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SCIENTIFIC IRRIGATION CHANNEL DESIGN

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The principles of design of channels which have *formed themselves in their own silt* have been determined empirically and given by Lacey in the Institution of Civil Engineers' Papers Nos. 4736 and 4893. This article presents them in a manner suitable for the canal engineer and explains their meaning and correct application.

1. The Formulae.

The first is $V = 16 \sqrt[3]{R^2 S}$ .....(1)

where V is the mean velocity, R is the hydraulic mean depth, and S is the slope.

This formula is the mathematical test for final regime. If it is not satisfied by site data the application of the formulae containing the silt factor will give inconsistent results.

By " final regime " is meant the final steady state of a channel reach which has formed its own *section and slope* in its own silt.

The determination of a final regime reach by site inspection is very difficult. A cutting, or semi-cutting reach, may be in good condition, have run without change for years, and have silt on its bed in a closure, but not be in regime as defined here. The formula (1) settles the question. Again, high outlet location in a channel may cause a progressive increase of the silt factor from head to tail. If (1) holds, the increase is genuine, and each small reach of the channel is in final regime with a different silt factor. The tremendous value of the formula is that it does not contain the silt factor.

The second formula is $P = 2.67\ Q^{0.5}$ .....(2)

where Q is the discharge running in the channel normally, and P is the wetted perimeter.

This formula, which also does not contain the silt factor, applies to initial regime, *i.e.*, to the condition of a channel which has formed its section in its own silt ; but *need not have had time to form its final slope.* Obviously it must apply in the limit when final regime has been attained.

The third formula is $V = 1.171 \sqrt{f R}$ .....(3).

This is Lacey's fundamental one and defines the silt factor F. It applies to *initial regime* (and of course to final). The physical meaning

of f is not known ; but it is a physical constant of " silt content " and appears to depend mainly on the diameter of the most prevalent silt below 0.6 mm. diameter in channels carrying sand only (and not boulders).

The formula replaces that of Kennedy, which had a different index for different canals, as well as a "silt factor" v/v_o which was not a physical constant of the "silt content" but, at low discharges, a noticeable function of the discharge.

There is some popular confusion about this Lacey formula for the following reasons :—

(*i*) It is believed that v/v_o (the Kennedy critical velocity ratio) is exactly equal to f. This is not so. There is a fairly close correspondence at certain discharges ; but mathematically it is impossible to have exact agreement in general. There is sufficient correspondence for an engineer who is switching over from the Kennedy theory to compare $\sqrt{f}$ with critical velocity ratio when he tries to visualize the type of channel to which a certain f applies.

(*ii*) Lacey, in his first paper, used a constant 1.151 instead of 1.171. The change does not represent the detection of error in his original work. It arose from his evolving an initial regime formula to replace the cumbersome Kutter's. This new formula contains a rugosity coefficient which depends on f and does not differ markedly from Kutter's N. It is possible to choose the numerical constants of his formulae so that when f=1.00 the new rugosity coefficient is 0.0225 which is the value of Kutter's N for Kennedy's Upper Bari Doab Canal channels since taken as standard for all canals (although it does not apply to all). So all that has happened is that Lacey has made the origin of his f agree with the origin of Kennedy's work. This makes the change over to the new theory all the more convenient ; and is a tribute to pioneer research by Kennedy.

(*iii*) It is popularly believed that the formula denies the Kennedy one. Now Kennedy's formula was quite a good fit *arithmetically* to his data ; but as he dealt with one silt grade only, and omitted very small discharges it is not surprising that his formula is not so good for smaller discharges, and gives different indices on different canals. Lacey's formula gives the same index for all canals, *and* fits the Kennedy data. It is a general formula, and we should expect to be able to explain it physically. The Kennedy one cannot be explained physically as it is not general.

(*iv*) There is an idea that, because the formula is the fundamental one, it is the correct one to use to find the f of a channel. Actually it is exceedingly bad for this purpose unless the data be collected with a care never found in standard hydraulic surveys. The error in f is (fractionally) twice that in v, and $v=Q/A$. Even if Q is found by current meter it may be nearly 3% wrong if the water is abnormally dirty; and normally Q is assessed from the not very accurately known draw-off statement of the distributary being analysed, so, except at the head, it has not much chance of precision. At channel tails its estimation is almost hopeless as tail discharges are notoriously fluctuating, and a regime condition postulates steadiness of discharge. Then again A, in an ordinary survey, is calculated from surface width, one depth, and the assumption of trapezoidal section with $\frac{1}{2}$: 1 side slopes and may quite well be 10% wrong. R, however, usually comes out accurate as P is assessed too large with A and the errors partially cancel.

The real use of the formula (in practice) is to determine channel shape by solving with (2) when f has been found by formula (4) (*see below*).

It is advisable to obtain United Provinces P. W. D. (Irrigation Branch) Technical Paper No. 1 and study the Regime Dimension Diagrams which give the simultaneous solution mentioned for a large range of f. Notice particularly that channel bed width is almost independent of f. The reason is that P and B are not much different except for very small discharges. This inflexibility of B is consonant with commonsense, for the expert engineer can usually guess channel discharge from inspection, and all he inspects is the breadth. Nevertheless the writer has seen perfectly well behaved channels remodelled to half their existing breadth with shocking consequences.

An abnormally broad channel is normally one designed at much less than its regime slope and prevented by continual silt clearance from attaining final regime.

The fourth formula is $S=f^{\frac{5}{3}}/1{,}788\ Q^{\frac{1}{6}}$ .....(4).

This applies to *final regime* only. It is the best for finding f from site data. 10% error in Q makes 1% in f; 10% in S makes 6% in f. S is the slope (expressed as a fraction, *e.g*, 0.25/1000).

The precaution to take in surveying is to impress on the surveyor that the not uncommon practice of assuming the correctness of masonry work B. Ms, finding the water-levels at them and assuming uniform slope in between is detected at once and will be verified at site and punished. Water levels (at full supply, of course) must be observed at every 1000 feet—and then an occasional genuine error is of no consequence to the analysis.

Using the Regime Slope Diagram of the United Provinces Tech. Paper No. 1 it takes only a few minutes to fill in f by this formula for the whole channel. The true f's can be spotted at once by their prevalence and their agreement with the f of other channels. In steep cutting reaches f will be abnormally high. If it is ever abnormally low the site should be inspected carefully to see if there is an error or a special reason.

Where f seems true the data for checking by formula (1) should be collected with special care at a few sites to make quite sure.

5. The formulae (1) to (4) are all that are required for remodelling. To summarise :—

(*i*) There are two formulae that do not involve f.

(*ii*) No. (1) is the criterion for final regime. If it holds, all hold.

(*iii*) No. (2) applies to initial regime only. It is very useful for mental assessment of approximate regime breadth. That it holds is not a proof that initial regime exists (*e.g.* a concrete channel might satisfy it approximately).

(*iv*) There are two formulae involving f.

(*v*) No. (3) is for initial regime only and is not suitable for finding f from ordinary survey data.

(*vi*) No. (4), the S, Q formula is for *final regime* only, and is excellent for finding f from site data.

Before giving more formulae it is convenient to discuss :—

II. 1. Application to Remodelling.

Defects of Conventional Remodelling. Remodelling may be done to satisfactory channels because proposed changes in irrigable area require radical changes in discharge ; or to unsatisfactory channels because they persist in silting.

In the former case it is usual to remodel to :—

(*i*) Existing or arbitrary sections.

(*ii*) Existing or arbitrary slopes.

(*iii*) A different silt distribution, by fitting radically different outlets and head regulators.

Assuming error (*iii*) is not made, a perusal of the Regime Diagrams, or inspection of formulae (1) to (4) will show that a reduction of discharge means that sections will tighten and the slopes increase. In particular, if Q is halved then S, the final regime slope, will increase by about 1/8th.

It is *very important* to note that reduction of outlet discharges will cause, at least the portion of watercourse between the outlet and the start of irrigation to steepen [watercourses obey formula (4) reasonably closely] ; so the new outlets should be designed for a *higher watercourse level* than found by survey.

As for (*iii*) if a channel fitted with KGO outlets be supplied with APMs set for proportionality it will silt badly, because the upper outlets will be starved of silt and cause f to increase from head to tail of the channel. In the latter case (*i.e.*, of remodelling of silting channels), there are usually the following defects :—

(*i*) to (*iii*) as above.

(*iv*) The possibility of unequal silt distribution in the channel to be remodelled is ignored.

(*v*) No test is applied to decide whether the channel is getting more " silt charge" (or, more definitely, a larger f) than its parent.

(*vi*) Inequality of f in the division is not investigated.

(*vii*) The possibility of the division itself having an abnormally high f is not investigated.

(*viii*) The policy at headworks is ignored.

If omission (*iv*) is not made it will often be found that large channels with silt trouble at the tail owe their troubles to the high location of the outlets and offtakes in the head reach ; and the remodelling of these offtake regulators (where the offtakes can conveniently take their fair share of silt) will effect an automatic and *permanent* cure. If analysis shows no cure the designer can save himself unnecessary remodelling, and will know exactly how much maintenance he will have to face.

(*vi*) to (*viii*) imply that remodelling is a circle matter.

Consideration of (*viii*) will probably stop the wrong practice of putting more silt into the canal because main line works are being endangered by scour. If there is silt trouble in the irrigating tracts it will usually be far cheaper to protect main line works, or even build falls, rather than accentuate silt trouble.

As for (*vi*) and (*vii*) there may be three divisions, each on a branch taking off from a main line tail trifurcation, with the division irrigating high land getting a larger f than those irrigating low land. Obviously the initial remedy is to remodel the trifurcation, distribute f fairly, wait for the effect of the new silt distribution to be felt, and then remodel to the new f.

II. 2. Rules & for Remodelling.

It should now be clear that the following procedure should always be followed in a large scale remodelling.

(*i*) Obtain preliminary surveys showing water surface slope and discharge of representative *distributaries* throughout the circle, choosing channels with plenty of filling reaches.

(*ii*) Fill in *f* by reaches in which the discharge does not drop by more than 10%, using the S, Q formula number (4).

(*iii*) Note what appear to be the true *f*'s and inspect the channels to see if these really fall in filling reaches.

(*iv*) Having thus decided approximately how silt is distributed between divisions, try to find the *f*'s of the Main Line and Branches. As these may be almost entirely in cutting it is best to reverse the treatment for distributaries, *i.e.*,

(*a*) Inspect for the few sites that may be in final regime.

(*b*) Check these for full supply conditions by formula (1).

(*c*) Those that pass the formula (1) test may be used to find *f*.

(*v*) If (*iv*) fails to give regime sections, and if daily silt analyses are done at Headworks, compare silt samples from the distributaries with the samples of *a whole year* at Headworks. The variable to deal with is the diameter of the most prevalent grade of silt, *i.e.*, the abscissa of the turning point on the silt grade curve.

It is very difficult to draw conclusions from these curves as the grade varies throughout the year but, judged on results, seems to average itself out as the silt passes through the canal system. However, *an indication may be* obtained whether Headworks policy is, in general, sending down more silt than usual.

(*vi*) Draw up a table showing slopes for various discharges from zero to the divisional limits on the assumption of (*a*) the prevailing *f* of each division, (*b*) the *f* that each division might expect if *f* were distributed equally.

(*vii*) Decide, from (*vi*), whether to try to distribute *f* fairly.

