REGIME CHANNELS.

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Introduction—Existing formulæ—Need for retesting—Variations—Fresh data—Average dimensions—Velocity and depth—Velocity and width—Comparisons—Diagram for designing—Summary—Appendices—Diagrams.

Introduction.

When an artificial channel is used to convey silty water, both bed and banks scour or fill, changing depth, gradient, and width, until a state of balance is attained at which the channel is said to be in regime. These regime dimensions depend on discharge, quantity and nature of bed and of berm-silt, and rugosity of the silted section; rugosity is also affected by velocity, which determines the size of wavelets into which the silted bed is thrown. Many of those responsible for such channels must have arrived at rules for their essential regime dimensions, but only Kennedy's work has become well known. Lack of exact knowledge, therefore, still leads in design to provision of dimensions too great in some directions, and in maintenance to a waste of labour and money on enlarging channels to unstable dimensions.

Existing Formulae.

The one step towards exact knowledge was the framing in 1895 of Kennedy's silt theory;* in 1904 he gave a rough rule † for the relation of widths to depths, and in 1907 further developed his silt theory.‡ In 1917 Mr. Woods published a list of dimensions of channels. §

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* "The prevention of silting in irrigation canals" by R. G. Kennedy, Indian P. W. D., Paper 2826 of 1894-5 of the Institution of Civil Engineers.

† "Instructions for grading and designing irrigation channels." Note by R. G. Kennedy, Chief Engineer, printed in Panjab Irrigation Paper No. 10.

‡ Introduction to "Hydraulic Diagrams" by R. G. Kennedy.

§ "Normal data of design for Kennedy channels." Note, dated 28th July 1917, by F. W. Woods, Chief Engineer, Irrigation Works, Panjab.

From his observations on channels of the Upper Bari Doab Canal Kennedy showed that the velocity of a channel in regime is independent of all factors but the depth, and that on that system the 'critical,' non-silting, and non-scouring velocity is

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

He stated, and proved algebraically (but the proof contains a fallacy), that the degree of silt-charge is the same on all channels of any one system, and suggested that his coefficient and exponent will not vary much on different systems, though greater silt charges will entail higher coefficients, and a greater proportion of rolling silt demand a slight reduction of his exponent

Writing in 1907, he abandoned his contention of equal distribution of silt charges, saying that passing excess silt into some offtakes would make as little even as $0{\cdot}8 \times V_o$ sufficient towards the tails of long distributaries. He laid down that "all main lines and branches should be given full V_o," but as any velocity over 3·5 feet a second might result in bank erosion, "any depth over 9 or 9½ feet should be avoided."

For his rule of widths Kennedy gives no data. Mr. Woods too gives no actual data, but states that his dimensions are based on measurements, mostly of channels of less than 1,200 cusecs discharge, on the Jhang Branch of the Lower Chenab Canal; he makes nine feet a limiting depth, and already at five feet his curve begins to diverge from the more or less regular law given by his observations, becoming asymptotic to his limiting depth; slopes are throughout taken so as to give velocities about V_o, but instead of varying gradually, are confined to the v[illegible] which Kennedy has made plates in his Hydraulic [illegible]

Need for Retesting

The writer found very few small cha[illegible] great as Mr. Woods specifies, while so[illegible] considerably exceed his limit. He also notice[illegible] rules were transgressed in design and in nature, [illegible] to his Hydraulic Diagrams, actual large channe[illegible] most small channels scour.

the aut[illegible] there mi[illegible] otherwis[illegible] so that th[illegible] trolling se[illegible] section, b[illegible] the se[illegible]

Kennedy's theory was based on twenty-two [illegible]tions of regime conditions; but there is no certainty that the regime standards were equal, and he has abandoned his contention that this is necessarily the case: it is suggested that channels carrying an average silt charge were still giving trouble and had not attained regime, so that the selection of stable channels showed

unconscious bias in favour of regimes of low silt charges. The writer has found great local and general variation of dimensions even on the same channel, and it is not certain to what extent Kennedy succeeded in choosing sites that represented fair averages on the channels he selected.

It therefore appears necessary to retest Kennedy's theory for depths, and to fix the law of variation of widths, and this the writer proposes to do with the data to which he has access; he proposes to do this by entirely empiric methods, so as to avoid bias in the choice or interpretation of data, as the factors are too various, and partly unknown, for the rational method to be successful.

At the same time the writer sets himself the object of providing as simple a means as possible of arriving at design dimensions for a case, the ruling factors of which are known; or conversely, of deducing the factors from a set of actual dimensions: hydraulic mean radii, velocities, and other steps in calculation are to be eliminated from the final result that is sought.

Variations.

In examining data of different points of a canal system that has run long enough to attain regime, great variations are observable; these are due sometimes to regime having been disturbed, sometimes to regime at different points being naturally different. The main causes of these variations are—

(1) Silt-clearance, berm-cutting (as distinguished from mere trimming of irregularities), the use of bushing, and the working of silting tanks.

(2) Use of regulators in heading up more or less at different times.

(3) Running of feeder channels with varying discharges: (distributaries are generally either run full or closed down).

(4) Breaches, which scour out the bed locally.

(5) Differences between the silt-drawing power of offtakes, not at present measurable, but causing an uncertain modification of regime in the parent channel and setting an uncertain regime in the distributary.

(6) The apparent tendency of silt to move in waves, so that a channel contains a succession of scouring and settling reaches.

(7) Variation of silt-charge at different seasons in main canals, diminishing towards the lower ends of the system of channels.

(8) Effect of different rugosities in allowing regime velocities to be attained with lesser or greater gradients.

Fresh Data.

