0{\cdot}8 \times Vo$ *would with full* Vo *discharge* 125 *cusecs.*

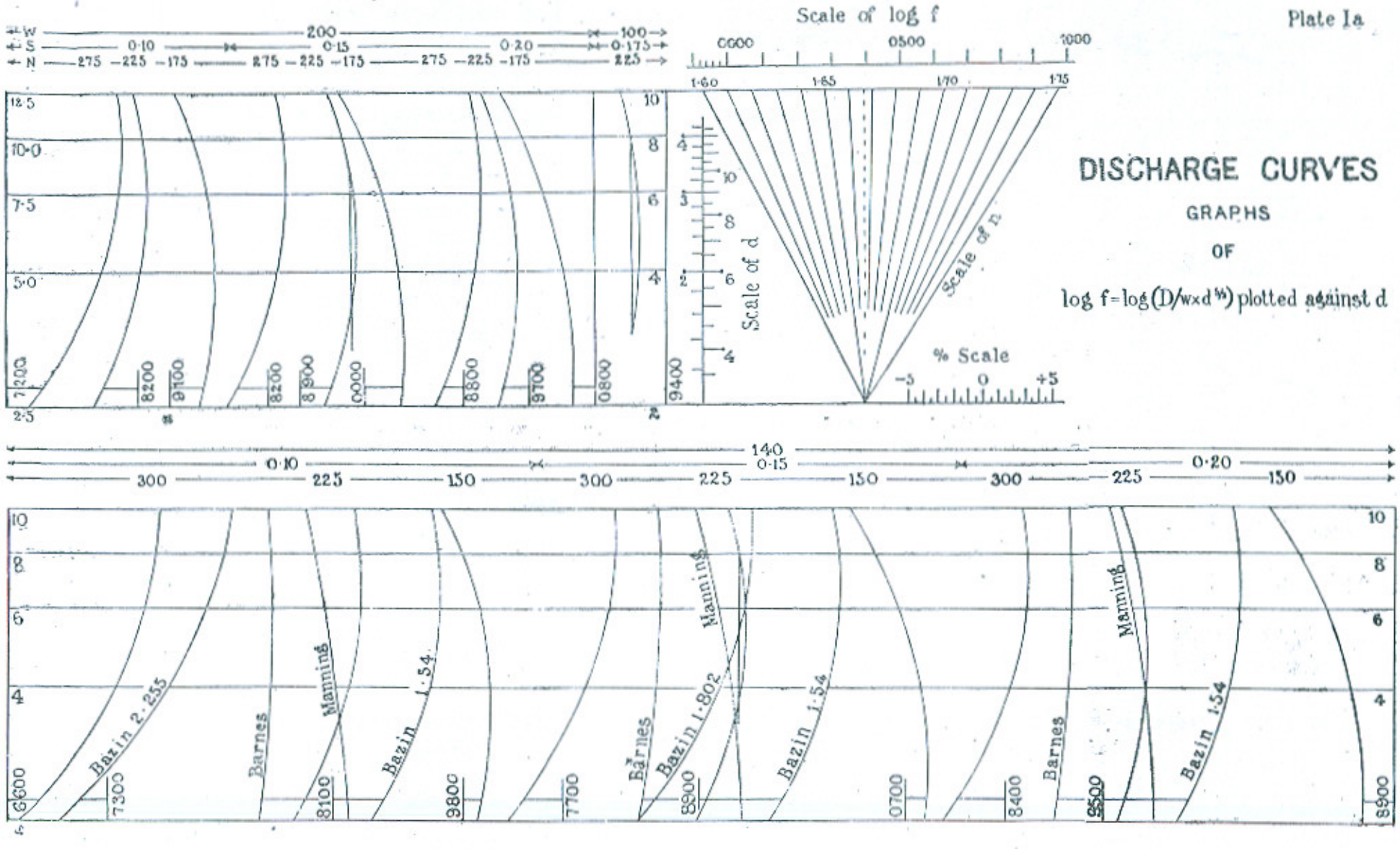
The ratio R_d *for* $0{\cdot}8 \times Vo$ *can be got accurately enough for all practical purposes by using the depth scale on the front against the width scale.*

Set depth 10 (*that is because here* R_v *is less than unity ; if it were greater than unity, the* 1 *mark should be used instead of the* 10 *mark*) *against width* 10 *; against depth* 8 *read width* 14·2 *; this means that for* $R_v = 0{\cdot}8$, *normal depths are* $1{\cdot}42 \times d_n$. *Reverse the slide ; set depth* 1·42 *against discharge* 125, *and against depth* 1·0 *read discharge* 70. *This means that a channel which with* Vo *and* d_n *discharges* 70 *cusecs, when raised to the required* $1{\cdot}42 \times d_n$ *will discharge* 125, *and when the velocity is reduced to* Vo *the discharge will be the required* 100. *So, find the normal channel for* 70 *cusecs, and run it at* 1·42 *times the normal depth.*

STANDARD DISCHARGE TABLE.

