THE ABSORPTION LOSSES OF PUNJAB IRRIGATION CANALS.

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The term "absorption losses," in this Paper, includes, according to current professional parlance, the losses of water suffered by a canal by evaporation from its water surface, as well as those due to percolation through the sides and bed of the channel. The magnitude of these losses attracted notice in the earliest days of modern canal history in this country; but since then the subject has received less attention, in the way of study and experimental investigation, than it might usefully have received.

Colonel Dyas' Discovery.

On the 4th April 1863 Colonel Dyas, R.E., wrote, from Madhopur, to Colonel Crofton, R.E., as follows :—

"Here is a little tit-bit of information for you. What do "you think of it? Startling, isn't it? But Cunningham (Ladak, "page 91) estimates the loss on Punjab rivers between the hills "and the junction with the Indus, at forty per cent. of their "minimum discharge at debouche from the hills in the cold "weather. In December 1860 Major Drummond and Mr. "Smithe took the opportunity of observing the discharge at "different points along the portion of the Bari Doab Canal then "open, *viz.*, from the head, at Madhopur, to the tail of the "Lahore Branch at Niaz Beg. They also observed the discharge

" of all the inlets to and outlets from the canal. I have worked " out the results, which are as follows :—

	Length in miles.	Loss per mile, cubic feet per second.	Total loss, cubic feet per second.
1. Main Line ...	28½	5½	156·75
2. Main Branch Upper	24	1½	36·00
3. Kasur Branch Upper	7	3¼	22 75
4. Main Branch Lower	209	⅗	125·40
5. Lahore Branch ...	60	⅗	36·00
6. Kasur Branch ...	85	1	85·00
7. Sobraon Branch ...	63	⅗	37·80
		Total ...	499·70

" or, say, 500 cubic feet per second ; which is one-sixth of " 3,000, the full supply.

N.B.—Nos. 1, 2 and 5 are from observation.

Nos. 3, 4, 6 and 7 are estimated.

" *Result.* It will require 1⅕ cubic feet per second at the " head of the canal to provide one cubic foot per second at the " head of a rajbaha (on the average).

" Now of course absorption in a new channel is greater " than in an old ; *i.e. if there be no tendency to cut in the old ;* " but, again, evaporation is not at its maximum in December, " so, for the present I suppose one source of error to counter- " balance the other."

Experience has shown that the conclusion arrived at by Colonel Dyas in 1863 was remarkably accurate ; although there has been little subsequent experimental investigation of the subject. Lieutenant-Colonel Scott-Moncrieff, R.E., in 1868, in his Report on the Irrigation Canals of Southern Europe, wrote as follows of the canals of the North-West Provinces of India (now called the United Provinces) :—

" The discharge is measured at the head of the canal, and " the water probably runs, on the average, three hundred miles

"before it actually reaches the fields to be watered. It is usual "to deduct about twenty per cent. for the loss by filtration, "evaporation, etc., *en route.*"

This was somewhat loose writing. Colonel Scott-Moncrieff probably meant that twenty per cent. was the estimated loss between the canal head and a rajbaha (or distributary) head; and he probably had in mind practice based on Colonel Dyas' conclusions of 1863.

Beresford's Studies (1875).

In a memorandum, dated August 1875,* Mr. J. S. Beresford drew attention to the subject of the absorption losses on our Indian canal systems. He discussed the theory of ground-water flow, and drew a distinction between "percolation," which he described as being due to gravitation; and "absorption," a term which he applied to flow by capillary attraction. He wrote: "Absorption is a more complicated process than percolation. The latter takes place through boulders or coarse gravel in precisely the same way that water issues through pipes in the bottom or side of a vessel; and the quantity discharged per second will depend on the size of the interstices of the stones, their number, the thickness of the stratum and the head of water. If the boulders and gravel are broken into fine sand, and the bund formed of this material, the principles of discharge are quite changed; the interstices now become so small that they act in the same manner as capillary tubes." According to his definition the term percolation would not apply to flow through fine sand or clay; but whatever definition we may adopt, it is clear that the flow through soil in a downward direction, assisted by gravity, must be far greater than similar flow in directions opposed to that of the force of gravity.