The degrees of variation obtaining make it necessary to examine a considerable mass of data to ensure truth and consistence in the averages; the writer has used hydraulic surveys made from 1915 to 1917 of the Lower Chenab Canal, a system of some 2,700 miles of channels dealing with some 11,000 cusecs. An important and regrettable omission is that the Main Line survey could not be used as it did not give widths; surveys of the Lower Jhang Branch, the upper reach of the Rakh Branch, and of the distributaries branching from this reach were not available; the data of Main Line distributaries were not used because they varied so greatly that even their averages would have been capricious; these surveys give only bed and water levels and widths, but neither velocities nor discharges.

From these surveys, widths between berms, depths, and gradients, were taken and averaged over one-mile lengths, using one mile in every three to five, practising no selection beyond avoiding irregular reaches; these widths were plotted against depths to logarithmic scales, and the gradient noted against each plotted point: to show the variations obtaining, Plate Ia gives the plot of data of the Bhowana Branch distributaries, with data of other branch canals added. The data of each branch system were next grouped and averaged, surface widths reduced to bedwidths under the usual assumption that side-slopes are $\frac{1}{2}$: 1, and these averages plotted, widths against depths (Plate IIa) and widths against gradients (Plate IIb).

Average Dimensions.

The average plots of width and depth (Plate IIa) fall well together, and clearly give the relation

$$b = 3{\cdot}8 \times d^{1{\cdot}61}$$

up to nine feet of depth, without any indication of a change of law beyond that point.

Plotted gradients (Plate IIb) being found not to follow an exponential law, velocities were calculated by the Kutter

formula, with N = 0·0225, and plotted ; these were found to follow an exponential law as in Kennedy's investigation, and this law was used to calculate the curve of average regime gradients.

Since the surveys used furnish no data of discharge and these cannot now be ascertained with any degree of reliability, this, the last of the quantities essential in designing, is calculated from regime width, depth, and gradient, under the assumptions accepted in the department, that is by Kutter's formula with N = 0·0225.

Velocity and Depth.

In plotting velocities for the purpose of deducing the law of gradients, a relation has been found that is expressed by

$$V_d = 0{\cdot}95 \times d^{0{\cdot}57}$$

as compared with Kennedy's relation

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

It must be remembered that Kennedy's velocities are "derived from the known full supply discharge and the measured cross-section area of the channel," while the velocities of the present investigation are those assumed in designing ; and as long as Kutter's formula with N = 0·0225 is used, the new relation should be followed.

It is not contended that Kennedy's relation is wrong, although for instance the third, fifth, and sixth of the causes of variation of regime noted above may apply to some of his data ; theoretical velocities would follow Kennedy's law if they had been calculated with values of N varying from 0·0253 at one foot depth, and 0·0215 at ten feet. A new investigation is required to fix a correct discharge formula for these channels ; without entering into criticism of the cumbrousness and possible inaccuracy of the Kutter formula, it is pointed out that all existing formula assume uniform rugosity in all channels covered by one value of coefficient ; silt-formed channels such as those under consideration, probably demand a regular variation of coefficient with size, such as could be covered by a new formula with constant coefficient ; not only are there differences between large channels and small, but also at different stages of supply in the same channel. The essential point is that the law of critical velocities and the discharge formula must be brought into agreement, since one or the other diverges from facts.

It has also to be pointed out that the above relation applies to the average silt-charge of the Lower Chenab Canal, and that there is at present no means of foretelling in design what departure from this average will be caused by any offtake. As to variation of law for different canal systems, having regard to the limited range of Kennedy's data, (only twenty-two points, all lying between depths of 2·2 and 7·0 feet), to the neglect and even denial of the fact that regime at all points of a system is not necessarily the same, to the suggested possible unconscious bias in choice of his sites for observation, and to the suggested error in the value of N assumed for calculating velocities in this investigation, there does not appear to be any reason for holding that the average regime of the Lower Chenab Canal differs from that of the Upper Bari Doab Canal ; this although they take off from different rivers (but of similar origin), and the former at a point some thirty miles more distant from the foot-hills than the latter. R. B. Buckley* quotes three-fourths of Kennedy's velocities as being correct for Sind, and suggests two-thirds as probably correct for Egypt, in both cases without any suggestion of change of exponent ; he also quotes a table of velocities deduced for the Shwebo and Mandalay canals in Burma by Mr. G. C. Stawell, which, according to P. A. M. Parker, † approximates to $V_o = 0{\cdot}91 \times d^{0{\cdot}57}$ that is the writer's exponent and nearly his coefficient. Under any set of conditions there is also some latitude in the difference between the velocity that just fails to cause scour and that which just suffices to prevent deposit.

Velocity and Width.

The relations of width and of velocity respectively to depth arrived at above, combined give the relation

$$V_b = 0{\cdot}59 \times b^{0{\cdot}355}$$

for Kutter velocities, and

$$V_b = 0{\cdot}50 \times b^{0{\cdot}40}$$

for Kennedy velocities. Considering this point theoretically a certain velocity is required along the sides of a channel, to strike a balance between berming and eroding ; the wider the channel, the greater a central and therefore also a mean velocity will this permit of, while the depth can adjust itself to this velocity ; there does not appear to be any reason for the existence of a maximum

* Irrigation Pocket Book, page 118.

† Control of Water, page 768.

velocity which will not permit of sufficient reduction towards the sides, if the width be sufficient ; nor, when there is no limit to the adjustability of depth, can the writer find any reason why the relation connecting velocities and widths should begin to change at some maximum value, or should differ in nature from that connecting velocities and depths.

While it is known that greater or lesser silt-charges demand greater or lesser velocities for equal depth, the case of widths is not necessarily similar : berms forming the sides of channels are composed of such fine muddy silt, so easily suspended in flowing water, that it flows equally all through a canal system : and berms formed of the same silt, at the same velocity, should be similar in character. There is, therefore, more reason for designing according to dimensions that will give V_b in all cases, than there is for the unvarying use of V_o or V_d. These conditions mean that of two channels carrying the same discharge, that which gets the greater silt-charge must be wider, shallower and steeper : to establish this fully would require intimate personal knowledge of a large proportion of the channels dealt with, and analysis of data which should include actual discharges or velocities ; as far as it is possible to judge without the latter, such channels as the writer does know on the whole confirm the conclusions arrived at.