	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9
0	*022*	*047*	*066*	*083*	*098*	*112*	*125*	*137*	*150*	*160*
	0·000	0·022	0·069	0·135	0·218	0·316	0·428	0·553	0·690	0·840
1	*171*	*183*	*192*	*203*	*212*	*222*	*231*	*241*	*249*	*258*
	1·000	1·171	1·354	1 546	1·749	1·961	2·183	2·414	2·655	2·904
2	*267*	*276*	*284*	*292*	*300*	*309*	*316*	*324*	*332*	*339*
	3·162	3·429	3·705	3·989	4·281	4·581	4·890	5·206	5·530	5·862
3	*348*	*354*	*362*	*369*	*377*	*385*	*392*	*398*	*404*	*410*
	6·201	6·549	6·903	7·265	7·634	8·011	8·396	8·788	9·186	9·590
4	*415*	*424*	*432*	*442*	*448*	*454*	*459*	*466*	*471*	*476*
	10·000	10·415	10·839	11·271	11·713	12·161	12·615	13·174	13·539	14·010
5	*482*	*489*	*497*	*506*	*512*	*515*	*522*	*528*	*531*	*540*
	14·486	14·968	15·457	15·954	16·459	16·971	17·486	18·008	18·536	19·070
6	*545*	*552*	*558*	*564*	*570*	*576*	*581*	*587*	*593*	*599*
	19·610	20·155	20·707	21·265	21·829	22·399	22·975	23·556	24·141	24·734
7	*604*	*609*	*615*	*621*	*626*	*631*	*637*	*643*	*649*	*655*
	25·333	25·937	26·546	27·161	27·782	28·408	29·039	29·676	30·319	30·968
8	*660*	*665*	*670*	*675*	*681*	*686*	*691*	*696*	*702*	*707*
	31·623	32·283	32·948	33·618	34·293	34·974	35·660	36·351	37·047	37·749
9	*713*	*717*	*722*	*728*	*733*	*738*	*743*	*748*	*753*	*759*
	38·456	39·169	39·886	40·608	41·336	42·069	42·807	43·550	44·298	45·051
0	*765*	*769*	*774*	*778*	*782*	*788*	*793*	*798*	*803*	*809*
	45·810	46·575	47·344	48·118	48·896	49·678	50·466	51·259	52·057	52·86
1	*813*	*817*	*822*	*827*	*832*	*836*	*841*	*847*	*852*	*857*
	53·669	54·482	55·299	56·121	56·948	57·780	58·616	59·457	60·304	61·156
2	*862*	*866*	*870*	*875*	*879*	*883*	*888*	*893*	*898*	*903*
	62 013	62·875	63·741	64·611	65·486	66·365	67·248	68·136	69·029	69·927
3	*908*	*913*	*917*	*921*	*925*	*930*	*934*	*939*	*944*	*948*
	70·830	71·738	72·651	73·568	74·489	75·414	76·344	77·278	78·217	79·161