Mr. Beresford derived from his theories on ground-water flow the inference that there is less loss by absorption from a canal in embankment, than from a similar canal excavated in the natural soil; the reason being that the absorbent power of an embankment is limited by the bulk of the embankment, just as flow through a sponge, used as a cork, in a bottle full of water turned upside down, is limited by the absorbing capacity of

* Republished in Punjab Irrigation Branch Paper No. X.

the sponge. In this memorandum, Mr. Beresford pointed out many ways in which water might be economized in irrigation ; as, for instance, by puddling the bed and sides of village watercourses with clay ; by reducing the undue length of village watercourses ; by amalgamating separate watercourses which happen to flow alongside each other for long distances ; by improvements in the alignment and design of distributaries, etc., etc. ; but he did not quantitatively determine the absorption loss in any particular case of a water channel. He assumed that these losses varied as the wetted soil surface ; and that they might be expressed as a function of the length of the channel. He overlooked the effects of water-depth and water-temperature on the rate of loss by ground flow.

Higham's Experiments (1874).

In May 1874, Mr. (afterwards Sir Thomas) Higham made some observations to determine the loss of water by absorption in the first fifty-two miles of the main line of the (Upper) Bari Doab Canal ; and stated the result as a loss of 272 cusecs out of a supply of 2,176 cusecs at canal head ; *i e.*, a loss of 12½ per cent., the area of water surface of the canal being 27,820,000 square feet. Expressed otherwise, the loss amounted to 9·78 cusecs per million square feet of water surface. The average water depth of the canal at the time of observation is not on record, but the measurement of discharge at the two ends of the fifty-two mile reach was made on the same body of water ; the interval of time between the two measurements being equal to the interval of space, divided by the mean velocity of the current. In order to simplify the determination of the problem, all distributaries offtaking from the canal were closed during the observations of discharge ; so that the difference of discharge at the two ends of the reach of canal could be attributed only to loss *en route* by absorption into the soil or atmosphere, or to errors of observation.

These observations were made by Mr. Higham personally. Similar observations were made at the same time, under his instructions, on the lower main branch of the canal, over a length of sixty-three miles ; but these latter observations were made by subordinates, and Mr. Higham disclaimed responsibility for their accuracy. They indicated a loss of forty-six cusecs from a water surface area of 21,105,000 square feet ; equivalent to a loss of only 2·2 cusecs per million square feet of

water surface, or less than one-quarter of that observed by Mr. Higham in the upper reaches of the main canal. In this case also we are not informed what the range of water depths was ; but, since all distributaries offtaking from this sixty-three miles length of canal were closed during the experiment, and since the capacity of the canal at the lower end was not more than half the capacity at its upper end, we know at least that the water stream must have been very shallow at the upper end of the length of canal under experiment.

Kennedy's Note of 1883.

In April 1883, Mr. R. G. Kennedy, Executive Engineer, wrote a valuable note on the subject of absorption losses on the Bari Doab Canal ; and startled the profession by calculations which, (if correct), went to show that only twenty-eight per cent. of the supply entering the canal head was utilized for irrigation ; the rest being dissipated, between the canal head and the fields, in absorption, or in preventable waste. Starting with the fact that the Roorkee experiments of Captain Allan Cunningham had shown that evaporation from the surface of a sheet of water reduced its level by only $\frac{1}{10}$th inch, or 0·008 foot, per diem, and that certain observations on the Bari Doab Canal in the summer of 1882 indicated an evaporation loss of only 0·015 foot per diem ; Mr. Kennedy formed the opinion that the loss by evaporation from a canal was insignificant in comparison with the loss by absorption into its soil. He used the symbol "c" to express the vertical sinkage, in feet per hour, of the surface of a body of water, in consequence of absorption, including evaporation.

He enclosed an area of 27,000 square feet of land with earthen embankments, and flooded it with water to a depth of from 0·2 foot to 1·0 foot. From time to time, throughout a period of eight days, he re-flooded this area in order to make good losses by absorption and evaporation ; and he also kept the land outside the embanked area flooded so as to exclude disturbing elements of lateral absorption. Plotting his data of observation diagramatically, he drew the inference (from his eight day experiment) that the value of "c" would vary from 0·037 foot in the case of water that had been stagnant for one week, down to 0·0195 foot in the case of water that had been standing for two years ; the corresponding results for one month, and one year, being 0·0305 and 0·0215 respectively. His

data would have been more conveniently appreciated if he had expressed them in terms of inches per diem, instead of in terms of feet per hour.