Plotted data being scanty in the region of bigger channels, the writer gives below four more data that have come to hand at the last moment :—

	Discharge	Dimensions	Gradient	Velocity
1.	11,000	257 × 11·6	0·125‰	3·61
2.	4,907	150 × 9·6	0·150‰	3·30
3.	9,500	280 × 10·8	0·157‰	3·08
4.	9,500	282 × 9·93	0·176‰	3·33

The first and second are the dimensions to which it was proposed to remodel the Main Line, Upper and Lower, in 1913 ; the third and fourth, rough surveys recently made of the Main Line Upper above and below the Chinawan escape. In the second, the width, depth, and gradient proposed, are quite near to the 147 × 9·7 graded 0·148‰ that the writer would have proposed. The third and fourth data show that the gradient of the first is much flatter than actually obtains ; the discharges noted, which are rough, give values of N of about 0·0285 and 0·026 : while the data certainly show that the

relations deduced by the writer and applying to all other channels of the system do not fit the Main Line Upper, these points make it useless to go into the question until the full survey now being made can be examined.

Comparisons.

Plate Ib compares regime dimensions that satisfy the above relations, with those given by Mr. Woods, and with those determined by Kennedy's rough rule for widths, his critical velocities, and his maximum velocity. Mr. Woods' dimensions, smoothed out slightly to a curve, give smaller channels $1\frac{1}{2}$ as deep, and half as wide as those of the writer ; the data now examined cover present conditions of the Jhang Branch channels, and show very few points of channels so deep and narrow ; his maximum depth is shown by data to be too low for this canal. Kennedy's dimensions nearly agree with the writer's for the smallest channels, but then gradually increase to $1\frac{2}{3}$ of his depths ; Kennedy's limiting depth and velocity are so closely approached by data following the writer's laws that, though the Main Line Upper data appear to confirm these limits, it would require a sudden change of law to conform to them, and for this the writer can find no reason ; these limits are 9·3 ft. depth with 0·137 % gradient.

Diagram for Designing.

Appendix I gives the essential dimensions, that is discharge bed-width, depth and gradient, of a small series of channels satisfying the relations for V_b and V_d ; for use in designing, a diagram is obviously better than a table, and without becoming confused one nomogram will serve for designing with different values of Kutter's N and with velocities that are fixed ratios of V_b and V_d. Such a diagram is given in Plate III, and is constructed as explained in Appendix II ; it will be observed that as long as V_b and the standard value of N are used, design calls for no more than the laying of a straight line across the diagram, and reading off the values this cuts on scales drawn on it ; in other cases, and in determining the factors of an observed set of data, further calculations, three at most, have to be made ; these are simple on either a slide-rule or the small nomogram given on the Plate. A full set of examples given in Appendix III covers all possible problems.

Summary.

To sum up then ; an important subject has been reopened after more than twenty years, when it was framed almost

in the infancy of modern irrigation science ; a new critical velocity relation has been determined.

$$V_d = 0{\cdot}95 \times d^{0{\cdot}57}$$

applicable to the velocities used in designing ; widths are fixed for average conditions by determining a similar relation between them and critical velocities, namely

$$V_b = 0{\cdot}59 \times b^{0{\cdot}355}$$

applicable also to design-velocities : but the data that the writer has so far been able to obtain do not make it possible to state with certainty that these relations continue above the values 150 ft. for width, 9 ft. for depth, 3·3 ft. for velocities : the converse of these relations can be given as

$$d_o = 1{\cdot}1 \times v^{1{\cdot}75} \qquad b_o = 4{\cdot}4 \times v^{2{\cdot}82}$$

for designing velocities, and

$$d_o = 1{\cdot}3 \times v^{1{\cdot}56} \qquad b_o = 5{\cdot}8 \times v^{2{\cdot}5}$$

for Kennedy's velocities : eliminating velocities, the widths, depths, and gradients have been arrived at necessary to carry any discharge with the above conditions, and a diagram provided from which these dimensions can be read off directly for all ordinary cases, and simply calculated for the rest : should data outside the range examined show a necessity for modification of the laws derived, the diagram can be redrawn to comply with such modifications.

The writer does not claim to have attained finality, but with the discussion he hopes to arouse, and the data that may be presented, substantial progress should result in a subject of undoubted importance to irrigation science

APPENDIX I.

Table of typical channels.

Depth in feet.	Bed-width in feet.	Gradient.	Discharge in cusecs.
1·00	3·8	0·396‰	4·09
1·25	5·5	0·346	8·26
1·60	8·1	0·304	17·7
2·00	11·6	0·267	35·6
2·50	16·6	0·241	71·6
3·15	24·0	0·219	147
4·00	35·4	0·199	314
5·00	50·7	0·180	630
6·30	73·4	0·167	1,310
8·00	108·3	0·157	2,795
10·00	153	0·147	5,580
12·60	224	0·138	11,510
15·85	325	0·131	24,200

APPENDIX II.

Construction of designing diagram.

A graphic representation is made of Appendix I, consisting of vertical scales of bed-width b, discharge D, depth d, and gradient S, graduated so as to be read by horizontal lines across the diagram ; the scale of d is divided logarithmically, those of b and d marked on parallel vertical lines, but those of D and S are not yet fixed laterally. Calling the values cut on these scales by any horizontal line b_1 D_1 d_1 S_1 , these will be such that a channel of bed-width b_1 and depth d_1 with $\frac{1}{2}$: 1 side slopes and rugosity represented by Kutter's $N=0{\cdot}0225$, must be graded S_1 to give a discharge D_1 , the velocity v_1 of which satisfies the relations for V_{b_1} and V_{d_1} .