Plate Ia



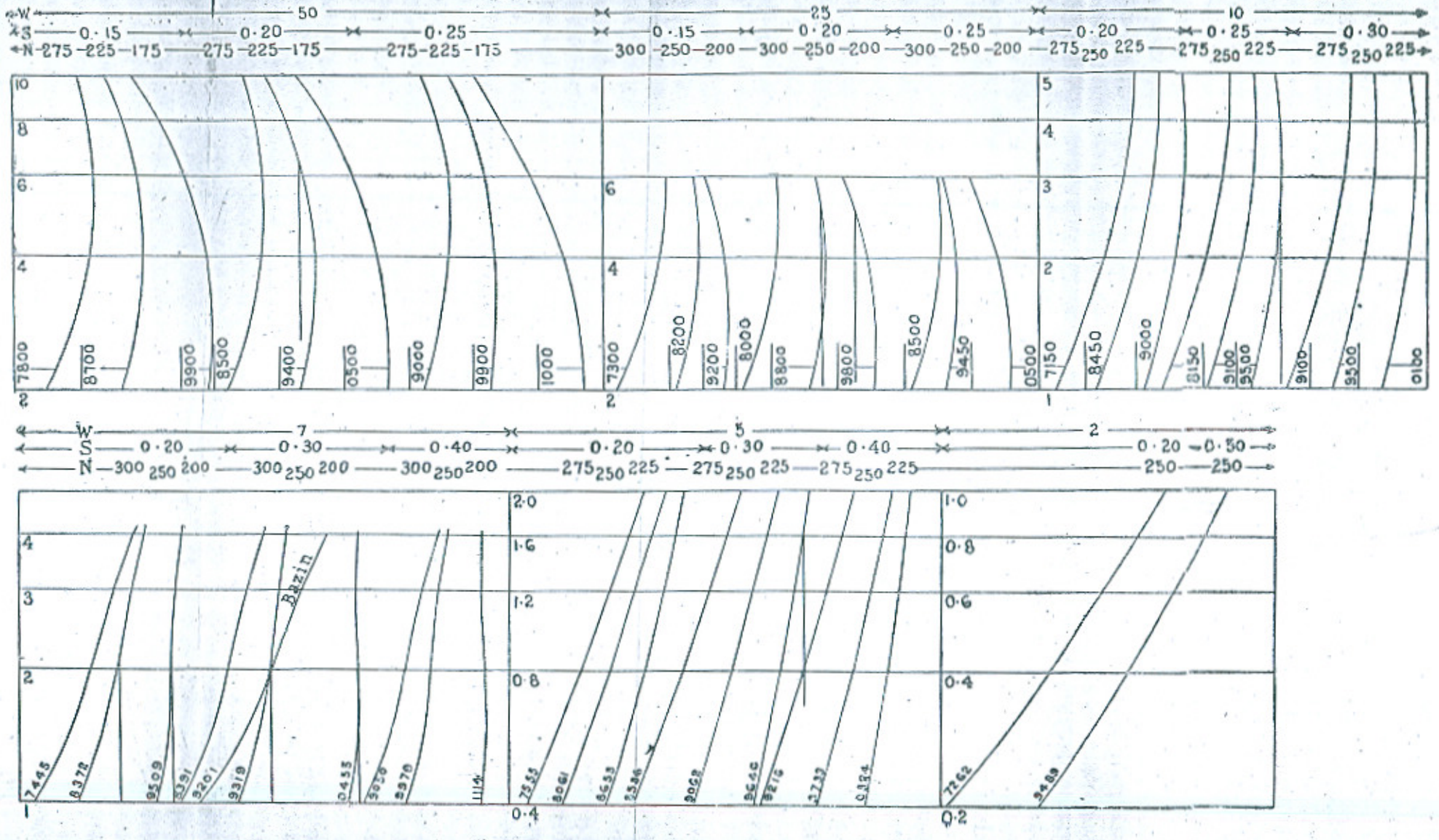
DISCHARGE CURVES

GRAPHS

OF

$\log f = \log (D/w \times d^{3/2})$ plotted against d

Plate Ib


W 50 25 10
S 0·15 0·20 0·25 0·15 0·20 0·25 0·20 0·25 0·30
N 275 225 175 275 225 175 275 225 175 300 250 200 300 250 200 300 250 200 275 250 225 275 250 225 275 250 225
10 8 6 4 2
7800 8700 9900 8500 9400 0500 9000 9900 1000
7300 8200 9200 8000 8800 9800 8500 9450 0500
5 4 3 2 1
7150 8450 9000 8150 9100 9500 9100 9500 0100
W 7 5 2
S 0·20 0·30 0·40 0·20 0·30 0·40 0·20 0·30
N 300 250 200 300 250 200 300 250 200 275 250 225 275 250 225 275 250 225 250 250
4 3 2
Bazin
7445 8378 9509 9391 9201 9319 0455 9078 8970 1114
2·0 1·6 1·2 0·8 0·4
7555 8061 8633 8536 8068 8640 8276 7732 0134
1·0 0·8 0·6 0·4 0·2
7262 8489
1 0·4

DISCUSSION.

The AUTHOR introduced his paper and passed round a number of slide rules which were tested by some of the members present.

MR. H. W. NICHOLSON said that the Author (page 74, paragraph 3) related that he supplied a number of diagrams to Mesopotamia in 1918. The engineers in Mesopotamia apparently never received these diagrams ; possibly they might have been torpedoed on the way. He thought the slide rule a dangerous thing as certain people might be tempted to look to it as an " automatic chief engineer."

He asked that the following problem should be solved by the author by means of the slide rule.

" What was the size of a channel of capacity 6,109 cusecs ; slope 1 in 9,090, Vo—·82."

The AUTHOR in reply said that it was of the kind of example 13, which he had described as probably the most incorrect to specify and which the slide rule was least made to solve.