Thus 0·037 foot per hour = 10·66 inches per diem.
and 0·0195 ,, ,, ,, = 5·6 ,, ,, ,,

It was a big jump, however, to infer the probable results of a two-year case from an experiment actually extending over only eight days ; and one may well doubt whether his data justified any lower value for "c" than 0·03 foot per hour, or 8·66 inches per diem, for water standing for any duration of time. From experiments in the irrigation of fields Mr. Kennedy deduced values of "c" varying from 0·04 to 0·05 for *rabi* first waterings in November, to 0·02 or 0·03 for second waterings in December or January, and as the average of sixty-three measurements made on watercourses he arrived at a mean value of $c = 0·034$ foot per hour.

For rajbahas, or distributaries, he arrived at values varying from 0·0077 to 0·016 ; and adopted a mean value of $c = 0·012$ as probably correct ; but we have no means of judging the reliability of his inferences from his data. For canals Mr. Kennedy adopted the data of Mr. Higham's observations of 1874, and of some which he attributed to Mr. Benton. For the main canal, in its first fifty-two miles, Mr. Higham's results gave a value of $c = 0·035$; and for its next sixty-three miles a value of $c = 0·00787$.

The discrepancy between these two results was great ; but Mr. Kennedy offered no explanation of it beyond an assumption that the soil in the first fifty-two miles was abnormally porous, "being full of boulders."

Kennedy's Results.

Mr. Kennedy's results were as follows :—

TABLE I.

Nature of water channel.	Vertical sinkage of water surface in feet per hour.			Vertical sinkage of water surface in inches per diem.			Loss by absorption in cusecs per million square feet of surface.		
	From	To	Average.	From	To	Average.	From	To	Average.
1	2	3	4	5	6	7	8	9	10
Flooded virgin soil...	0·037	0·02	0·028	10·66	5.6	8·1	10·3	5·6	8
Cultivated land ...	0·05	0·02	0·035	14·4	5·8	10·1	13·9	5·6	9·75
Watercourses	0·11	0·015	0·034	31·7	4·3	9 8	30·6	4·2	9·4
Rajbahas ...	0·016	0·0077	0·012	4·6	2·2	3 5	4·4	2·1	3·3
Branch canals ...	...	...	0·0079	...	...	2·28	...	...	2·2
Main canal	...	...	0·035	...	...	10·1	...	...	9·75

In para. 4 of his Note, dated April 1883, he wrote :—

"Thus we may expect the rate of absorption to be smallest on the main canal, larger on rajbahas, and largest on water courses." Yet, on inspecting the table above, we see that the rate of loss on the main canal was about the same as on water-courses and fields ; but three times as great as on rajbahas (or distributaries) and about four or five times as great as on branch canals. Of this inconsistency Mr. Kennedy offered no satisfactory explanation, beyond a suggestion that the first fifty-two miles of the main canal were located in boulder-soil ; a suggestion which was not in accordance with fact. He does not appear to have recognized that the depth of water in any particular case, or its temperature, could have any appreciable influence on the rate of absorption.

Higham on Kennedy.

Mr. Kennedy's superior officer, the Executive Engineer who forwarded this Note of April 1883 to higher authority, remarked, in sending it on, that the rate of absorption was a function of the depth of the water; and this was agreed to by the higher authority, (Mr. Higham), who, in reviewing the Note, said that "this may afford a partial explanation of the fact that the value of c is four times as great over the main line and main branch upper, as in the lower branches." And, in para. 14 of his review of the Note, Mr. Higham went on to say: "It would be interesting to ascertain whether the great loss on the main line depends in any way on the depth, upon which depends the question whether narrow and deep channels will lose less by percolation than wide and shallow ones having the same discharge." The investigation suggested by Mr. Higham does not appear, however, to have been taken up, and for long past it has been the practice of the Punjab Irrigation engineers to reckon the losses by absorption (including evaporation) on main and branch canals (*i.e.* on all channels discharging over 250 cusecs) at about eight cusecs per million square feet of wetted surface of channel (see page 123, Buckley's "Facts, Figures and Formulas") without regard to the depth of water or any other consideration than the area of the wetted surface of the channel.