Consider a line of inclination i through b_1 and some other depth d_2 ; a channel of these dimensions will require a gradient S_2 to give the same velocity v_1 , and the resulting discharge will be D_2 ; by marking the points at which the inclined line cuts the graduations D_2 and S_2, repeating the process with lines of the same inclination through other values of b, and connecting the points so obtained, the scales of D and S would be fixed laterally so that lines of inclination i across the diagram give channels of velocity still satisfying the relation for V_b : but as the scales of b and d are parallel and the latter logarithmic, the ratio $d_2 : d_1$ is constant as long as i is constant ; and since v_1 is Vd_1 as well as Vb_1 it is also a fixed ratio R_d of Vd_2 .

The second step in construction is therefore to mark a scale of inclinations logarithmically so as to read R_d directly. Next the scales of D and S are fixed laterally in the manner described, for suitable values of R_d. On this diagram one line almost straight and vertical suffices for the scale of D, but that of S is a curve of varying position depending on i, the inclination of the line joining b and d. The diagram is now such that if any line across it cuts the scales at values b D d and S, a channel of bed-width b and depth d, with $\frac{1}{2}$: 1 side slopes and rugosity represented by Kutter's $N = 0{\cdot}0226$, must be graded S to give a discharge D, the velocity v of which satisfies the relation for V_b and bears to V_d a ratio given by i, the inclination of the line measured on the scale of i.

If a channel of size $b \times d$ be found actually to discharge D_a instead of D_t as read on the line joining b and d, then obviously the ratio R_b of v to V_b will be

$$R_b = D_a \div D_t \qquad \text{and} \qquad R_d = i \times R_b$$

and if the actual gradient be S_a instead of S_t, approximately

$$\frac{N}{0{\cdot}0225} = \frac{D_t}{D_a} \times \sqrt{\frac{S_a}{S_t}} \quad \text{and so N} = \sqrt{\frac{S_a}{S_t}} \times \frac{0{\cdot}0225}{R_b}$$

And if a design be required with velocity other than V_b and value of N other than 0·0225, the above formulæ will give the value of i to be used, the D_t through which the inclined line should be laid, and allow of correction of the S_t obtained to give the necessary S_a.

APPENDIX III.

Examples of use of the designing diagram.

1. Design a channel to carry 1,000 cusecs,
a horizontal line through D = 1,000 gives

$$65' \times 5{\cdot}8' \text{ graded } 0{\cdot}172‰$$

2. Design a channel to carry 1,000 cusecs with $0{\cdot}95 \times V_d$
a line of inclination 0·95 through $D = 1000$ gives

$$61' \times 6{\cdot}2' \text{ graded } 0{\cdot}157‰$$

3. Design a channel to carry 1,000 cusecs with $0{\cdot}95 \times V_b$
apply the first formula above to calculate, or use the small nomogram in the manner of Fig. 1 : this figure is marked with four quantities, 1·0, Rb which in this case is known, D_a known, and D_t to be found ; these four quantities are connected in pairs with the connecting lines intersecting on the appropriate support, that for D : connect the pair of known values, in this case 1·0 and Da ; spot on the support for D ; connect to the third known value, R_b and read off

$$D_t = 1{,}053$$

apply the second formula above to calculate. or use the small nomogram in the manner of Fig 2 in the way just described for calculating D_t
and read off

$$i = 1{\cdot}053$$

a line of inclination 1·053 through $D = 1{,}053$ gives

$$64' \times 5{\cdot}4' \text{ graded } 0{\cdot}191‰$$

DISCUSSION.

MR. LINDLEY, introducing his paper, said a letter had recently come into his hands in which the writer piously disclaimed "the temerity of trying to improve Kennedy's diagrams" and to those of a like way of thinking, his paper would be an act of vandalism. Another correspondent had written that "the conclusions and opinions of Mr. Kennedy and other pioneers have too long been treated with an awed respect which forbade any part of them being questioned, even in the light of further information. It does not lessen, but increases the honour of such giants of the past, to build on the foundations they have laid." Mr. Kennedy too agreed that further investigation was needed now that there were so many more channels to choose from, and any one who had not merely accepted Mr. Kennedy's theory blindly but had studied his paper and data, would welcome the following more detailed description of the channels which he had observed. "As to the Bari Doab Canal experiments of 1893 or so, at that time the whole of the canal had been built up into steps by numerous falls from the head downwards. Each step had acted as a silt trap with a silt bed above each fall, which collected any scour that had occurred above. This had been going on for many years, and all the older falls had caused a fixed regime above, and some of the newer were still acting as traps to a small extent; but further down the canal this action had come to a stop, and in each reach there was at the lower end such a silt trap as to ensure that the supply was fully silt charged, as if it were not it would take more silt. In the data then collected, only such permanent channels were selected in the canal; and on the distributaries, only the head reaches were taken, *i. e.*, before the outlets had drawn off any silt. Most of the channels had a side silt-berm also. Since the graph of V and *d* gave a consistent locus, it was, humanly speaking, certain that the silt charge was constant, *i. e.*, $\propto D$, since there was nowhere any accumulation of silt going on, as shown by years of personal observation."

The Egyptian Ministry of Public Works had favoured him with copies of their literature on points coming within the scope of his paper, and other correspondents had made useful suggestions to which he proposed to refer in replying to the discussion.

To the causes accounting for variation of regime dimensions* should be added the latitude between the velocities that would

* Page 65.

on the one hand just allow deposit, and on the other hand just cause scour.

Some of his correspondents had been puzzled over the statement at the foot of page 68, so he would put it in another way. Assume a supply to be admitted to a channel with silted bed and silt formed sides, all factors being free to vary except the degree of the silt charge and the velocity; it was already accepted that the depth would adjust itself to the velocity by silting or scouring, till a balance or regime was reached: if the channel were relatively narrow, higher central velocities would persist so close to the sides that they would be cut and the channel would widen; if it were relatively wide, the velocities at the sides would be so much reduced that the berms would grow; and between these lay the regime width that it was one of the objects of his paper to determine. The data in the paper were satisfied by a law similar to that already accepted for depths, and he could not find any reason either why the law should be of a different form, or why it should change its nature outside the range of dimensions covered by the data. Since, with a given degree of silt charge, a certain velocity demanded a certain width and depth, and since to give that velocity with those dimensions demanded a certain gradient, it followed that for fixed regime conditions the regime dimensions were all fixed by nature, and this law was independent of the precise form or value of the relations.