(*viii*) Decide Headworks policy.

Only after this should one continue with,

(*ix*) Prepare standard hydraulic surveys with the following differences :—

(*a*) Slopes should be recorded on the surveys as so much per 1000 feet, over reaches in which the discharge does not drop by more than 10%.

(*b*) *f* by the S,Q formula should be filled in for these reaches.

(*c*) Outlet and offtake crests should be marked in red lines.

(*x*) Inspect the channels, with the surveys, and mark the filling reaches that look as if they might be in final regime. Note whether these give consistent *f*s.

(*xi*) If (*x*) leaves any doubts (say due to *f* increasing from head to tail) analyse a few sections by (1).

(*xii*) Decide whether irregular *f* distribution shown up by analysis should be rectified by alterations to channel head regulators and outlets (bearing in mind that it is easy to give a right angle offtake more than its fair *f* ; but almost impossible to give it less permanently—the sole exception being with outlets).

(*xiii*) If the head regulator of the division has been altered to give an even distribution of silt a head distributary should be remodelled to the expected *f*, and if it succeeds then the divisional head regulator remodelling has been a success and the whole division can be remodelled with confidence.

(*xiv*) The *f*'s to expect everywhere being now known remodelling can be done to the Regime Sections and Slopes of U. P. Paper No. 1.

There is, of course, no need to interfere with non-regime cutting reaches unless they are obstructions. But if a distributary be raised throughout it must be remembered that the oversteep cutting reaches will not rise except from their lower ends to a point where the regime slope from the raised level of the lower regime reaches cuts the old slope of the cutting reach, plus a small backwater curve length.

(*xv*) In sections tightened in remodelling bush lightly, as a channel needs a start.

II. 3. Some Useful Facts.

1. Proportional distributors usually distribute *f* equally.
2. It is almost impossible to give a right angle offtaking channel less than the parent *f* ; but the reverse is easy.
3. Outlets (APMs and OFs) are an exception to 2, probably because they are so much masked by their wings.
4. A channel usually needs artificial aid to change rapidly from one regime condition to another, because an equilibrium condition is not easily disturbed.
5. The bed of a channel over 250 cusecs *may* take years to silt.

III. Some Actual Errors.

The mistakes of others are cheap lessons.

1. *Raising a Channel in Cutting.* An 80-cusec channel, some 20 miles long, had the first six miles to the first fall in cutting in hard soil. The reach was equipped with outlets with inadequate command. The slope in cutting was 0.20/1000 but the regime slope according to *f* further down, and the parent *f*, was 0.13/1000. The outlets of the reach ended at about 20,000 *i.e.*, 10,000 feet above the fall.

All the falls were raised by 0.80. Now, as the difference between cutting slope and regime slope was 0.07/1000 it follows that the rise at the outlet two miles above the fall would be 0.80 minus 0.70, plus some amount due to backwater, *i.e.*, 0.10 only, plus backwater; and two miles more above that there would be no rise at all.

After two years of useless bushing (which scours the bed and causes a worse drop eventually) the channel had to be re-remodelled because the anticipated rise did not occur.

2. *Interfering with a satisfactory channel.*—A 13-cusec minor had silted till it very occasionally drowned its head, and the tail was dry; but it had attained steady slope and had the *f* of its parent (in spite of a very special silt-excluding head). It was remodelled by raising the tail outlet (which was not necessary), building a fall in its middle, and silt clearing to impossibly flat slopes.

Two silt clearances were done in the following hot weather, and surveys taken monthly. After that the fall was pulled out, the tail lowered and the channel redesigned to Lacey with the *f* of its parent. This put it back to its previous condition and it has been satisfactory since, just on the point of drowning out. It may drown occasionally as some of the outlets are a bit high.

3. *Interfering with Breadth.*—A 70-cusec channel had 15 miles mainly in cutting and a slope of 0.225/1000 throughout. Had the channel been able to scour down to regime it would have had about 0.15 slope at the head and 0.21 at the end of the 15 miles. The channel head reach had run for years with 16.5 feet bed-width.

In remodelling the bed-width was reduced to 8.5 feet (for 70 cusecs!) and all the outlets built out to this at considerable expense. The existing slope was retained. On bushing a reach down to 8.5 feet the bed scoured to as much as 7 feet in places. The channel now runs without bushing to its old width and is deplorably ugly. The outlet throats are so abnormally long that the minimum modular heads are much less than theoretical; so some outlets do not form standing waves.

The source of this error is instructive. It was ordered to design for a *cvr* about 0.85 and accept the existing slope. Now, had the final

regime slope been used in finding v/v_o a bed width of about 23 feet would have been obtained. With the final regime slope and the existing bed width of 16.5 feet the *cvr* would be about 0.81. So the assumed *cvr* of 0.85 was not a bad guess (it was taken from experience on other channels).

Given that the officer who issued the orders did not know the Lacey Theory his orders were quite sound (although it would have been more reasonable to find the *cvr* of the channel, instead of assuming it had that of some neighbours) *had the channel had a final regime slope.* The designner, of course, could not have observed the pre-remodelling breadth, nor have used his working knowledge of channel breadths.

Provided Kennedy's theory be combined with another condition, such as $P=2.67Q^{0.5}$, and a good practical knowledge of channel behaviour, and is never applied to small discharges, it is possible to get out passable designs ; but the practical knowledge must be really good, which implies that it is gained by making mistakes.

4. *Reducing both supply and slope.*—A 20-cusec minor 20,000 feet long had the tail outlet drowned out, all outlets requiring continual moderate silt clearance, and the minor head just formed a standing wave. The tail got frequent silt clearances, usually unrecorded (this is a warning against accepting minor data too readily). The *f* of the minor, its parent, and the parent's parent were almost equal, so obviously the minor was not getting excessive silt. The proposal was to raise the tail and flatten the slope.

The futility of this project is apparent. Take the mean slope as corresponding to about 10 cusecs and the *f* of 0.64. It comes to 0.18/1000. Formula (4) shows that halving the discharge adds about 1/8th to the slope, so after remodelling we should expect a rise of 0.0225/1000, *i.e.*, 0.45 on the whole minor. The tail would have to be raised 0.40 as a minimum, and the other bad outlets similarly. But, in addition, the halving of outlet discharges will increase the watercourse slopes. One watercourse was 7000 feet long before irrigation started and had about 3 cusecs discharge, with a slope of about 0.23/1000. This would silt up about 7/8 of 0.23 due to reduction, *i.e.*, 0.20. So we must design for a rise at the minor head of about 0.45 plus 0.40 plus 0.20 equals 1.05 feet.

In the actual case the parent had a fall 2 miles above the minor head, so bank raising due to raising the parent this amount would have been cheap.

The absurdity of the original proposal is seen at once when it is considered that it means running on a rough average, 5 cusecs at 0.15/1000, implying that *f* of the minor would have to drop to 0.54. Is this possible by head regulator alteration ! Let us test by accepting Kennedy's theory. The reduction in *f* is roughly equivalent to reducing v/v_o from 0.8 to 0.735. According to Kennedy, silt transporting power is roughly proportional to *cvr* to the 2.5th power. So we should have

to reduce the silt content to $(0.735/0.80)^{2.5}=0.81$ a—reduction of 20%. As the channel was already getting a fair share, this reduction is not practicable. Even if it were, the 20% would go into the tail of the parent, which happens to be of the same size as the minor.

5. *Interfering with outlets.* A 100-cusec channel fitted mainly with KGOs was refitted with APMs set for proportionality. It promptly started to silt.

This kind of silting occurs mostly at the tail. The tail slopes being large compared with those at the head, it follows that if f be allowed to increase towards the tail there is normally a greater total drop over the distributary than if f is kept uniform throughout. Of course, if the land slope is great at the tail the effect does not matter.

Another case was an 8-cusec minor, originally fitted with pipes, at or below bed level. On fitting OFs with high crests its total drop increased.

IV. Design of offtakes.

As equal distribution of f is essential to obtain the least average slope of a whole system, offtake head design deserves special mention; but as there is not the wealth of data on this subject that is available on channel flow this section cannot be dogmatic.

1. A right angle offtake from a straight channel tends to take more than its fair share of silt.

On this there has been a good deal of agreement since at least the time of Lindley. Model experiments to show why it should be are beautifully illustrated in Bombay P.W.D. Paper No. 52 by C. C. Inglis. But it should be remembered that a bias of opinion is given in this direction by the old method of assessing silt charge from v/v_o, which is not a physical constant and will be found to increase as Q decreases even though f remains constant. Further, the fact that an offtake gets more than its fair share of bed water is not *proof* that this extra water takes its full amount of silt with it. Again the fact that high outlets in a channel cause high f at the tail is not *proof* that the outlets get short *quantity* of silt—it may mean a differentiation of grade. Mere consistence with a hypothesis is not proof.

It is best to state 1 as :—

> " A right angle offtake from a straight channel tends to have a larger f than its parent."

As f depends both on quantity and quality of silt this statement includes previous opinion as to quantity, and adds an opinion as to quality.

That *f* depends on quality is given by Lacey. Of its dependence on quantity there is proof in the reduction of *f* from 0.92 to 0.65 from Khadir Branch to Khadir Distributary owing to adding drainage water from a pumping station in between (*vide* Table I).

Having made it clear that *exact* knowledge of distributary behaviour is not available the writer now states his findings on an 800-cusec system including a 55-mile long parent, the *f* being very nearly 0.64 throughout the parent, with a slight increase from head to tail.

1. Of all the offtakes (excluding outlets), which included a special silt-excluding head for a 13-cusec minor, and a flume head of an 8-cusec minor set at half the depth of a 250-cusec parent, the only one with *f* less than the parent was for 3 cusecs, with an H of 1 foot, in a parent of depth about 3.5 feet, and the difference was slight.

2. Proportional distributor distributed *f* equally.

3. Flume heads with 2H wings, even when set high, gave parent *f* very nearly. (Flume heads are not set too near bed level in any case.)

4. Flume heads with old type 45 degree wings took excess *f*.

5. Gate heads with floor about parent bed level took noticeable excess *f*.

6. The draw-off from the branch consisted of, approximately 35% gate heads, 25% flume heads, 30% direct outlets and 10% absorption. The gate heads got about 5% excess *f* on the average, the flumes were fair, and the absorption would make *f* tend to increase uniformly throughout. A rough calculation on the lines given in III. 4 suggests that the outlets get, on an average, about 6% short *f*; and this is consistent with the slopes observed on a few of the high ones. About half the outlets were at the tail and probably got a fair share, so the ones working under true branch conditions probably got about 10% short silt.

It appears that existing type heads are satisfactory if they are used with discrimation, according to the following rules:—

1. To counteract the tendency for *f* to increase owing to absorption, fit the offtakes of Main Lines and Branches with heads that will draw excess silt, such as :—

   (*a*) Undershot heads with low floors.

   (*b*) Flumes with wings that will cause turbulence.

   (*c*) Flumes with divide walls which cut off less than the offtake discharge from the parent channel, the bed between divide wall and berm being *pakka*.

Item (*c*) is suggested from Bombay Technical Paper No. 52 and not from personal experience.

2. Fit all minors that can afford to have *f* appreciably greater than the parent with heads as per (2) above ; or as per (3) if experience shows them successful.