Kennedy's Calculations.

Assuming that the rate of absorption loss on the Bari Doab Canal was 9·75 cusecs per million square feet of water surface in its first fifty-two miles of main canal, and 2·2 cusecs per million square feet of water surface in each of its branches, Mr. Kennedy calculated that the total loss by absorption in the main canal and its branches (between canal head and distributary offtakes) was 411 cusecs out of a canal head discharge of 2,036 cusecs; that is to say twenty per cent. of canal head supply; also, on the assumption that the average length of each distributary continuously in flow was ten miles, with a mean water surface width of 10·5 feet, he calculated that the absorption loss on distributaries throughout the canal system averaged six per cent. of the canal head supply. Assuming, again, that the average length of the irrigating watercourses was 4,000 feet, with a water surface width of 3·5 feet, and a watercourse head discharge of 0·48 cusec; he calculated that the aggregate absorption losses

on watercourses amounted to twenty-one per cent. of the canal head supply.

In this way he calculated that the proportion of water reaching the irrigated fields was $100 - (20+6+21) = 53$ per cent. of the canal head supply ; and, after calculating that the depth of water required on the fields for irrigation purposes was only 0·815 foot for each crop, he came to the conclusion that only twenty-eight per cent. of the canal head supply was needed for the irrigation of the crops actually raised, and that therefore twenty-five per cent. of the canal head supply *must* be being wasted by bad methods of irrigation.

The need for more precise calculations of Absorption Losses.

In a Note * dated July 1891 Mr. Kennedy re-affirmed the general accuracy of his calculations of 1883, and especially that which estimated the absorption losses of branch canals in average loamy soil at only 2·2 cusecs per million square feet of water surface. The general experience of Punjab canal engineers has, however, led them to reject this figure as too low ; and for many years past they have usually calculated the absorption losses of main and branch canals at the rate of about eight cusecs per million square feet of wetted surface of channel ; and it remains to consider now whether this is a sufficiently correct formula for general use. If eight cusecs be the correct rate of absorption loss for canals of all sizes ranging from 250 cusecs capacity upwards ; and if 9·4 be the correct rate of watercourses discharging five cusecs, or *less* ; there must be something defective in a calculation which puts the rate for rajbahas, discharging from 5 to 250 cusecs, at a value so low as 3·3 cusecs per million square feet of the surface. There must be some factors governing the rate of the absorption loss which require further investigation and determination.

Theory of the Flow of Water through Soils.

The study of the flow of water through soils, natural or artificial, has been conducted, in the past, in Europe and America, chiefly from the point of view of conditions affecting the water-supply of towns, and of pumping water from wells

* See Punjab Irrigation Branch Paper No. X.

under high pressure. The equable steady flow of water percolating from earthen canals, or reservoirs, appears to have received less attention, and the results stated by different authorities differ widely in their essential features.

The subject was ably reviewed by Baldwin Wiseman in Paper No. 3594 of Volume clxv of the Minutes of Proceedings of the Institution of Civil Engineers (September 1906) as follows :—

" Darcy, in 1856, stated that the velocity of flow of ground " water was proportional to the slope of the hydraulic gradient, " and varied for the same head inversely as the thickness of the " strata penetrated. Roberts, in 1861, demonstrated that the " flow of water through sandstone varied with the pressure. " Hagen, in 1869, questioned the variation of flow with pressure, " but agreed with Darcy that the flow varied inversely as the " thickness of the strata traversed. According to Seelheim, who " also investigated the question of pressure in connection with " porosity in clays and sands, the flow varies faster than the " pressure producing it; whilst, according to Hazen, who has " done much work on the relative size of sand grains and the " effect of the size of the grains upon the flow, the velocity of " flow is more nearly proportionate to the square root of the " head.