MR. BIHARI LAL UPPAL said that the author had tried to fix the law of variation of widths and depths, from the data to which he had access, not by any rational method, as he said, but entirely by empiric rules. He connected the average widths and depths by the relation $b = 3{\cdot}8\, d^{1{\cdot}61}$. The normal data of widths and depths given by Mr. Woods, if smoothed out to a curve, were more or less connected by the relation $b = 2{\cdot}09 d^{1{\cdot}59}$ so that there was a big difference in the co-efficient, and a slight difference in the exponent. The author had collected data from the Jhang branch channels, which appeared to be shallower than those from which Mr. Woods had collected his data, and they were also shallower than the channels of the Lower Jhelum Canal, from which he had himself prepared a statement, showing the bed-widths from one to forty feet. The corresponding depths existing in these channels had also been given under the bed widths, while the depths, according to

Mr. Woods and Mr. Lindley, had been added to show at a glance how the channels of the Lower Jhelum Canal compared with those already fixed under authority, and those now advocated by Mr. Lindley. The results had also been plotted, and the diagrams showed that—

(1). Channels of bed widths up to ten feet mostly agreed with Mr. Woods's data and not with Mr. Lindley's.

(2). The Khadir, Lalian and Deowal distributaries were even deeper than given by Mr. Woods's formula. The reason for this was not far to seek, as these channels were long ones, and in their tail reaches, where smaller bed widths occurred, they were able to work with flatter slopes and greater depths, as much of the silt had been carried off in the offtakes of the upper reaches.

(3). Channels, having bed widths of from ten to twenty feet, generally agreed with Mr. Woods and not with Mr. Lindley. The Lalian was still slightly deeper than Mr. Woods's formula suggested, but the Khadir was slightly shallower.

(4). Channels of twenty to forty feet bed-widths agreed neither with Mr. Woods nor with Mr. Lindley, with the exception of Kirana, which agreed with Mr. Lindley in the reach with 28 to 34 feet bed-widths.

It was thus clear that the new relation which the author advocated could not be followed everywhere. The relation must depend upon the grade at which a channel could work without silting or eroding.

MR. J. H. MIDDLETON produced a diagram to show that the averages of data of channels on the Lower Jhelum Canal agreed with Mr. Lindley's curve of the relation of bed-width to depth up to fifty feet bed-width, but for larger bed-widths diverged therefrom, and for still greater bed-widths agreed more closely with Mr. Woods's figures, given in his pamphlet on the Normal Data of Design of Kennedy Channels. He also pointed out that data derived from one particular channel, the Lalian distributary, which had a bed-width varying from thirty to fifty feet, was almost in exact accord with Mr. Woods's figures already referred to.

MR. F. W. WOODS said that this was a subject which was, in a special sense, his own ; since it had engaged his attention for more than twenty years. More than fifty years ago Colonel Anderson, R. E., as a result of a study of the hydraulic conditions of the Punjab rivers and inundation canals, drew attention to the fact that natural streams had a tendency to form for themselves, by alluvial process, channels whose widths bore to their depths a certain range of ratios varying with the discharges of the streams, and Colonel Dyas, R. E., following Colonel Anderson's views, designed the main line of the Bari Doab Canal with a width fifteen times its depth, for a discharge of 3,000 cusecs. Since then, however, no attention had been paid to this subject of the ratio of width to depth in designing Punjab irrigation canals.

About the year 1901 the speaker collected statistics of width, depth, gradient, etc., of nearly two hundred different sites on branches and distributaries of the Lower Chenab Canal in the Jhang Division, and in 1904 and 1907, as mentioned by Mr. Lindley, Mr. Kennedy utilized these data, together with others of his own collection, in laying down some sort of rule as to suitable ratios of width to depth. Scant attention had, however, been paid to these rulings by Punjab canal engineers, and this continued oversight led him, in 1917, to issue a paper, in which he laid down, for general guidance, what he considered to be suitable data of design for those who were designing channels on the Kennedy system. These data were based on Kennedy's diagrams and on certain observations made by himself on the Western Jumna and Bari Doab Canals as well as on the Lower Chenab Canal. In issuing these instructions he pointed out that it was desirable that his results *should be checked with data of actual measurements of natural alluvially formed channels in good regime.* Mr. Lindley, presumably acting on this advice, had collected data, from which he had deduced a set of normal data of design, which differed materially from those suggested by himself ; these ratios of width to depth being greater than his own for channels discharging less than 2,500 cusecs, and less for channels of greater discharge. The value of Mr. Lindley's results depended entirely, however, on the degree of discrimination exercised in the selection of his statistical data.

As regards the larger channels, discharging over 2,500 cusecs, with a bed width and depth exceeding a hundred feet

and eight feet, respectively, Mr. Lindley's data were scanty; and he admitted * that his graph, as regards these larger channels, did not accord with the existing data of the main line of the Lower Chenab Canal.

As regards the smaller channels he was on safer ground; and his data indicated that, especially as regards channels discharging less than three hundred cusecs, such channels, on the Lower Chenab Canal, were very much wider and shallower in the years 1915-17 than they had been fifteen years earlier. But from his description † of the manner in which he had collected his data, it was evident that neither he, nor they, had any assurance that those data were the data of channels *in stable regime*; and in the absence of such assurance, the arguments he based on his data were less cogent than they might otherwise have been.