3. When it is desired that an offtake should not take more than the parent, fit it with an OF with gentle approaches or, if it happens to be undershot, with a divide wall that will cut off *not less than* the offtake discharge from the parent.

V. Outlets.

Kennedy says, in the introduction to his curves, that *outlets should be at bed level*, and the writer has noticed that final regime channels of a small discharge, when fitted with high crest outlets, silt till the bed reaches outlet crest levels, or sometimes higher. This hardly affects the slope ; but makes a tremendous difference in distribution unless the outlets are adjusted, which should never be done by raising the crests again, a common error.

Obviously OFs and APMs are useless for channels of depth more than about 3.5 feet, as setting them at bed level would lead to impossibly small breadths and large mmh's.

The only sound type of outlet for a Branch is a pipe through the bank at bed level, followed by a flume in the watercourse. The pipe should be bell-mouthed to cut out shock loss, the bell-mouth should be cast iron to minimise tampering, the barrel velocity should not be less than canal velocity, the exit from the barrel should be gentle, and the flume should have an iron crest to prevent tampering.

APMs and OFs should be set as low as possible, even below bed-level.

These counsels of perfection cannot be followed in the very many cases where outlet command is poor. It is these exceptions which will have great flexibility, and make up for the rigidity of low-set APMs and OFs.

The pipe with flume type of outlet is flexible, which adds to the value of its use in headreaches.

In replacing an old outlet by a new one designed to draw silt the subsequent *silting of the watercourse* must be allowed for. Assume 30% on the slope of a mile, or 20% on the length before irrigation starts, whichever is greater, as a guide for all watercourses not in deep cutting.

To summarise, fit APMs and OFs at bed-level whenever they will work there with the anticipated silted watercourse levels; and when the channel is too deep use pipe-flume outlets.

VI. Minors.

With f=0.80 and Q=4 cusecs the final regime slope is 0.30/1000. This is probably more than the general slope of the land. As there are few canals with f below this figure the reason why minors are notoriously troublesome is obvious.

One must just face silt-clearances, and refrain from the bad practice of making long tail extensions for the sake of perhaps one outlet. The application of the Lacey theory would show most of such areas uncommanded.

The general defectiveness of minors, unfortunately, makes it almost impossible to obtain honest data about them. Local officers have no powers to sanction silt clearances and sanction is difficult to obtain, so silt clearances are done without authority. Anyone who does not carry on this bad policy either becomes very unpopular or gets sanction to a remodelling, which is doomed to failure. Worse than unauthorised clearance is the policy of fitting roof blocks on upper outlets when the channel is drowned at the head. This policy is usually capped by keeping a tail gauge register, based on the wrong principle that if the tail is getting excess all is well. Actually the upper outlets are being starved. The result of this kind of deception is that a further deception has to be practised in the discharge table. Either, it is a theoretical one on an upstream gauge, but there is no standing wave ; or it is an obsolete downstream gauge table.

There are two morals :—

1. Local officers should have powers to silt clear minors.
2. Never believe a minor survey, till conversant with the site for several months.

VII. Deductions from Analysis.

This section illustrates how, without a complete knowledge of the Lacey theory, a very painstaking collection of data can lead to wrong deductions ; but with the full knowledge, and a few facts gleaned from site and records, a useful addition can be made to knowledge.

Appendix I is mainly a table made by Mr. Khangar, Executive Engineer, Kirana, from data collected in his division in 1934. He took data averaged over 1,000 feet reaches. Then, using the fundamental formula (3) he found f, and used this f to deduce the theoretical channel elements, including slopes.

The labour involved in collecting the data, and even working out a new slope formula to suit it, almost makes one regret that the interests of hydraulic science make it imperative to point out the incorrect application.

Firstly the regime of the sections was obviously assumed from their good appearance and permanence. Reference to a map shows that they cluster round Rest Houses ; and a gauge register shows that the full supplies of Northern and Southern Branches are some 10% greater than the discharges during Mr. Khangar's investigations. Sections 1, 2, 4 at site are in cutting.

To find what were really final regime sections the writer has made column 11 which shows the value of $V/\sqrt[3]{R^2S}$. According to formula (1), the channel is in regime for a value 16. Only sections 3, 6, 11, 16 and 18 satisfy this test with almost complete accuracy but a few others approximate to it. These are the only ones on which it is worth testing the Lacey theory ; and to show clearly how accurate it is, column 13 has been added, showing f calculated by the S,Q formula. Notice that as the coefficient 16 [of formula (1)] is departed from, the discrepancy between f by formulae (3) and (4) becomes more and more marked. To make the matter clearer, Appendix II abstracts the only sections worth considering, giving them in order of increasing deviations from the ideal coefficient 16. But, in this table, the theoretical channel elements have been found from the f obtained from the S,Q formula of which we shall call f_S. This gives the sizes even closer than f_R. But the method is no excuse for the popular habit of talking of the two f's of a channel. If two f's are found by the two formulae the channel is not in final regime. The point is that if a channel is a little off regime and f is found from the S,Q formula and used in design, there will not be the trouble that would arise from finding f by the fundamental formula and proceeding to get the slopes wrong. To illustrate this point two columns are given showing the slope that would be found from f_R and the error per mile by using f_R, if f_R were right. As f_R is likely to be too low, and as a channel makes small changes from equilibrium unwillingly, the proportion of these errors per mile to be noticed in practice will be small, till we get to errors of more than about 0.5 in C.

The second defect in Appendix I is that B and D are calculated on the assumption of trapezoidal sections which do not exist exactly at site. In practice this is of small moment ; but in so far as Appendix I was intended to be a criticism of the Lacey theory it has to be pointed out that the correct elements to check on are P and A, and not those based on an arbitrarily assumed shape.

So little of the data now remains as useful that one might think it useless. On the contrary, a site inspection of sections 1 to 4 and half of Khadir Branch, combined with the writer's knowledge at headworks makes it possible to give a fair forecast of what is happening in the Circle.

In 1929 a record flood breached into the Main Line of the Lower Jhelum Canal, probably bringing large silt deposits. The Headworks

was badly damaged, and it is also likely the river was left with large silt deposits to wash away. In 1932 a silt wave showed itself in the Main Line by a very disturbing rise of water level 25 miles from the head (one of the few filling reaches). So disturbing was it that still pond regulation was started at headworks in August 1932 and has continued ever since. The paucity of records makes it difficult to say whether the canal *system* has got a smaller silt factor now than before the flood. The only pointer is the famous Mithalak Distributary (*vide* Congress Paper 154 of 1932) which from 1901 till 1928 when it was, very wisely, allowed to run at its final regime slope, has been remodelled *ad nauseam* to impossibly flat slopes. In 1928 it had an f of 0.96 still rising. According to local information it has had no silt clearance since 1932 and been steady with f of 0.94. It seems from this, and from the steady behaviour of the Main Line at 25 miles since 1932, that the silt wave brought in by the river breach, or perhaps from the head, has passed, and the still pond regulation has made a small but noticeable decrease in f from pre-flood days.

The Main Line ends at 37 miles and divides mainly into Northern Branch and Southern Branch with full supply discharges, in round numbers, of 1700 and 1200 cusecs. With its head regulator in the same block as these is Southern Feeder of about 350 cusecs, and a bit upstream is a channel of 85 cusecs (Rattokala) which obviously draws excess silt. A mere glance at the channels in closure shows that Northern Branch receives a much heavier "silt charge" than Southern Branch and Feeder. Let us check roughly the distribution of f between Northern and Southern Branches by the method of III (4) last para., *i.e.*, translating the Kennedy $(v/v_0)^{2\cdot5}$ rule into Lacey $f^{1\cdot25}$ one, and assuming that differentiation of silt grade is unimportant.

The Main Line f by the S,Q formula at 25 miles is normally 0.90. But formula (1) does not hold absolutely exactly. Accept 0.88 as a better value. Take Northern Branch f the same as of Mithalak Distributary (as that has a high crest) at 0.94. Take Southern Branch f as 0.80 for reasons given later. Assume Southern Feeder to have the f of the Branch, and Rattokala to have that of Northern Branch. This should not be far wrong and, allowing for the small discharges, the final error should be very minute. We now have

(*i*) A parent of $f = 0.88$, splitting into

(*ii*) An offtake of $f = 0.80$ and Q about 1550 cusecs.

(*iii*) Another offtake of $f = 0.94$, and Q about 1800 cusecs.

As (*ii*) is about 10% short in f it is about 12.5% short in "silt charge".

As (*iii*) is about 7% excess in f it should be about 9% short in "silt charge."

So (*ii*) rejects about 0.10×1550 or 155 " silt units "

and (*iii*) takes about 0.09×1800 or 162 " silt units "
from a total of 3,350 cusecs or 3,350 units.

For a rough method the discrepancy of 7 in 3,350 is very good, and confirms the choice of *f*'s.

So we now have a canal in steady condition, with an initial *f* of very closely 0.88, which divides into two Divisions, Sargodha Division on Northern Branch getting 0.94, and Kirana Division on Southern Branch getting 0.80. These are the values which could be attained if silt were distributed fairly in each division.

It now remains to justify 0.80 for Kirana Division from Appendix I. Just beyond section 3 (RD 52,000 Southern Branch) is a regulating fall combined with the heads of Khadir Branch and Wan Escape, side by side on the left bank of the Southern Branch. Mr. Khangar himself has commented on the heading up at this site, which causes a big *f*. One cannot trust the coefficient 16 here as it must have arisen accidentally during one of the many conditions of flow at the site. What is very evident at site, in closure, is that the heading up during closure or shortage of Khadir Branch (and the escape) causes large silt deposits which, on opening the Khadir Branch full, wash into and cause locally high values of *f*. The reverse might occur to a small extent if Wan Escape were run when the Khadir Branch was closed. The cure would be to raise the Khadir Branch and Wan Escape heads to normal bed level. The case is one of " bedding down " rather than " heading up."

Proceeding down Khadir Branch to 96,000 one finds it obviously in final regime. This agrees with the coefficient for section 16. But the final regime is the regime of the excess silt charge from time to time. The *f* of 0.92 was true for the time it was taken ; but is not true after the silt wave has washed out. It is of no use for judging the system as a whole.

At 96,000 is a pumping station where, on an average, about 25 cusecs are pumped from a drain into the branch for the whole year. This accounts for part of the big drop in *f* to 0.65 in Khadir Distributary which takes the bulk of the water from the branch. The whole drop (even if we measure it from 0.80) must be due to the many causes whose relative importance is hard to assess. The Khadir Distributary must be ruled out for finding *f*.

Lalian Distributary and Khadir Distributaries are practically the continuations of the Southern Branch below the Khadir Branch offtake. The site shows the forward portion of the Southern Branch unlikely to be influenced by silt waves from the ponding up at section 3. The writer has not seen these distributaries but, judging by those already dealt with, all of which have been inspected in closure, one must expect

minors to get excess f as their crests are low (relative to the bed at site) and their wings of ancient type likely to cause turbulence. Therefore the distributaries should be expected to show f decreasing from head to tail. All the sections of Lalian except 12, 13 and 15 are good enough to give an indication of f and 11 is exact. It is clear that f starts at about 0.80 and is 0.75 in the middle and less still at the tail. The reason for the rather sudden drop to 0.75 is clear from the minors shown on a map, though, part of it may be due to small seasonal irregularities or other causes. The value 0.80 is about what could be imposed throughout by suitable minor head and outlet design. As for the Kirana Distributary, it has no minors of note before section 6 and its f there is definitely 0.81.