" Fuertes, in a continuation of this work, has shown that " a small variation in the size of the grain materially affects the " velocity co-efficient. Of the more purely physical investigations " Cohen, in 1892, showed that the viscosity of the water varied " inversely as the pressure ; and thus confirmed Seelheim's " statement that the flow increased faster than the pressure ; " whilst Thorpe and Rodgers, in 1894, showed that the " viscosity varied inversely as the temperature. Slichter, from " observations on a well at the University of Wisconsin, stated, " in contradiction of Seelheim, that the flow did not increase so " rapidly as the pressure.

" Lee has stated that the rate of flow of water through " the pores of a rock in the immediate vicinity of a well is " greater than at points more remote, the rate diminishing more " quickly with a small well than with a large one."

Baldwin Wiseman made certain experiments of his own, to determine the rate of flow of water under pressure through

cylinders of stone, thirteen inches in diameter, and three, and six, inches high, and drew the following conclusions therefrom:—

"From an inspection of the diagrams it is at once evident "that the flow does not vary in any direct manner with the "pressure, diameter of grain, or porosity, through any consider- "able range of pressure. With the Bradford and Bath oolites, "excepting the three-inch Bradford, between the pressures of "five, and twenty-five, lbs. per square inch, the discharge increases "continually with the pressure; but with chalk a peculiar "phenomenon occurs; with the Mottisfont chalk there is a steady "decrease of flow per unit pressure between five, and twenty-five, "lbs. per square inch, succeeded by a steady increase between "twenty-five lbs. per square inch and the pressure under which "it failed; with the Micheldever chalk there is a small increase "between five and ten lbs. per square inch, followed by a decrease "between ten and fifteen lbs. per square inch, succeeded by an- "other small increase between fifteen and twenty lbs. per square "inch, which in turn gives place to a continuous decrease until "the load of rupture is reached. The probable explanation of "this phenomenon is that the flow increases with the pressure up "to a critical velocity, beyond which any increase of pressure is "expended in eddies and in the enlargement of the pores by rup- "turing the septa between continuous pores. With an enlarged "cross section the flow might once more become steady, and "continue so until the increasing pressure gave rise to a critical "velocity. With the harder rocks, however, no such oscillatory "variations were observable within the range of the pressures "covered by the experiments; but the flow increased faster than "the pressures up to a certain load, and thenceforward decreased "continuously.....It is evident that for the same rock the loss of "pressure at any given depth is directly proportionate to the "surface pressure."

Baldwin Wiseman and Osborne Reynolds.

Baldwin Wiseman was probably correct in supposing that the vagaries of discharge through rocks and through soils, exhibited by the experiments of different observers under varying conditions, can be accounted for by the hypothesis of the transgression of the "critical" velocity, which marks the limit of resistance of the material of the filter under excessive pressures. What probably happens is a transition from "capillary" flow to "pipe" flow, or *vice versa*, accompanied, or preceded. or followed in certain cases, by enlargement of pipe-waterway through the pores of the filter.

In 1884 Professor Osborne Reynolds said at the Royal Institution:—"In rivers, and in all pipes of sensible size, experience has shown that the resistance increased as the square of the velocity; whereas in very small pipes, such as represent the smaller veins of animals, Poiseuille has proved that the resistance increased as the velocity. Now, since the resistance would be as the square of the velocity with sinuous motion, and as the velocity with direct motion, it seemed that this discrepancy could be accounted for if the motion could be shown to *become unstable* for a sufficiently large velocity." Professor Reynolds used the expression "steady motion" to denote such movement of the stream line which has not broken, or is not breaking, into eddies, and "sinuous motion" when the stream line is breaking, or has broken into eddies; and he found experimentally that the eddies were formed suddenly, at a critical velocity, when the law of resistance changed.

The Simpler Aspect of our Special Problem.

In the particular problem, however, which is the subject of this Paper, *viz.*, that of percolation through alluvially-deposited loamy soils, under very moderate heads of pressure, and at very low velocities, the case is greatly simplified by the fact that this critical velocity, limiting the resistance of the structure of the soil, is not exceeded. The flow is regular, and follows the law of flow through capillaries, which has been enunciated as follows by Poiseuille:—"La vitesse dans les tubes de tres petit diametre est proportionelle à la presion, en raison invers de leurs longueurs, et proportionelle au carre de leurs diametres".

Turneaure and Russell.