At short notice he gave the dimensions as between 530 feet by 5 feet deep and 620 feet by 4·5 feet deep.

Note.—The Author afterwards found that he had, in error, reversed one of the factors and that the actual design given by Mr. Nicholson was correct.

MR. H. W. NICHOLSON said the actual designed size of this channel was 140 feet by 12·2 feet.

R. B. PRABH SINGH said that in the paper the Author calculated the value of " s," and asked why it was necessary to calculate " s " when it could be obtained by direct observations.

He considered the methods of calculating the discharges proposed by the Author had the advantage of simplicity but they were certainly just as liable to abuse as the existing methods in use in the Irrigation Department.

Paragraphs 13, 14 and 15 of the paper described three methods of obtaining discharges but there was no mention of the usual method employed, *viz.*, by using the Kennedy diagrams.

MR. W. P. THOMPSON said that in his practice he had never felt the need to alter discharge tables frequently, but of course when large variations occurred such as occasionally took place in small channels before and after silt clearance, where silt clearances were still needed, it became necessary to prepare fresh discharge tables to suit the altered conditions. The occasions for using large correction factors were few and far between, as a general rule, and were not to be taken as evidence of the usual standard of work in the Irrigation Department as might be supposed from the remarks in paragraph 20.

MR. W. C. CHOPRA pointed out that it was not necessary to trouble about bed-width and slope, etc. in framing a discharge table from an observed discharge. Every vertical line on Kennedy's Discharge Diagrams represented a discharge table, if one point on it coincided with the observed discharge and the depth at which it was observed. This use of Kennedy's Diagrams was discovered by him when Mr. Paddy first circulated in the Department the formula $D=kd^{\frac{5}{3}}$. On receipt of this he (Mr. Chopra) at first doubted that discharge depended on depth alone, as this would mean that "if any two channels (whatever their bed-widths, surface slopes and roughness, etc.) happened to have the same discharge at a given depth, they would have equal discharges at equal depths," and this seemed half paradoxical. It was, however, tested by him on Kennedy's diagrams (which took all the above factors into consideration) and found to be quite correct. It occurred to him then that a vertical line on Kennedy's Diagrams represented a correct discharge table, if one point on it indicated observed discharge and depth. This method of framing discharge tables for distributaries was often employed by him with success. All that was required was to observe a careful discharge, and on *any sheet* of Kennedy's diagrams to find out the point of intersection of the curve for *observed discharge* with *the line of depth at which the discharge was observed*, and the vertical line through that point was the discharge table required. In the formula $D=kd^{\frac{5}{3}}$, the coefficient K absorbed all the elements except depth.

MR. F. C. GLASS referring to the remarks in the last sentences of paragraph 3 said the engineers employed in the Irrigation Department in Mesopotamia during the War were an excellent body drawn from almost all parts of the globe. His experience was, that they had to rely on their own calculations for discharges. Sometimes they used Buckley's tables and Garrett's Curves.

It was not possible to use Kennedy's diagrams owing to the fact that slopes were as flat as 1 in 25,000. Generally the value of Kutter's N was taken at ·027 to ·03 and the critical velocity about 0·6 of Kennedy's Vo.

Although the metric system was officially in use, it was only actually adopted to a very small extent. The military authorities did not like it ; the general procedure was to shew all measurements on drawings in both British and Metric units.

He thought the Author should withdraw the last sentence of paragraph 3 relating to the Mesopotamian engineers, if he wished the engineers of the world to adopt the slide rule.

The AUTHOR, replying to the discussion said that the diagrams sent to Mesopotamia were not torpedoed, as the Chief Engineer there and one or two other engineers of the author's acquaintance acknowledged their great usefulness.

Direct observation of "s" was not satisfactory : S. Prabh Singh probably had in mind the common practice of assuming that the depth of silt was given by the difference between gauge-reading and average of soundings taken during a discharge ; the discharge site might be on a hump or in a hollow.

He had not described the way of taking discharges from Kennedy's Diagrams, as this was so well known as not to need description.

He had recently had to deal officially with one of Mr. Thompson's discharge tables ; the Author in his work aimed at and was securing a considerably higher degree of accuracy in distribution.

Mr. Chopra was correct in pointing out that to take a discharge table from Kennedy's Diagrams, it was only necessary to find a place at which the required discharge ran with the required depth ; bed-width and slope and rugosity did not matter for this purpose.

In reply to Mr. Glass, he regretted if he had been unjust in his remarks, but he could only go on the information that reached him. It was to simplify the laborious calculation they had to make that he supplied the diagram referred to and the figures quoted by Mr. Glass would have been very helpful in its preparation.