Mulkana minor takes off a little below section 6 and, allowing for its rather bad coefficient of 15.1 it would not be far wrong to assume it too had f of about 0.81 if a final regime reach could be found on it.

As for the other minors the fact that f_S comes less than f_R is abnormal and the reader is referred to V.

VIII. Conclusion.

This paper has been written after seven years of progressive study of the use of Lacey methods, to present those methods in a manner suitable for the canal engineer, and to remove those popular misconceptions which occur only too frequently and into which the writer has also fallen at times.

A warning is required by the would-be sceptic, that should he try to check the Lacey formulae *properly* he may disagree slightly. This is because they averaged the data of provinces and countries. Certain research officers with adequate data have found differences in the coefficients but not in the indices. The differences are small, and will not affect practice. It will be found most profitable to apply the theory and judge by results.

Finally, Mr. Lacey was not referred to about this article ; but it is believed to express his views soundly, with the exception of the $f^{1.25}$ rule, which is derived from Kennedy, neglects differentiation in silt grade, and has neither disapproval nor approval from Mr. Lacey so far ; nor does the writer claim more for it than that it seems to fit the Lower Jhelum Canal data rather well.

APPENDIX II.

TABLE COMPARING ACTUAL CHANNEL ELEMENTS WITH THOSE FOUND FROM f_s FOR VARIOUS VALUES OF (MEAN VELOCITY) $V = C\sqrt{RS}$.

	Serial No.	$C = \frac{V}{\sqrt{RS}}$	Q.	S (per 1,000).	B.	D.	A.	P.	$R = A/P$.	V.	f_R.	f_S.	S_{f_R}.	Error/Mile.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
served ..	6	16.0	217	0.16	25.0	4.0	116	36.8	3.16	1.87	0.81	0.81		
culated ..	..	..	..	**0.16**	**31.3**	**3.6**	**119**	**39.3**	**3.02**	**1.83**	..	..	**0.16**	*Nil.*
served ..	11	16.0	139	0.15	24.1	3.2	86	32.7	2.63	1.62	0.75	0.74		
culated ..	..	..	..	**0.15**	**24.0**	**3.3**	**85**	**31.4**	**2.69**	**1.64**	..	..	**0.15**	*Nil.*
served ..	16	16.0	354	0.18	40.4	4.0	169	48.3	3.49	2.10	0.92	0.92		
culated ..	..	..	..	**0.18**	**40.8**	**4.0**	**173**	**50.2**	**3.44**	**2.07**	..	..	**0.18**	*Nil.*
served ..	18	15.9	222	0.117	31.1	3.9	130	39.3	3.30	1.72	0.65	0.65		
culated ..	..	..	..	**0.117**	**30.9**	**4.0**	**131**	**39.8**	**3.28**	**1.71**	..	..	**0.117**	*Nil.*
served ..	14	15.6	23.2	0.18	6.5	2.25	19.4	12.3	1.58	1.20	0.67	0.71		
culated ..	..	..	..	**0.18**	**8.1**	**2.0**	**20.1**	**12.8**	**1.53**	**1.20**	..	..	**0.16**	**−0.19**
served ..	10	15.5	204	0.17	27.4	3.7	113	36.8	3.07	1.81	0.78	0.82		
culated ..	..	..	..	**0.17**	**30.0**	**3.5**	**113**	**38.0**	**3.08**	**1.81**	..	..	**0.155**	**−0.08**
served ..	21	16.5	144	0.106	22.7	3.6	90.0	30.6	2.94	1.60	0.64	0.61		
culated ..	..	..	..	**0.106**	**24.0**	**3.6**	**92.8**	**32.0**	**2.91**	**1.61**	..	..	**0.115**	**+0.05**
served ..	9	15.4	285	0.16	35.0	4.1	150	43.5	3.45	1.91	0.78	0.82		
culated ..	..	..	..	**0.16**	**36.0**	**3.9**	**149**	**45.0**	**3.43**	**1.92**	..	..	**0.147**	**−0.07**
served ..	7	15.3	368	0.16	34.7	4.8	176	44.6	3.95	2.08	0.81	0.85		
culated ..	..	..	..	**0.16**	**42.0**	**4.1**	**181**	**51.1**	**3.54**	**2.03**	..	..	**0.15**	**−0.06**
served ..	20	16.7	135	0.10	24.3	3.28	87.5	31.6	2.77	1.54	0.62	0.59		
culated ..	..	..	..	**0.10**	**23.0**	**3.45**	**85.4**	**30.9**	**2.76**	**1.58**	..	..	**0.108**	**+0.04**
served ..	5	15.3	423	0.17	47.0	4.1	213	59.5	3.59	1.99	0.81	0.91		
culated ..	..	..	..	**0.17**	**45.0**	**4.15**	**200**	**55**	**3 62**	**2.13**	..	..	**0.14**	**−0.15**
served ..	17	15.2	276	0.17	37.8	3.8	149	45.2	3.30	1.85	0.75	0.85		
culated ..	..	..	..	**0.17**	**38.0**	**3.8**	**143**	**44.3**	**3.22**	**1.93**	..	..	**0.15**	**−0·10**
served ..	24	15.1	31.1	0.24	8.4	2.2	24	14.6	1.64	1.:0	0.75	0·85		
culated ..	..	..	..	**0.24**	**10.0**	**2 0**	**25**	**14.9**	**1.68**	**1.24**	..	..	**·019**	**0·25**

APPENDIX I.

OBSERVATIONS OF CHANNELS IN STEADY CONDITION.

Serial No.	R. D. of channel.	Observed data.								Elements according to f_R.										
		Discharge.	Slope.	Bed width.	Depth.	Area=A.	Wetted Perimeter=P.	H. M. Depth $R=\frac{A}{P}$	Mean Velocity=V	$C=V/\sqrt{R^3 S}$.	f_R	f_S	$\sqrt{f}$ from $V=1.17\sqrt{f}\sqrt{R}$	Slope.	Mean Velocity.	Wetted Perimeter.	Area.	Hydraulic mean depth.	Depth of channel.	Bed width of channel.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
								Northern Branch.												
1	6450	1506	1/6662	104.0	5.96	632.8	120.7	5.41	2.31	14.1	.72	.95	.85	1/9499	2.43	103	620	6.02	6.77	88.2
								Southern Branch.												
2	5850	1141	1/6250	82	5.74	503 5	98.5	5.11	2.27	14.1	.74	.97	.86	1/8892	2.34	90	487	5.41	6.13	76.3
3	52650	1143	1/6250	85.6	5.16	469.08	99.3	4.72	2.44	15.9	.93	.97	.96*	1/6393	2.52	90	455	5.06	5.68	77.3
4	61000	816	1/6666	65.5	5.3	383.6	81.9	4.68	2.13	14.4	.71	.89	.84	1/9191	2.18	76	374	4.93	5.67	63.1
								Kirana Distributary.												
5	2770	413	1/5850	47	4.07	213.4	59.5	3.59	1.99	15.3	.81	.91	.90	1/6950	2.04	55	207.5	3.78	4.39	45.1
6	92000	217	1/6250	25.0	4.0	116.2	36.8	3.16	1.87	16.0	.81	.81	.90	1/6460	1.83	39.3	118.7	3.02	3.59	31.3
								Lalian Distributary'												
7	1500	368	1/6250	34.7	4.77	176.3	44.6	3.95	2.08	15.3	.81	.85	.90	1/6844	2.00	51.1	184.0	3.60	4.20	41.7
8	39500	290	1/6666	33	4.00	157.00	45.3	3.47	1.85	15.1	.72	.80	.85	1/7911	1.85	45.4	156.6	3.46	4.1	36.1
9	56500	283	1/6250	35	4.1	149.9	43.5	3.45	1.91	15.4	.78	.82	.88	1/7114	1.89	45.0	151.0	3.36	3.97	36.0
10	61000	264	1/5880	27.4	3.7	113	36.8	3.07	1.81	15.5	.78	.82	.88	1/6853	1.78	38.0	114.7	3.02	3.62	29.9
11	91000	159	1/6666	24.1	3.18	85.8	32.7	2.63	1.62	16.0	.75	.74	.86	1/7175	1.64	31.4	84.6	2.69	3.3	24.0
12	104000	121	1/6900	23.7	2.84	77.0	32.4	2.38	1.58	16.9	.78	.82	.88	1/6540	1.63	29.4	74.4	2.53	3.1	22.6
13	109000	112	1/7150	20.2	3.01	68.3	28.3	2.41	1.64	17.5	.81	.70	.90	1/5920	1.64	28.2	68.2	2.42	3.0	21.6
14	173200	23.2	1/5560	6.5	2.25	19.4	12.3	1.58	1.2	15.6	.67	.71	.82	1/6655	1.18	12.8	19.7	1.54	2.20	7.9
15	178600	8.3	1/2860	3.2	1.48	6.05	7.1	.98	1.19	17.3	1.06	.92	1.03	1/2895	1.16	7.7	7.15	.93	1.34	4.7
								Khadir Branch.												
16	38000	354	1/5479	40.35	4.01	168.59	48.26	3.49	2.10	16.0	.92	.92	.958	1/5647	2.07	50.2	172.7	3.44	4.03	40.8
17	99000	276	1/5970	37.77	3.83	149.36	45.23	3.30	1.85	15.2	.75	.85	.866	1/7435	1.847	44.3	149.2	3.37	3.99	35.4
								Khadir Distributary.												
18	18000	252	1/8511	31.13	3.87	129.54	39.25	3.30	1.72	15.9	.65	.65	.806	1/9601	1.768	39.8	130.5	3.28	3.97	30.9
19	87000	176	1/6579	31.66	3.33	113.05	39.15	2.89	1.55	14.3	.61	.78	.780	1/9642	1.605	35.35	109.2	3.09	3.81	26.8
20	121000	135	1/10000	24.26	3.28	87.54	31.57	2.77	1.54	16.7	.62	.59	.789	1/9826	1.547	30.9	86.9	2.81	3.60	22.3
21	143100	144	1/9389	22.68	3.61	89.98	30.61	2.94	1.60	16.5	.64	.61	.801	1/9747	1.581	32.0	91.3	2.86	3.53	23.1
22	204000	65.5	1/10000	14.10	2.75	46.41	21.67	2.14	1.41	18.4	.68	.55	.826	1/7343	1.415	21.6	46.3	2.14	2.76	17.4
23	261060	13.7	1/5000	4.50	1.72	11.53	9.63	1.20	1.19	21.2	.80	.70	.929	1/4339	1.179	9.9	11.6	1.16	1.61	6.4
								Malkana Minor												
24	1500	31.1	1/4170	8.4	2.2	24.0	14.6	1.64	1.30	15.1	.75	.85	.87	1/5760	1.29	14.9	24.1	1.62	2.17	10.0
25	5000	30.0	1/3640	8.5	2.2	22.5	13.9	1.62	1.33	14.8	.81	.91	.90	1/5250	1.31	14.6	22.9	1.57	2.09	9.9
								Kandi Minor.												
26	600	19.4	1/3120	8.5	1.46	14.3	12.4	1.16	1.35	18.0	1.15	.95	1.07	1/2940	1.38	11.7	14.1	1.20	1.57	8.2
27	2000	11.7	1/2740	7.9	1.10	9.6	10.9	0.88	1.22	18.5	1.23	1.00	1.11	1/2490	1.29	9.2	9.1	.99	1.32	6.2
28	3500	7.7	1/2780	5.7	1.05	7.1	8.9	0.79	1.08	17.6	1.08	.94	1.04	1/2590	1.16	7.4	6.7	.90	1.29	4.5
								Mangni Minor.												
29	1500	10.61	1/2630	6.2	1.23	8.4	9.2	0.92	1.26	18.5	1.24	.98	1.12	1/2400	1.28	8.7	8.3	.95	1.29	5.8
30	8500	6.78	1/2130	3.7	1.2	5.5	6.7	0.82	1.23	18.0	1.37	1.05	1.17	1/2000	1.22	6.99	5.5	.78	1.05	4.75

* At this site supply is headed up for regulation, causing deposit of coarse silt. Hence value of $\sqrt{f}$ is high.