Mr. Lindley had stated ‡ that he had noticed in the speaker's pamphlet on "Normal Data of Design" that "Kennedy's rules are transgressed in design and in nature, because, according to Kennedy's diagrams, actual large channels should silt and most small channels scour."

This statement was as sweeping as it was obscure; and he would like Mr. Lindley to make his meaning clearer. Evidently he had read into Kennedy's diagrams a theory which Mr. Kennedy himself was not conscious of; as might be inferred from the following extract from a letter which he had himself recently received from Mr. Kennedy:—"I got a note from Lindley about the practical design of non-silting channels; but so far I do not think he has advanced matters. It is not so easy to collect *reliable data*. Your memo. on the subject agreed better with any figures I had, though of course I had very little to go on. I sent you some months ago a diagram with your results shown on it. More in the same direction are wanted, but in any data collected the greatest care is necessary in selecting only those channels whose bed silt and also self-silted side berms are nearly stable, and are self derived and long continued."

Although the admittedly erroneous nature of some of Mr. Lindley's empirical hydraulic data, and the doubtful reliability of the rest of them, deprived his conclusions of much

* *Vide* page 70.
† *Vide* pages 65—66.
‡ *Vide* page 64.

of the value which they would otherwise have for canal engineers, he had found his paper, nevertheless, very interesting; especially as regards his effort to evaluate the critical velocity of streams in the lateral direction. According to Dupuit's theory, which was the real basis of Kennedy's hydraulic diagrams, there must be a critical velocity, expressible in terms of the width of channel, for stability of *regime* in the sides of a channel corresponding to Kennedy's critical velocity which was expressed in terms of water depth; and a reference to this view would be found in the paper which Mr. Schönemann presented to this Congress in 1916. If Mr. Lindley would continue his investigations, and collect statistical data of streams in really stable *regime*, ranging in discharge up to a maximum of 20,000 cusecs, and determine values for the critical velocity in planes parallel to the stream bed, somewhat on the same lines as Kennedy had dealt with the critical velocity in the vertical plane, he had no doubt he would arrive at really useful results in due course, but in the collection of his data he should be careful to ascertain, by direct observation and measurement, the actual water surface gradients, velocities, and discharges, of his *regime* channels.

MR. C. A. COLYER mentioned his experience on the Lower Swat Canal. Silt was divided into two classes, *i.e.*, rolling or bed silt, and suspended silt, and he wished to emphasize the great importance of the formation of berms from suspended silt—a matter largely neglected by investigators. He had found in the North-West Frontier Province that channels, having a small ratio of width to depth, usually developed a central velocity much higher than the side velocity, and that this caused a series of small vortices, with their peripheral velocities acting in the opposite direction to the main flow in contact with the sides of the channel, which resulted in the partial neutralization of the main side velocity, and a consequent deposit, or growth, of a berm. These berms were usually attributed to the growth of weeds below the water surface, but he had dug out both old and new berms on such channels and had found no remains to warrant the conclusion, whereas the quick formation of a pure silt berm, on a pitched flume, in a freshly silt-cleared channel, seemed to corroborate the theory of anti-vortex formation. If this were confirmed by past or future experience of other engineers, it would behove them to carefully consider the ratio of central to side-velocity in designing or remodelling distributaries.

MR. LINDLEY, replying, said that in spite of his emphasis on the point, some members appeared to consider the formula connecting width and depth, given in the body of the paper, as intended to be general ; but with critical velocity ratios other than unity it became—

$$b = 3{\cdot}8 \times \left(\frac{R\,a}{R\,b}\right)^{2{\cdot}82} \times d^{1{\cdot}61}$$

Mr. Kennedy and Mr. Woods had both taken exception to his having used a mass of unselected data, instead of observing only reliable data of channels in stable *régime*. The list of possible causes of variation in *régime* dimensions on page 65 gave an idea of the mass of data needed in the absence of intimate personal knowledge ; but having already had two sets of investigations spoilt by transfers, he was restricted to a method that would not call for years of study on the spot. Mr. Woods had stated that both Mr. Kennedy and himself had utilized his Jhang data for the rules of width that they had formulated, and the difference in their respective conclusions was exhibited on Plate I b. The effect of selection was further shown in the conflicting conclusions of Messrs. Behari Lall Uppal and Middleton regarding *régime* on the Lower Jhelum Canal. Sufficiently reliable selection being impossible, he had used a complete set of data, making the usual assumption that *plus* and *minus* errors balanced about the true mean.

Mr. Woods was correct in believing his own note to be the germ of the present paper ; but he had found that channels, which he knew, did not confirm Mr Woods's normal data, and that several other amplifications were called for. The gradients given by Mr. Woods were only those calculated to give V_0 ; his dimensions did not plot to a smooth or even a regular curve ; no attempt had been made to state what causes fixed widths ; and only one set of normal data having been given there was no provision for different *régimes*. Also, to illustrate by a simple numerical example, if the width were found twice the depth for two feet depth, three times for three feet, four times for four feet and so on, it was simpler to state that the width was the depth squared, than to give a table of this " variable co-efficient."

Mr. Woods questioned his statement that Kennedy' rules were transgressed in design and in nature, but few if any large modern channels in the Panjab had been designed with the full V_0 that they specially demanded, yet they were

believed to run as designed. At the other end of the scale, his Plate IIc showed that in most small channels the velocity was more and not less than Kennedy's critical.

The subject of the paper was of admitted interest and importance, but he had to confess to disappointment that the discussion had advanced the question so little. Much would have been gained from a set of data of some other canal system, from any data of large channels, or from a discussion of the possible form of the velocity-width relation.

Since the meeting of the Congress, Mr. Woods had been good enough to let him see his original data, and these, and the surveys from which they were taken, showed that the channels of the Jhang Division were then narrower—some as little as half the present width—correspondingly deeper, but on the whole at the same gradients. The canal system was then of only about half its present age, and in the interval the river had also been adjusting its *régime*. At the first bifurcation of the canal, the Jhang side was credited with always having taken less than its fair share of silt, so that the mean for the Jhang channels would be narrower and deeper than that for the whole canal, but measures had since been taken to equalize this with apparently some success.