In Turneaure and Russell's Treatise on Public Water Supplies, (Article 85), it is stated that "the velocity of flow of a ground-water stream is a function of the hydraulic gradient, or slope, on the one hand, and the resistance to flow offered by the particles of soil on the other. Experiments by Darcy, Hagen, Hazen, and others, show that the rate at which water at a given temperature will flow through any particular sand, or fine gravel, follows closely the law of flow through capillary tubes, that is, the velocity is approximately proportionate to $\frac{h}{l}$ where h is the head and l the distance through which the water flows. (In the case of a stream flowing through such material, down a uniform slope, $\frac{h}{l}$ would be the size of the slope angle). The velocity is also dependent upon the size of the grains of the

material, it being nearly proportionate to the squares of their diameters."

Clibborn's Roorkee Experiments (1896).

Colonel Clibborn's Roorkee experiments on the flow of water under pressure through sand taken from the bed of the River Chenab at Khanki, indicated the following conclusions:—

(1) the percolation discharge through a given length of sand varies directly as the head of pressure.

(2) The percolation discharge, with a given head of pressure, varies inversely as the length of sand traversed.

(3) The percolation discharge, with sands of different degrees of consolidation, varies directly with the interstitial spaces.

(4) The pressures transmitted by water under certain heads, through sand at different distances, vary inversely with the distances.

Factors of the Problem.

It appears to be sufficiently clear from the evidence before us, that the percolation flow of water through soils, under moderate pressures, and at low velocities, is liable to vary with:—

(*a*) the area of the surface of the soil exposed to the water pressure,

(*b*) the head of water pressure,

(*c*) the temperature of the water,

(*d*) the degree of porosity of the soil,

(*e*) the distance travelled through the soil.

Of these five factors we are not, in the case of percolation from irrigaton channels, concerned with (*e*). Once the percolating water passes the line of the wetted perimeter of the cross-section of the channel, it is lost to us, no matter what may happen to it farther on in the subsoil.

As regards factor (*d*), it is thought that, although a strictly accurate absorption loss formula ought to take account of the varying degrees of porosity of the soil of water channels, it is not necessary nor conveniently practicable to do so. Our Punjab irrigation canals are dug, from head to tail, for

hundreds of miles, through an average loamy soil, alluvially deposited ; which does not, probably, differ very markedly, in degree of porosity, from tract to tract, over tracts of considerable extent. It is true that the *subsoil* in the upper reaches of the Punjab doabs, near the foot of the Himalayas, is composed largely of boulders and shingle; that further downstream the subsoil is gradually refined down to coarse sand, fine sand, and clay ; and that in the tail reaches of the doabs a finer and more compact clay predominates ; but the top layer of soil, which contains our canals and distributaries, appears to be of much the same quality, *qua* porosity, from end to end of the doabs. The structure of the surface soil at Gurdaspur, or Pathankot, is not visibly different from that of the surface soil at Lahore, or Amritsar, in the Bari Doab ; and the writer is not aware that any difference of porosity has been proved to exist in the past between the soil of the head reaches, and that of the tail reaches, of our principal canals. True, Kennedy supposed that Higham's experiments of 1874 indicated an abnormal degree of porosity in the soil of the first fifty-two miles of the Bari Doab Canal; but even Homer nods, and later experience has shown that the porosity of other canals, like the Lower Chenab and the Lower Jhelum, in soil further from the Himalayas, and quite free from boulders and shingle, is not less, relatively, in the upper reaches of those canals, than that of the Upper Bari Doab Canal.

It is probably true that in spots, here and there, and from point to point, the porosity of the soil containing our canals varies, with a hard stiff clay here, and a sandy loam there ; but it is thought that, mile for mile, the variations are averaged to disappearance. If any appreciable length of canal, in boulder soil, or in sandy soil, were found to be unduly porous, it would not be left in that condition, but would be protected with a lining of clay puddle, or other waterproof material ; but, it is believed that, as a matter of fact, no such abnormal porosity has ever been proved to exist.

Hansi Canal Experiments (1898).