DISCUSSION.

The **author** pointed to certain corrections in the paper and remarked that no introduction was required as everything he had to say was contained in the paper.

Mr. **R. K. Khanna** wondered how many people who had studied Mr. Blench's paper carefully, as he had certainly done, could confidently undertake to design an irrigation channel based on Mr. Blench's exposition of the Lacey Theory. Without fear of losing his bet, he felt that he could safely bet against anyone, including Mr. Blench, to say what exactly was meant by initial and final regime, and whether a channel which had been running satisfactorily for, say, twenty or forty years, would be entitled to be considered to have attained final regime. Another enigma of the Lacey theory was 'f'. Of course, as Mr. Blench had stated, the physical meaning of 'f' was not known. But he must be a bold man who, after studying Mr. Blench's paper most thoroughly, could say that he knew something about 'f', or that he could even approximately assume a value of 'f' for designing a channel. Mr. Blench had laid down complete knowledge of the Lacey Theory, as an essential qualification for a would-be designer of irrigation channels. But was there anyone except Mr. Lacey himself and possibly Mr. Blench also in possession of that complete knowledge? He asked if Mr. Blench himself, after seven years of progressive study of the use of Lacey methods, was prepared to design a set of channels by these methods. At least uptil the last year, when he presented his paper on the Lacey Slope Formula, Mr. Blench had not been able to discover many existing channels which satisfied Lacey formulae.

Mr. Blench had discussed four principal formulae of the Lacey Theory in his paper. The author of the paper considered the formula No. 1 to be the mathematical test or the 'criterion' for final regime. But the author of the theory, Mr. Lacey, as would appear from his remarks on page 193 of the 'Indian Engineering' for December 1935, claimed that it was a general velocity formula of the type of the speaker's general velocity formula, *viz.*, $V = 13 \cdot 07\ R^{\cdot 58} \times S^{\cdot}$ for computation of velocities of flow in all alluvial channels without reference to initial or final regime. Mr. Khanna asked whether the author was expected to know more about the formula than its exponent? As both of them were there, the exact significance of this formula would be explained

The second formula of Mr. Lacey, *viz.*, $P = 2 \cdot 67\ Q^{0 \cdot 5}$ applied, according to Mr. Blench, to initial regime, and obviously it must apply

in the limit when final regime had been attained. Mr. Khanna believed that channels which had been running satisfactorily for a number of years could be taken to be at least in initial regime, even though they might not have attained the dignity of final regime as prescribed by the test of the application of the first formula. As mentioned in his pamphlet "Energy Theory of Flow of Water," Bhatinda Branch of the Sirhind Canal, in its last eleven miles below Teona fall and its three distributaries, Teona, Lambi, and Lalbhai, had been running satisfactorily for years; so these might be taken to be at least in an initial regime. And yet their wetted perimeters were $2{\cdot}4\ Q^{0{\cdot}5}$, $2{\cdot}9\ Q^{0{\cdot}5}$, $2{\cdot}3Q^{0{\cdot}5}$ and $2{\cdot}6\ Q^{0{\cdot}5}$ respectively. Not one of them had $P=2{\cdot}67Q^{0{\cdot}5}$. The first and second formulae of Mr. Lacey were obviously interdependent. So if the first formula was prescribed as the test of regime, and it was claimed that the wetted perimeter for channels in regime must be $2{\cdot}67\ Q^{0{\cdot}5}$, then they were only moving in a circle.

The third formula of Mr. Lacey, *viz.*, $V=1{\cdot}17\sqrt{fR}$ was also discussed by the speaker in the "Energy Theory of Flow of Water." It would be sufficient to point out that with 'f' as unit corresponding to Kutter's $N=0{\cdot}0225$ the velocities worked out by the Lacey formula were 10 to 15 per cent. more than those worked out from the Chezy formula with Kutter's co-efficients.

The fourth formula of Mr. Lacey, *viz.*, $S=\frac{f^{5/3}}{1788Q^{1/6}}$, was the only one recommended by Mr. Blench for working out the values of 'f' obviously because 'f' would undergo the least variations with variations in Q and S. On the basis of this reasoning the most suitable formula for working out the values of 'f' would be one in which 'f' would remain constant for all the variations of Q and S.

Mr. Khanna confessed that in spite of his best efforts he had not quite been able to grasp the application of these formulae to remodelling, or the rules, etc., for remodelling proposed by Mr. Blench. Possibly nothing less than seven years' progressive study of the use of Lacey methods, would enable one to understand or apply the fifteen rules and instructions of Mr. Blench. But it was doubtful if many Irrrigation Engineers had the youthful spirits of Mr. Blench for the study of Lacey methods, or his patience for abstruse scientific study, which after seven years of strenuous research had left Mr. Blench still groping for the meaning or application of Lacey's 'f'. As for the actual application of Lacey methods to the solution of irrigation problems, one might, according to an Indian proverb, as well prescribe sparrow's milk for a sick person, as strive to discover the correct values of 'f' for any set of channels. The test of final regime of any channel was whether Lacey's formula No. 1 would hold, and not whether a channel had

been in steady regime for any length of time; perhaps not a single channel existed in the world which would satisfy the essential condition of finality of regime. And when the standard of reference was non-existant, no one could design after the imaginary model of a perfect Lacey channel.

Continuing Mr. Khanna stated that it had been suggested to him that in these days of advancement of science one must go into the root of the matter and the function of silt in flowing water, and that if the ordinary views as expressed by him based on simple observational facts were to be accepted, all the hydraulic laboratories of the world might as well be closed down. Mr. Khanna remarked that the time was soon coming when they would be faced with the choice of closing down either the canals, or the hydraulic laboratories because if this super-scientific investigation about the silt particle went on they would soon forget how to design any artificial channel at all.

Dr. **N. K. Bose**, congratulated Mr. Blench on such a clever and beautiful annotation of Mr. Lacey. In some places, he was afraid, he had conveyed too much significance into certain relationships which Mr. Lacey himself had never dreamed that they could convey. As an instance Mr. Bose cited Mr. Blench's way of labelling different relationships of Mr. Lacey as belonging to initial regime or final regime. Mr. Blench had given no indication of how he arrived at this.

Before the speaker discussed the four individual formulae quoted by Mr. Blench he made a general statement about empirical relationships :—

Empirical relationships would not stand the usual operations of mathematics such as elimination, differentiation and other similar operations that could be safely performed on relationships derived from strict theoretical considerations only. Lack of appreciation of this draw-back of empirical relationships had led very often to unnecessary complication. Of the four formulae of Mr. Lacey put forth by Mr. Blench in his paper (paragraph 5) as being all that were required for remodelling, the formulae (2) and (3) were direct, *i.e.*, could be and had been derived from observational data. These were

$$P \propto Q^{\frac{1}{2}}$$

and

$$V \propto R^{\frac{1}{2}}.$$

The speaker purposely refrained from putting in the constants of these formulae as they were certainly different from what Mr. Lacey had given.

The other two relations (1) and (4) were derived relations and consequently suffered from the draw-backs which all relations derived from empirical ones were subject to.

The formula (1), $V=16\sqrt[3]{R^2S}$ which Mr. Blench called the *relation* had been derived by Mr. Lacey from two empirical relations of which one was given above $V=C'\sqrt{R}$ and which was the same as the Chezy one $V=c\sqrt{RS}$ and the other was $V=K R^{\frac{3}{4}}S^{\frac{1}{2}}$ which was given by Hermanek about 1908 to hold good for depths varying between 1·5m to 6m.

This derived relation was fundamentally wrong and if compared with the data collected in the Research Institute, it was not the relation of best fit. The Regression Equation of best fit as pointed out by Dr. Bose in the introduction of his paper 192 was

$$\frac{V}{\sqrt{R}}=2\cdot5\times S^{1/10}$$

Relation (4) was also a derived relation as was pointed out by Dr. Bose the previous year in the discussion on Mr. Blench's paper No. 184.

So that of the four formulae put forth by Mr. Blench only one is sound $P=2\cdot68\,Q$. The relation (1) was definitely incorrect and relations (3) and (4) suffered from the presence of 'f'.

Mr. Blench had said that the two 'f's given by (3) and (4) approached each other when the constant in (1) also approached 16. This was to be expected as the formula (1) could be derived from relation (3) and (4), as he had shown last year in his discussion of Mr. Blench's paper No. 184.

Mr. Blench's contention that 'f' distributed equally between the parent and the off-take was not correct. Seven sites had been observed on the Jhang Branch and its distributaries near about Kot Khudayar. The values of 'f' as calculated from Lacey's formula :—

$$S=370\cdot68\times10^{-6}\ f^{3/2}\ R$$

for these sites are given here.