Mr. Kennedy has recorded that in 1898 he found the Chenab silt to be heavier than that of the Bari Doab Canal, judged by the test of its falling velocity in water; and in his paper he anticipated a lower exponent for a greater charge of bed-silt. What was suggested at the foot of page 64 would also entail that if his data had been observed some years later, and had included channels then still silting, the mean curve would have given higher velocities for small channels.

A correspondent, Mr. W. L. C. Trench of Bombay, had suggested a difference between the velocity-depth and velocity-width relations: "within the limits with which we deal, any appreciable addition to the depth makes a very appreciable difference in the average velocity; but in a wide shallow section the horizontal velocity curve is exceedingly flat in the centre and bends sharply towards both ends; and a substantial addition to the breadth merely prolongs this central almost flat portion, and leaves the curves at the ends (and therefore the actual edge velocity) almost unaffected". Expressed in the manner of the illustration of what was stated on page 68

given in introducing this paper: Assume a small and a large channel formed to regime dimensions in the manner described; the relations arrived at in this paper mean that increasing both velocities in a certain proportion would entail equal proportionate increases of both depth and width in both; Mr. Trench considered that the larger channel would widen in a greater ratio than the smaller. The point could not be decided theoretically, but the suggestion seemed sound, though unfortunately he had been unable to obtain data of big channels to fix it empirically. A form similar to that suggested below for the general velocity-depth relation would satisfy this too.

Mr. Trench had observed that his (and Mr. Kennedy's) velocity-depth relation gave zero velocity for zero depth, "but with grains of sand or silt, there must be a velocity below which the sand will not be moved, be the depth ever so little." This coincided with the suggestion made, but not worked on, in the pamphlet "Irrigation Practice in Egypt" that the general form of the equation should be

$$v = q + k \times d^n$$

Mr. Kennedy had stated that his relation assumed all silt to be carried in suspension, while actually there was doubtless a small quantity simply rolling on the bed, which was proportional to V and not to V^2. The present exponential form was at any rate accurate enough for the range of depths to which it was at present applied.

Referring to Buckley's quotation of $\frac{3}{4}\ V_0$ as approximately true for Sind, Mr. Trench stated that this was so on the Jamrao Canal for depths from $3\frac{1}{2}$ to $4\frac{1}{2}$ feet, and fairly safe for greater depths, but quoted other smaller channels running with 1·4 and 1·8 V_0.

Mr. C. C. Inglis of Bombay collected regime data while in Sind, but had been unable to obtain access to them in time for quotation or use. Regarding the Jamrao Canal, he stated that the distributaries were not run full, so that the conditions were not constant, and it was difficult to say what *regime* was.

Mr. Trench suggested that for flat countries, where only little fall was available, a velocity-depth relation was wanted, giving the minimum velocities necessary to avoid silting, rather than the mean between silting and scouring. It must be remembered that a channel designed to this would silt if run at less than the full supply, and that silt once deposited required a greater increase

of velocity to pick it up again, but under some circumstances it would be more economical to limit the gradient, at the cost of occasional silt-clearances.

From the Egyptian literature he had received it was at once obvious that the collection of reliable data there was more difficult than in the Punjab, because gradients were exceedingly flat (one in ten to twenty-five thousand), and discharges very variable. Side-slopes originally cut 1 : 1 were said soon to flatten to $1\frac{1}{2}$: 1 or even 2 : 1 ; so that apparently berms did not form.

A note by Mr. R. G. Kinder compared depths and velocities of small canals in the Behera (delta) ; these were taken from observed cross-sections, water levels of flood conditions, designed gradients, and were calculated by Manning's formula with N = 1/40. He distinguished canals that silt, those that after silt-clearance silt slightly and then remain stable, and those that do not silt ; he showed that the curve for $\frac{1}{2}V_0$ fairly divided the silting and non-silting channels, which range from $2\frac{1}{2}$ to 7 feet depth ; he quoted Mr. Harris as having found $\frac{1}{2}V_0$ to apply also to three large canals in the Behera, and this was nearer the mean than the $\frac{2}{3}V_0$ that Buckley suggested.

In another note Mr. A. D. Butcher took Kennedy's original figures ; remarking that the data are all of stable channels, and that to fix the limits of stability, data of silting and of scouring channels were also wanted, he drew round the data two purely empiric curves (not expressible in formulæ) for a non-silting and a non-scouring velocity, bounding the region of stability; he showed that a channel that is non-scouring at a certain depth was still non-silting at a much less depth, and that for a given depth and gradient there was a range of widths that would give velocities within the stable zone, and he fixed these limiting dimensions.

A paper by Messrs. Molesworth and Venidunis, " Irrigation Practice in Egypt " pronounced $\frac{2}{3}V_0$ as too high for Egypt, and stated that " recent enquiries seem to point that in Lower Egypt, for canals of the first magnitude, the critical velocity will be from

$$0{\cdot}38 \text{ to } 0{\cdot}48 \times d^{\frac{2}{3}}$$

(all the formulæ and coefficients quoted have been converted from metric to English units). The paper went on to work out a formula for the widths necessary to give the required velocity with different values of this coefficient, depths, gradients,

and side slopes, arriving at a system of designing that seemed more ingenious than practical, since a slight change of rugosity such as was quite likely in practice, would theoretically entail a relatively large change of *regime* width.

Apparently, to accord with general practice, the following values were suggested for the coefficient (k) in a formula connecting width and depth.

$$d = k \times \sqrt{b}$$

deep perennial canals, (steep)	1·45 to 1·65
shallow ,, (flat)	1·3 to 1·45
deep basin canals up to 60 ft. width	2·0
,, ,, ,, ,, 100 ft. ,,	1·9
,, ,, ,, over 100 ft. ,,	1·8
shallow ,, ,, ,,	1·45 to 1·6

Since the above coefficient decreased for bigger channels, b varied as a power of d greater than the square, while this paper deduced the power 1·61.