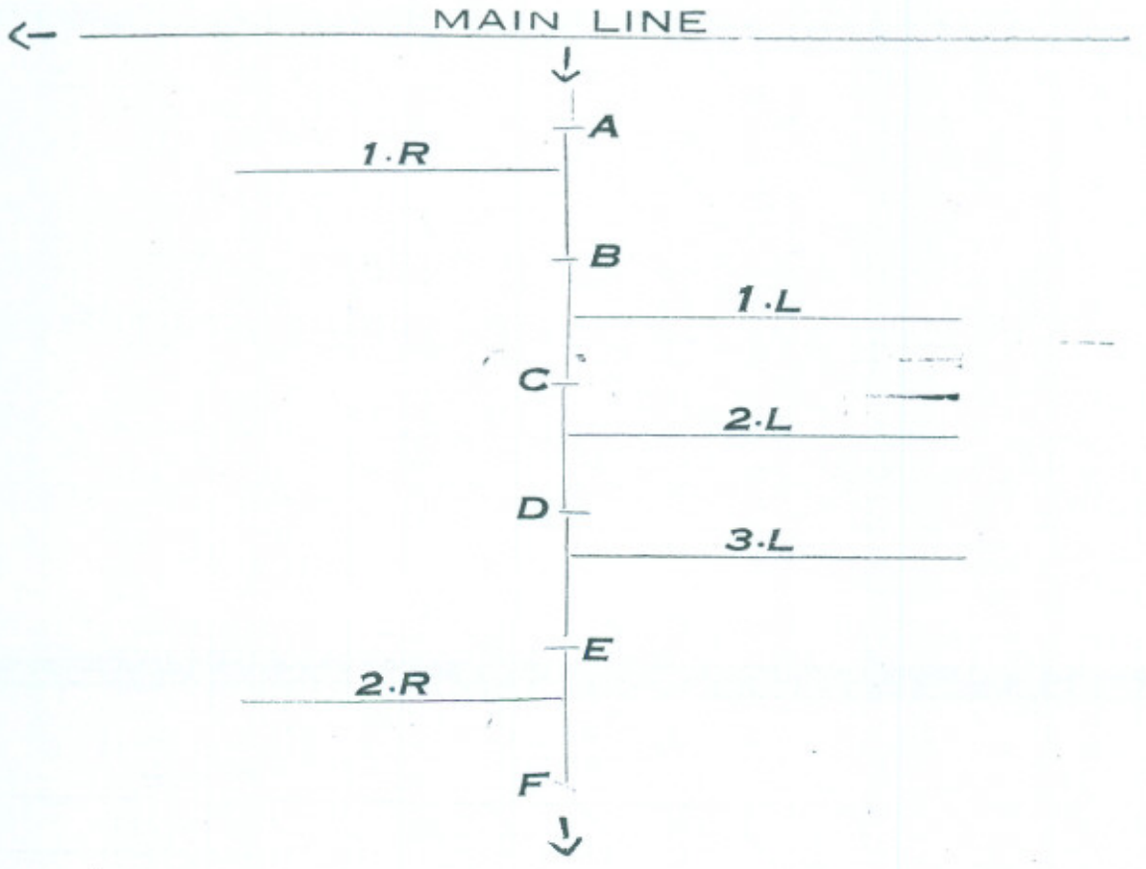
Channels.	Jhang Branch.	Chiniot Distributary.	Sarangwala Distributary.	Gugiana Distributary.	Jamal Distributary.	Jatti Khai Distributary.	Nasrana Distributary.
f.	1·09	1 39	·87	·73	·82	·74	·63

These did not show any sign of equality.

Mr. **G. L. Bhandari** congratulated Mr. Blench on his lucid exposition of Lacey's formulae for channels in equilibrium. Most of the defects in remodelling based on existing or arbitrary slopes were due to a want of study of the 'f' of the channels or the silt distribution on the canal and how it was going to be effected by an alteration in the type of the outlets and head regulators. Mr. Blench's notes would be of considerable help in designing channels on a more scientific basis.

Mr. Bhandari stated that he had made a study of regime channels in his charge. The results of observations were given in Appendix III. There was one point on which he would ask for further information. Having determined the 'f' of a parent channel, the question arose whether the off-takes from the same should be designed with the same value of 'f' and whether it was possible at, say, a bifurcation to obtain the same 'f' in the two branches as had been fixed for the parent.

The following observations abstracted from Appendix III would show that the above might not be possible.



	Discharge in cusecs	'f'
Parent at A	456	0.73
1 R.	153	0.83
Parent at B	292	0.81
1 L	10	0.85
Parent at C	250	0.78
2 L	10	0.89
Parent at D	225	0.77
3 L	65	0.94
Parent at E	145	0.76
2 R	34	0.82
Parent at F	80	0.68

Continuing the discussion Mr. Bhandari said that it would be noticed that the 'f' of 1 R and the 'f' of the parent at B were practically equal; but they were much more than the 'f' of the parent at A. There was a Gibb's wall built at the head of 1 R and it was clear that it was working very efficiently as a proportional silt distributor, provided the quality of the 'f' of the off-take and the 'f' of the parent below the off-take was accepted as a correct indication in that direction. Any attempt to reduce the 'f' of 1 R to 0.73 would mean an increase in the 'f' at B. Lower down the off-takes took more than their proportional share of silt and that accounted for the gradual drop in 'f' along points C, D, E. & F. Mr. Bhandari asked the author if he would proceed to design the two branches at the first bifurcation with the same 'f' or if he would modify this 'f' in proportion to the reduced discharges of branches or briefly whether 'f' varied directly with Q and if so in what manner. Mr. Lacey had not dealt with this aspect of 'f' in his papers before the Institution of Civil Engineers. According to Mr. Bhandari, it was simpler to work out 'f' from the formula $f = \sqrt{\frac{V\,S\%_{\circ}}{0{\cdot}4476}}$ instead of the formula $S = f^{\frac{5}{3}} / 1788\ Q^{\frac{1}{6}}$. Both gave the same results.

Mr. **A. R. Sethi** agreed with Mr. Blench that correct levelling was very necessary for all Irrigation works. He said that he happened to be in charge of the Sub-Division where Mr. Blench had done some remodelling of channels. He found by actual levelling that on one of the channels, *viz.*, 1R/2R/10R the crests of outlets although checked after construction by the sub-divisional officer were mostly wrong, differences varying from 0·04 to 0·47 ft.

He referred to page 8 of the paper where the author had quoted the case of a 13-cusec minor under the heading 'interfering with a satisfactory change.' Mr. Blench was possibly referring to 1L/2R/10R as that was the only channel so designed in accordance with Lacey's formula. If so, it would be interesting for the members of the Congress to know that

in October 1935, the channel was found to be badly silted up, leaving a working head of 0·3′ only and getting a shortage of 40 p. c. at its tail. In fact the tail of this minor suffered the maximum shortage in the Sub-Division.

Mr. **Sardari Lal Malhotra** congratulated the author for writing a clear and painstaking paper on a subject of vital importance to engineers. The methods of applying the valuable Lacey formulae had been lucidly described by the author, and remodelling of the channels to stable conditions had been made fairly easy. He, however, requested the author to elucidate some of the points in detail.

The author had stated that the formula No. (2) was true in the case of initial regime. As Q of a channel was fixed, from this formula it followed that P was fixed. The channel in initial regime had been described by the author as one having attained its section but still in the process of attaining the final slope. The presumption was that the channel was meant to be still steepening its slope, and consequently decreasing the sectional area. With a constant perimeter, the channel could only decrease its sectional area by silting the bed and scouring the sides. He asked if he was correct in assuming that after a channel had attained initial regime it would continue to retain a fixed wetted perimeter, but would alter its slope, sectional area and velocity in the process of attaining the final regime, which was indicated by formula No. (1).

If a channel answered correctly to discharge perimeter relation No. (2) and also to the silt factor formula No. (3), was it not in final regime? It should evidently be in final regime, its P & R were both fixed then. It must then also answer to the formula No. (1) for final regime.

The author had stated that 'f's' should be equally distributed all over the circle. This did not appear to be necessary to Mr. Malhotra as ' f ' is dependent on the silt content and grade, which could be varied in channels with different commands. It was possible to pass more silt into a channel with good command, outlets on which could dispose off the portion allotted to them.

It appeared that in a big major distributary which was in regime, the value of ' f ' at its head could be easily adopted for the whole system.

In the Western Jamna Canal, especially on off-takes of Sirsa Branch there were old barrel outlets which were even below the silted beds of channels. The intensity on these channels was only 33 p.c. being half that on the colony canals. These channels had run for years, and in most reaches appeared to be in regime. As the channels, however, were very long comparatively due to low intensity, they were subjected to many disturbing factors, and tails in many cases suffered shortages. The shortages could, to a large extent, be attributed to the barrel outlets and moduling of outlets appeared to be necessary. In replacing these barrel outlets by A. P. M.'s and O. F.'s the crests had to be kept

practically at the silted bed levels but this was not always possible. He asked the author to suggest a suitable value of 'f' for such cases. Should it be a little higher than that prevailing at present or coincident with that? It appeared impossible to devise a modular outlet, with silt-suction power of that of a barrel, and moduling of outlets and raising their crests were bound to upset the existing silt contents and regime of the channels.

The silt sucking power of the outlets appeared to be an important factor in the stable working of a channel, and if regime was to be maintained outlet-crests should be left undisturbed.

The author had stated that after altering a Head Regulator of a Division a channel in the head reach should be remodelled to new 'f' and if it succeeded, the same 'f' could be used for other channels. What period did the author fix for determining whether 'f' allowed was correct? It would take some time before a channel would deviate to an objectionable extent from designed data, requiring alteration and rectification.

He asked about the procedure to be followed in raising supply for improving command. The system followed was that the masonry work should be raised, while off-takes upstream should be left undisturbed till the effect of this change on the channel had been determined. At the tail of Habri Distributary of Sirsa Branch the working head on both the off-takes was ·12′ only. The 'f' at tail was 1·12 and that of the bigger off-take was 1·2 in the head reach. The section of the off-take seemed to be a regime one. What procedure did the author suggest for this channel? He asked if the existing value of 'f' of off-take, *i.e.*, 1·2 was to be adhered to, or if it was to be reduced to 1·12.

Mr. **Downing** asked the author to explain exactly how he determined the true velocities against which he compared those recorded by the current metres.

Mr. **C. C. Inglis** in a written communication congratulated the author on his very excellent and timely paper. As he was on his way home on furlough he could not produce confirmatory data, but he would say that he had arrived at very much the same conclusions as a result of studying Sind data about 40 p.c. of which had agreed very exactly with Lacey formulae; while the data, taken as a whole, also had agreed and in the case of individual channels known to him personally all those which had not agreed were not in final regime for definite reasons. He was in complete agreement with the author's insistence on the value of the Lacey formulae for analyzing the condition of canal systems; and was satisfied that in time, working from the final regime of Lacey formulae, it would be possible to understand and allow for variations from regime. He did not think, however, that the stage was yet reached where silt charge could be taken into account—see variation in silt

charge from 170 to 475 grams in two successive observations in Experiment 3, quoted in App. IV of Pandit Sharma's paper 189. As regards the big drop in 'f' from 0·92 to 0·65 from Khadir Branch to Khadir Distributary, he suggested that this was probably not due to dilution but to the water added being alkaline, which would lead to dispersion and a drop in viscosity.

Mr. Inglis cited two cases as an addition to "Errors" to the Author's list :—

(*i*) A channel was constructed according to the Kennedy formula to pass 530 cusecs. It was 7 feet deep at the head and gradually decreased to 5 ft., the channel being made gradually wider to compensate for the reduction in depth. It never gave its designed discharge and had silted continuously. It had been redesigned with almost the same slope, but of the correct shape according to Lacey.

(*ii*) A canal with a discharge of about 2,600 cusecs was remodelled, the sides being 'bushed' to reduce the width, to save cost of bank raising; the idea being that the bed would scour and that shape did not matter. At the same time, the head, which had originally drawn clear water from the outside of a river bend, was remodelled so that it drew water from a straightened channel at right angles. Before remodelling there was a drop of 2'·6" into the Canal. It, however, rapidly silted to a new slope, until the head became drowned and the discharge decreased. As a result of model experiments at Khadakwasla, an approach channel was constructed from the nearest upstream concave bend in the river and the canal allowed to scour its sides. The drop into the canal when he last heard was 1'·6"; but the heavy silt had, of course, been washed down the canal, which had necessitated raising the banks at considerable cost. This was an extreme case of what the author calls "interfering with a satisfactory channel." It could not be too strongly emphasized that remodelling unless carried out on scientific lines was a dangerous expedient, which might lead to trouble and expense for years. The author's point that silt excluded from one channel must be accommodated elsewhere was also very important but Mr. Inglis was of opinion that the attrition of bed silt is appreciable and goes far towards neutralizing the rise in 'f' due to losses.

Mr. **Gerald Lacey** remarked that Mr. Blench was to be congratulated on a very useful practical paper. Mr. Blench had said that it would be found profitable to apply the theory and judge by the results. There was no doubt that the most useful formula to apply was that connecting the slope with the discharge. The slope was the average over a long reach and there was only a small error, and that constant, in the discharge, if any error existed.

So long as the wetted perimeter was given even approximately by equation (2), equation (4) would be found very reliable as a means of calculating the value of 'f', the silt factor.

The difficulty in calculating the silt factor, either from values of V and R, or from values of R and S, arose from the fact that V and R as a fact varied throughout the reach, and one cross section was not always sufficient to characterize it.

When Mr. Blench stated that the physical meaning of the silt factor was unknown, he was not entirely correct. To begin with the silt factor was proportional to V^2/R, which was a proportional to V^2/gR, the dimensionless Froude number, and a criterion of dynamic similarity.

He, the speaker, had found that on Kennedy's channels where the silt was all of the same order, coarse silt, the Froude number was practically constant. Similarly on the Madras Canals, where the silt was all of the same order, fine silt, the Froude number was again a constant but smaller owing to the silt being finer.

It was clear that the ratio V^2/R was a criterion of regime, and also that it was a function of the silt grade. For that reason it was called a silt factor.

Dr. Bose's paper had shown that the silt factor was not directly connected with the diameter of the silt particle. That was because the temperature was involved, and also the mix. A fine silt with a mix that involved much internal friction in the boundary layer might give the same value of V^2/R as a coarser silt more freely moving. That meant effectively that the silt factor as a means of rigidly computing the diameter of silt particle was not of great use. On an existing system, however, when the construction of a new channel was contemplated it was more useful to know the ratio V^2/R from the existing regime channels and proceed to construct new channels dynamically similar.

Tchikoff had shown that if the energy of flow diagrams were drawn, substituting the hydraulic mean depth R for the vertical depth D, the velocity head in all channels with the same silt factor, bore a constant ratio to the hydraulic mean depth of flow. In other words the energy of flow diagrams for all channels with the same silt factor, were similar. The silt factor was clearly a criterion of dynamic similarity. It was clear also that with increase in the numerical value of the silt factor fine silt would be replaced by coarse silt, coarse sand by shingle, and shingle by boulders.

If two channels carried silt of different grades and both were in regime there could be no rigid dynamic similarity. The small channel in coarse silt for example was not a true model of the larger channel in fine silt. The wetted perimeter relationship however persisted and that had also a physical significance.

Thus writing—

$$P \propto Q^{\frac{1}{2}}$$
$$P^2 \propto PRV$$
$$P/RV = \text{a constant.}$$

The product RV was clearly 'q' the hydraulic discharge per foot run. Hence in all regime channels q/P=a constant.

In other words *the discharge per foot run* was a constant, and the scalar discharge was rigidly maintained. Effectively that means that if it was desired to construct a model and the material employed was very different from that in the prototype the only thing that could be done was to maintain the scalar discharge, and thus *model* the discharge.

Mr. **Blench** in reply referred Mr. Khanna to a more careful reading of his paper, and a study of Mr. Lacey's original papers. Whatever interpretation Mr. Khanna might have put on the alleged remarks in Indian Engineering, the papers read in the Institute of Civil Engineers stood as facts. It did not seem justifiable to say a theory was difficult because it took time to study at first. New theories had to be studied from all angles. After acceptance they were put into a standard form and became easier. Of course, a work based on enlarged knowledge required more training on the part of the applicant.

Mr. Bhandari's support was much appreciated. The "analysis of regime channel" was on the right lines. It required criticism only in detail, *e.g.*, it would be more logical to average cols : 11 and 13, so that S would not appear in one result although appearing in the other ; and some of the sections appeared to be rather a lot off the final regime. This criticism was meant to be helpful. Actually Mr. Bhandari had got a clear idea of his channels' behaviour by making a first approximation at a large number of sites, not all perfect ; and obviously he had got all that was required to allow him to remodel soundly. His averaging of f's raises an interesting theoretical point, not published before. If a channel of well-silted bed had hard irregular sides these would cause turbulence which would lift from the bed some silt that would otherwise be rolling, and make a smaller velocity adequate. This meant that such a channel would have a smaller 'f' from col : 13 than from col. 11. In such cases the averaging of the f's was reasonable. But in a section utterly off regime it was doubtful if an average would have a meaning.

To Mr. Blench it appeared that 12L had minors which got a bit more than normal 'f' and this countered the effect of absorption, and possibly direct outlets that got less. The result was a channel with quite uniform 'f' throughout.

Regarding the query about points A and B a study of the site and its history would probably explain matters. As for equal distribution of 'f' this was dealt with in the Author's section IV. There was no objection to putting excess 'f' into an off-take that could stand it, as explained in IV, it was best to have 'f' normally a little excess in off-takes to counter the effect of absorption and other offtakes that might take less. This was excellently illustrated by Mr. Bhandari's own analysis.

The author observed that Mr. Sethi's remarks on 1L/2R/10R were based on a very cursory reading of the author's Section III para. 2. That

para. reads " A 13-cusec minor had silted till it occasionally drowned its head. This (remodelling) put it back to its previous condition and it has been satisfactory since, just on the point of drowning out. It may drown occasionally as some of the outlets are a bit high."

The channel was improved to the best possible, and had done exactly what the author said it would. Mr. Sethi might with advantage study the Lacey slope formula and he would see that once drowning had occurred the discharge dropped and the regime slope increased rapidly (for such a small discharge). Had he known this he would have silt cleared as soon as necessity arose, and saved work and money.

The remarks on 1L/2R/10R were not understood. The channel had nothing to do with the paper. The author did not get remodelling done on it ; but finished off a bit of a complete remodelling of which he utterly disapproved, and only checked a few of the outlets. He asked if the sub-divisional officer referred to by Mr. Sethi was the author and if so, did Mr. Sethi recheck alone ?

The author in replying to the points raised by Mr. Malhotra said that in the attaining of final regime the channel would go through the changes decided by the initial condition, and it might require some help. Thus if a channel was made originally much too wide it would tend to become irregular and would need training. Mr. Malhotra's difficulty seemed mathematical, to which the reply was that P being known from Q in (2), R was known from (3) *if V was known*. But V passed through various values in the attainment of final regime, so there was a different R for each condition, and consequently a different shape. Mr. Blench agreed with Mr. Malhotra that there might be reasons for not distributing 'f' equally, *vide* Sect. II/1 which laid down that it should be distributed fairly, the meaning being clear from the context. Regarding the channels on the Western Jumna which were so troublesome with being almost drowned out, the author suggested that the ' f 's found from sites should be used, keeping the old low pipes with flumes built in the watercourses *vide* Section V. It was to be expected that ' f ' would decrease from head to tail of distributaries with the present outlets. If sufficient head was not available for W. C. flumes, then matters might be left alone, except for change in barrel size. A detailed answer could only be given after analyzing according to Section II/2. The author advised silt exclusion at headworks if the whole system was troublesome.

The answer to the query as to how long to wait to see if a new ' f ' had occurred, after a change of head regulator, was one full silting season for distributaries. As for the query about the tail bifurcation (into two minors) the author asked if Mr. Malhotra was sure of ' f ' and if he quite understood that ' f ' could be altered without a change of head design. With both offtakes almost drowned out one cannot be improved without making the other worse. He suggested that one of them might be made the continuation of the parent, without any head at all.

Regarding the procedure in raising levels in big channels Mr. Blench said that if the channel is steeper than final regime (due to being in cutting) raising at falls would not work for upstream *vide* Sec. II/2 second part of (xiv). If one were sure that the rise would occur, then it was often best to leave offtakes in the reach affected till the rise occurred, but there were few circumstances where a little ingenuity would not make it possible to devise temporary offtake arrangements.

Replying to Mr. Downing the author remarked that originally the base for " true velocity " was a $2\frac{1}{2}$-year average discharge table of a meter flume, based on current meter observations. This table could not be expected to be true but it gave a steady origin for recording deviations of daily discharges. As it was, for the changes of deviation that were investigated, the absolute position of the origin was immaterial. The underlying assumption was that one gauge on a meter flume meant one discharge, and it could be proved that this was correct to very fine limits. The data had been given to the Research Institute.

The author considered Mr. Inglis's support as gratifying. The point about Khadir Distributary would be worthy of test by the Research Institute, although dimensional analysis suggested that 'f' from the slope formula varied as V, for the " viscosity " of turbulent flow was not that for viscous flow necessarily. Silt attrition might be tested in a laboratory. According to the author's recollections the matter had been mentioned before the Central Board of Irrigation.

Dr. Bose's comments required in the main, a mathematical reply. But his general remarks that too much significance had been given to Mr. Lacey's relations was to be decided by Mr. Lacey. The reasons for formulae and their significance were not given as the paper was essentially practical. The author denied Dr. Bose's statement that empirical relations would not stand the operations of mathematics. A constant did not cease to be a constant because it was derived empirically. If Dr. Bose was thinking of " constants " such as occur in the Chezy formula, and were not constants, then he was right. Also if he was thinking of operations involving other variables than those used in deriving empirical relations, he was again right. Thus Lacey's constants contain viscosity, and it would be wrong to differentiate with respect to viscosity, and expect zero answer. But any operations involving the variables of observation only were legitimate. The whole of physics was based on empiricism. In support of this the author cited the theory of gravitation, or of electricity. The point was illustrated from Dr. Bose's own paper. Using his (which is really Lacey's) equ., (3) in its other form $P/R=7.12V$, and eliminating his K from his Equations (1) and (2) the " Bose regime test formula "

$$V=52500\ RS^{\frac{2}{3}} \quad \ldots.(4)$$

would be obtained. But Dr. Bose stated that he had found that $V=2.5R^{\frac{1}{2}}\ S^{\frac{1}{10}}$ ....(5) and denied that one should accept (4).

substituting K_1 for K in his formula (1) and K_2 for K in formula (2), P would be known from (3) for any given Q. One could find S and K. from (1) ; R. S. and K_2 (not P, which is known) from (2). His (5) contained V, R, S, of which V was not an unknown because it could be determined from Q=VRP. Thus a relation was obtained between R, S, K_1 and K_2. According to Dr. Bose $K_1=K_2=K$ and it could be told from the silt curves, that K was no longer an unknown. There were thus three equations (1), (2) and (5) between two unknown R, S, and any two would in general give different values than any other two. This might be viewed in another way, using K_1 as determined from observation on silt curves ; then there would be three equations for the three unknown R, S and K_2 , so K_2 would have a value different from K_1 which was against Dr. Bose's theory. Stated mathematically his equations (1), (2), (3) were adequate for a full solution, so the introduction of (5) without adding to the number of variables produced indeterminateness.

Regarding the Lacey Regime Test Formula being " derived ", it was only historically so. Having arrived at the fact that such a formula should hold, it was tested (*vide* I. C. E. paper 4893 Fig. IV)- against 188 observations for velocities ranging upto 16.2 feet/sec., and for a range of bed silt from the finest imaginable up to shingle and boulders. Had the subject been approached from dimensional considerations this would have been one of the first formulae tested and the fundamental slope relation would then have been " derived".

A brief dimensional analysis would set the matter on a firm theoretical footing, and place alternative Regime Test Formulae in their proper perspective.

If a channel formed itself finally in its own silt the two non-dimensional quantities S, the slope and P/R the shape would depend on V R, D, p. g. and be of the form $\Sigma p.V^a R^b P^d g^e = c$ .....(a).