As the result of examining the data of a large number of "recognised good Egyptian canals" the paper suggests

$$d = 0{\cdot}18 \times (s \times 50 + 4{\cdot}0) \sqrt{b}.$$

A warning was given against the use of any universal formula regardless of local conditions, and to illustrate this, it compared the head reach of a canal taking off above Thebes, with a tail reach 90 miles from an offtake in the Delta, both being 46 ft. wide and graded 1 : 20,000 ; the former 16½ ft. and the latter 9 ft. deep ; while one would expect the difference to be in the opposite direction. The writers, like himself, deprecated the waste of labour and money involved in periodically clearing channels to dimensions that nature would not accept for *regime* running.

To sum up the present state of knowledge of the subject dealt with the paper.

1. It was already accepted that for *regime* a relation (depending on silt-charge) existed between velocity and depth ; and the relation arrived at in this paper was suggested as more correctly applicable in the Punjab, at any rate to theoretical velocities, than that of Kennedy ; but an extension of the enquiry was needed to show the range of stability. The exponential form of relation sufficed to cover a limited range of variation of data, but the general form would

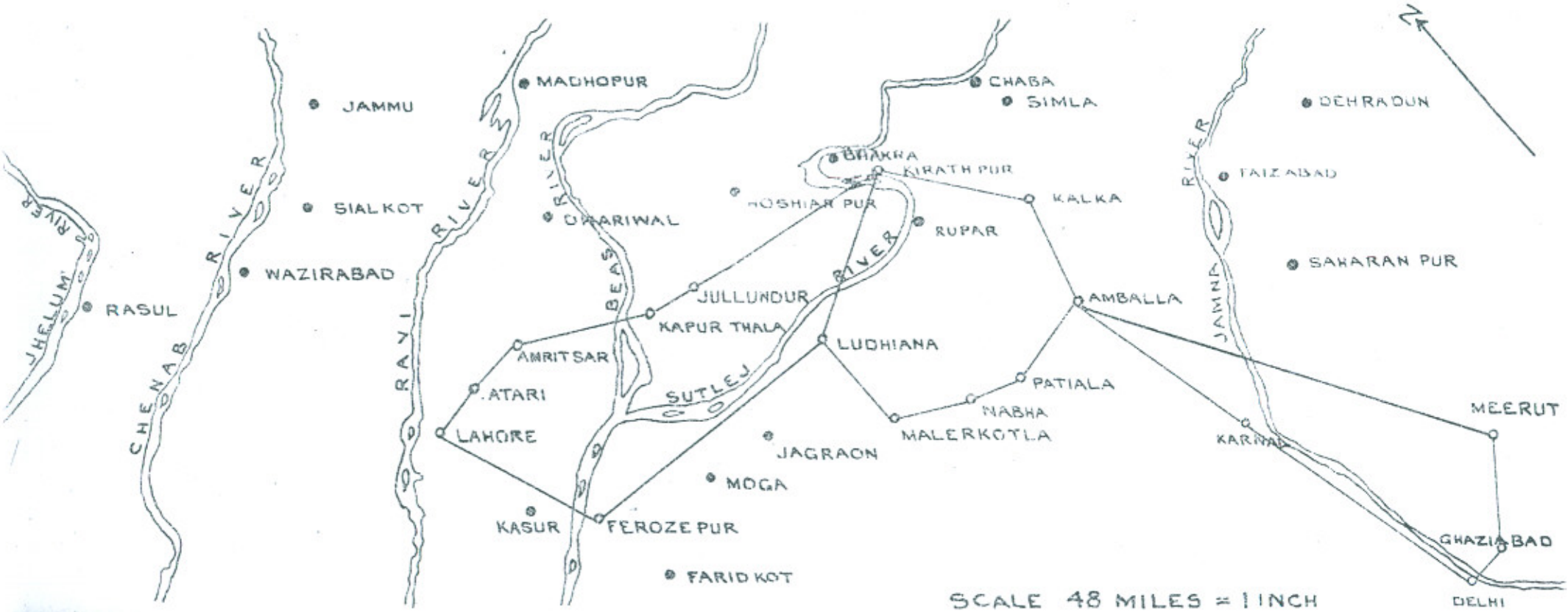
probably have to be different, and the form suggested was

$$V_o = q \times k d$$

The fixing of values in this relation would be assisted by investigations such as that of the Royal Geographical Society (Research Department) and of the California University.

2. A similar relation must exist between velocity and width, and while the form and values arrived at in the paper were accurate enough to allow of the use of his diagram (Plate III) up to about 600 cusecs discharge, the relation should more correctly have another form, as suggested by Mr. Trench. This form might well be similar to that suggested for velocity and depth, but his data did not include big enough widths to allow of his fixing it correctly at present.

3. The existence of these two relations, whatever their form and values, meant that the dimensions, width, depth and gradient, of a channel to carry a given supply loaded with a given silt-charge, were all fixed by nature.


JHELUM RIVER
RASUL
CHENAB RIVER
JAMMU
SIALKOT
WAZIRABAD
RAVI RIVER
MADHOPUR
BEAS RIVER
GURDASPUR
HOSHIAR PUR
CHAMBA
SIMLA
BHAKRA
KIRATH PUR
KALKA
RUPAR
JULLUNDUR
KAPUR THALA
AMRITSAR
ATARI
LAHORE
SUTLEJ RIVER
LUDHIANA
PATIALA
NABHA
MALERKOTLA
JAGRAON
MOGA
KASUR
FEROZE PUR
FARID KOT
AMBALLA
JAMNA RIVER
DEHRADUN
FAIZABAD
SAHARAN PUR
KARNAL
MEERUT
GHAZIABAD
DELHI
N
SCALE 48 MILES = 1 INCH