Equating indices of M, L, T on each side (dimensions of V) are L^2T^{-1}) and reducing the form (*a*) becomes $p\left(\frac{V}{RV}\right)^c\left(\frac{gR}{V^2}\right)^e$ .....(b)

Now $\frac{V^2}{gR}$ was the Froude number of ship model experiments and $\frac{VR}{V}$ was the classical Reynold's number. But $\frac{V^2}{gR}$ was by the Lacey fundamental formula, proportional to 'f'. This was the inner meaning of 'f ' from this point of view— proportional to the Froude number. How it could be linked with silt did not matter, but it was interesting to note that the Froude number was proportional to the ratio of kinetic energy of flow to pressure plus potential energy, and it was the K. E. which moved the silt, so it was not surprising that

experience had shown 'f' to be a physical constant of what was generally understood as "silt content."

Putting P/R of the form (*b*) one would expect experiment to show a relation between P, R, and V, of the form.

$$P/R = p\left(\frac{v}{RV}\right)^c \left(\frac{gR}{V^2}\right)^e \quad \ldots\ldots\ldots(c)$$

The experiment had shown that

$$P = 2\tfrac{2}{3}\, Q^{1/2} \quad \ldots\ldots\ldots\ldots(d)$$

Squaring each side and dividing by A, (d) would become

$$P/R = 7.12V \quad \ldots\ldots\ldots\ldots(d')$$

which meant that $c = e = -1/3$ and the true form of (*d'*) was

$$P/R = \frac{\text{const} \times V}{\sqrt[3]{vg}} \quad \ldots\ldots\ldots\ldots(e)$$

Now using the form (*b*) to get a slope formula one would expect relation of the form

$$S = p\left(\frac{v}{RV}\right)^c \left(\frac{gR}{V^2}\right)^e \quad \ldots\ldots\ldots\ldots(f)$$

But experiment had shown that

$$V = 16\sqrt[3]{R^2S} \qquad \text{or} \qquad S \propto \frac{V^3}{R^2} \quad \ldots\ldots(g)$$

Putting in the value of the indices that satisfy this relation,

$$S = \text{const.}\,(V^2/gR)^{\frac{5}{3}} \left(\frac{VR}{v}\right)^{-} \quad \ldots\ldots(h)$$

And as $VR \propto P \propto Q^{\frac{1}{2}}$ this would give the S, Q formula

$$S \propto {}^{5}/Q^{\frac{1}{6}} \text{ since } f \propto V^2/R \quad \ldots\ldots(h^1)$$

Working back to find the nature of the constant in $V = 16\sqrt[3]{R^2S}$ the real formula would be $V = k(g^{\frac{5}{9}}\, v)\ \sqrt[3]{R^2S} \quad \ldots\ldots(i)$

Thus it was evident that if Lacey had approached his subject from the dimensional viewpoint he would have almost certainly investigated the Froude number, and found his V, F, R, relation as before, and then discovered his P, Q, and Regime Test Formulae, neither of which contain 'f'. Having established these the slope formulae containing 'f' would have followed by simple algebra. This was the line of approach that would appeal to the mathematical physics. That the theory was treated differently gave all the more credit to the physical insight of the author, and the accuracy of his work.

With the above theory it was now possible to test the Bose and Khanna Regime Test formulae. In Dr. Bose's $V=2.5R^{\frac{1}{2}} S^{\frac{1}{10}}$, assuming it to be correct, Mr. Blench put in the value of indices in (f) that would satisfy it, and got for (h), $S \propto f^5$ which was hopelessly against facts. Next Mr. Blench tried $V=52{,}500\ RS^{\frac{4}{3}}$, as got by eliminating K from Dr. Bose' Congress Paper Equations. This would lead to $S \propto f^{\frac{1}{2}}/Q^{\frac{1}{8}}$ which was also sadly different from experiment. In the same way Khanna's $V=13.07R^{0.58}\ S^{0.3}$ would lead to $S \propto f^{1.75}/Q^{0.09}$ Here the index of 'f' was not bad ; but that of Q indicated that, for the same 'f', channel slopes decreased with increase of discharge at about half the rate one found in practice. This was particularly interesting because, in those works of Mr. Khanna read by the author, it was found that he derived his results incorrectly, but was always rather successful in getting formulae that did not differ greatly in form from common ones used by Mr. Lacey, or in older practice. The acid test of deriving other formulae from them on dimensional principles exposed their essentially unsound derivation. It might be this of which Dr. Bose was thinking when he said that empirical formulae would not stand mathematical operations. What he meant was that unsound empirical formulae would not stand them. The fault lay not in the empiricism ; but in the dynamical unsoundness arising from bad data. Thus his own formulae stood condemned because the Regime Test Formula derived from them was different from that which he found by independent means (and data). In contradistinction to this all Lacey formulae fitted in with facts.

This disposed of the mathematics and physics of the subject. It only remained to deny Dr. Bose's statement that the speaker had said that 'f' distributed itself equally between parent and offtake (as a matter of course).

Replying to Mr. Lacey the author thanked him for his appreciation of the practical value of the Paper. He had to admit some errors in the test, unavoidably due to not receiving proofs before publication. Certainly the physical meaning of 'f' was known ; it was only the exact corelation between it and silt diameter, and packing, that had not been finally established. A slip of the pen existed in Para. 5 of Section 1, where initial regime formulae were said to hold for initial regime " only ". The word " only " was to be omitted. Finally it had been stated in Section 1 that current meters went wrong in dirty water. Since that was written research by the speaker at Rasul had established that silt content had no appreciable effect ; the error was due to temperature change at the rate (at the observation site) of about 1 p. c. for 6° Centigrade. This result could not be checked in tanks where there was no initial turbulence to be effected by temperature change.

APPENDIX III.

AN ANALYSIS OF REGIME CHANNELS.

Serial No.	Name of Channel.	Site of R. D.	Observed discharge "Q".	Observed Area 'A.'	Observed wetted perimeter "P".	Observed slope "S".	Mean velocity $V=\frac{Q}{A}$	H.M.D. $R=\frac{A}{P}$	Calculated $P.W=2\cdot67Q^{\frac{1}{2}}$	'f' calculated from $S=\frac{5/3}{1788Q}^{1/6}$	"f" calculated from $f=\frac{\sqrt{V8\gamma}}{\sqrt{0\cdot4476}}$	"f" calculated from $f=\frac{0\cdot73\ V^2}{R}$	"f" as mean of Col. 11 & 12	$\sqrt{f}$	Designed C.V.R. (Kennedy).	Designed slope ‰	Remarks.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	12 L ..	18000	456	235	59	0·12	1·97	4·0	57	0·74	0·73	0·72	0·73	0·85	0·95	0·125	
2	do. ..	44000	292	143	42	0·15	2·04	3·4	45	0·80	0·82	0·90	0·81	0·90	0·92	0·125	
3	do. ..	69000	250	137	42	0·15	1·82	3·26	42	0·79	0·78	0·75	0·78	0·88	0·89	0·125	
4	do. ..	81000	225	129	40	0·15	1·74	3·22	40	0·78	0·76	0·69	0·77	0·88	0·87	0·125	
5	do. ..	96000	145	87	34	0·155	1·67	2·56	32	0·76	0·76	0·79	0·76	0·87	0·85	0·125	
6	do. ..	146000	80	60	27	0·15	1·33	2·22	24	0·70	0·67	0·59	0·68	0·82	0·85	0·125	
7	1R-12L ..	9000	153	85	33	0·17	1·80	2·58	33	0·82	0·83	0·92	0·83	0·91	0·91	0·15	
8	do. ..	285000	95	63	26	0·18	1·51	2·42	26	0·80	0·78	0·69	0·79	0·89	0·90	0·15	
9	do. ..	465000	82	56	24	0·20	1·46	2·33	24	0·84	0·81	0·67	0·82	0·91	0·88	0·15	
10	do. ..	69000	56	37	21	0·20	1·51	1·76	20	0·81	0·82	0·95	0·82	0·91	0·94	0·20	
11	do. ..	79000	36	28	18	0·21	1·29	1·56	16	0·82	0·78	0·78	0·80	0·90	0·92	0·20	
12	1L-12L ..	3000	10	9	9	0·29	1·11	1·00	8·5	0·85	0·85	0·90	0·85	0·92	0·91	0·25	
13	do. ..	8000	7	6·5	7	0·34	1·08	0·93	7	0·90	0·90	0·91	0·90	0·95	0·95	0·25	
14	2L-12L ..	5000	10	9	8	0·32	1·11	1·12	8·5	0·90	0·89	0·80	0·89	0·94	0·94	0·25	
15	do. ..	8500	5·6	5·6	6·5	0·38	1·00	0·86	6·3	0·94	0·92	0·85	0·93	0·96	0·90	0·25	
16	3L-12L ..	3500	65	43	24	0·26	1·51	1·79	22	0·95	0·94	0·93	0·94	0·97	0·89	0·175	
17	2R-12L ..	18000	28	19	13	0·22	1·47	1·46	14	0·80	0·85	1·08	0·82	0·91	0·91	0·20	
18	2R-1R-12L ..	3000	8	7	8·5	0·39	1·14	0·82	7·6	0·98	1·00	1·16	0·99	0·99	1·0	1·30	
19	do. ..	6500	6	6	7	0·35	1·00	0·86	6·6	0·90	0·89	0·85	0·89	0·94	0·99	0·30	
20	3R-12L ..	8000	21	14	11	0·28	1·50	1·27	12	0·90	0·97	1·29	0·93	0·96	0·95	0·25	
21	do. ..	23000	13	9·6	8·5	0·34	1·36	1·13	9·6	0·96	1·01	1·20	0·98	0·99	0·94	0·25	
22	4R-12L ..	3000	10	9·6	8	0·30	1·04	1·20	8·4	0·86	0·84	0·66	0·85	0·92	1·1	0·40	
23	14L ..	13000	166	97	34	0·17	1·71	2·85	34	0·82	0·81	0·75	0·81	0·90	0·93	0·15	
24	do. ..	32000	119	77	30	0·18	1·55	2·57	29	0·82	0·79	0·69	0·80	0·90	0·92	0·175	
25	do. ..	53000	85	58·6	33·8	0·23	1·45	1·73	25	0·90	0·87	0·89	0·88	0·94	0·95	0·20	
26	do. ..	68987	63	42	24	0·25	1·50	1·75	21	0·93	0·92	0·94	0·92	0·96	1·0	0·225	
27	do. ..	77980	40	31·8	21·7	0·25	1·26	1·47	17	0·88	0·83	0·79	0·85	0·92	0·92	0·225	
28	1R-14L ..	24000	6	5·8	6·5	0·32	1·03	0·89	6·5	0·85	0·86	0·87	0·86	0·93	0·90	0·25	
29	3R-14L ..	28000	5	5	7	0·37	1·00	0·71	6	0·92	0·91	1·03	0·91	0·95	1·01	0·35	
30	7 B. R. ..	3000	11	9	8·5	0·25	1·22	1·06	8·9	0·79	0·83	1·02	0·81	0·90	1·04	0·225	
31	do. ..	13000	5·6	4·7	6	0·36	1·19	0·78	6·3	0·91	0·98	1·34	0·94	0·97	1·1	0·40	