The writer ascertained, by experiments on the Hansi Branch Canal, about the year 1898, that the porosity of ordinary loamy soil varied greatly, even at points only a few feet apart ; but these variations were due to surface cracks resulting from variations of temperature. The *modus operandi* was to fix pipes, varying in length from eighteen inches to eighteen feet, vertically

in the soil ; and to notice the velocity of sinkage of columns of water within the pipes. Even when the surface soil was removed to a depth of five feet, and the pipes fixed in the freshly exposed subsoil, some variations of percolation flow were observed, at points only a few feet apart ; and hair-cracks were noticed in the newly exposed soil. Such hair-cracks, however, due to atmospheric changes of temperature, would not occur in a canal bed whilst the canal was in flow ; and, in any case, local variations of porosity, of such character, would disappear when averaged over mile-lengths, or several mile-lengths. It is thought, therefore, that our formula for losses by absorption on irrigation canals may neglect the factor of variations due to soil porosity, in the generality of cases.

Proposed Absorption Formula

We are left then with the three factors :—

(*a*) Area of wetted surface of channel.

(*b*) Head of water pressure.

(*c*) Temperature of the water.

Taking (*a*) and (*b*) together, we see that the percolation flow is proportionate to the area of the wetted surface and to the mean head of water pressure against it ; but, since, in a canal of trapezoidal cross-section, the mean head of pressure on the side slopes is only half of that on the bed of the canal, it is simpler to reckon that the percolation flow is proportionate to the full water depth on the bed, and to the "reduced wetted surface," composed of the area of the bed added to half that of the side slopes.

The absorption formula might then be expressed as :—

$$Q = \gamma\, a\, d\, f^n$$

where Q = absorption loss in cusecs

γ = a co-efficient

a = *reduced* area of wetted surface

d = depth of water on bed

f^n = some function of the temperature of the water, expressed in degrees Fahrenheit.

The rate of percolation flow, as well as the rate of evaporation, varies with the temperature ; yet it is not convenient, in practice, to affect great precision in the introduction of this factor into the absorption formula ; for the temperature varies from day to day, and from day to night, all the year round. The mean temperature of one month differs from that of the next ; and the mean temperature of one month in one year is not the same as that of the same month the next year. The temperature of the water in canals is less variable than that of the atmosphere ; yet it is variable in the same way, though in less degree. It is perhaps hardly worth while to frame a formula expressive of all such changes ; since what we are concerned to know chiefly, is the loss by absorption from our channels over considerable periods of time. At most we might assume a mean temperature for the summer and another for the winter ; but even this would not take into account the differences of temperature of the water in large, and in small channels, respectively. It will probably be simplest, therefore, and sufficiently accurate for practical purposes, if we adopt a co-efficient c in the formula

$$Q = c\ a\ d$$

Where c is a co-efficient varying with the capacity of the water channel, and which will take into account the variation of the temperature of the water with the size of the channel it flows in.

Amritsar Experiments.

In October 1910 the writer reported on a series of experimental observations which were carried out near Amritsar, from March to September of that year, in order to determine the value of puddled clay as a practical waterproof lining for earthern channels. Two elevated tanks were formed, with bed and banks of sand, the bed being above ground-surface level ; and lined with different thicknesses of puddled clay. A third tank of about the same dimensions was dug out of the natural soil, and not lined with puddle. It was dug to a depth of $5\frac{1}{2}$ feet below ground-surface level ; and its bottom was only $2\frac{1}{2}$ inches above the level of the subsoil water table. The bottom of the tank was 28 feet square, and its sides were sloped at $1\frac{1}{2}$ to 1. The tank was filled with water to a level five feet above its bottom ; and at that level its water surface was 1,849 square feet ; the area of its bed and side slopes 1,989 square feet ; the area of its bed alone was 784 square feet ; and its cubic contents of water 6,585 cubic feet.

The water level in the tanks was allowed to sink, by percolation and evaporation, from five feet to four feet in the lined, and to about three feet in the unlined tank ; when all were refilled to the five feet depth. These operations were repeated, and observations were continued, for twenty-eight days from the 15th March ; after which the tanks were emptied of water, and kept empty for twenty-one days. The same operations were repeated over and over again till the end of September, the tanks being kept filled with water for periods of from twenty-eight to thirty-nine days, and emptied, and kept empty, for periods of from twenty-one to twenty-four days.

We are not concerned here with the results of observations on the puddled tanks, but with the percolation from the unlined tank excavated in the natural soil. In this tank the water depth sank sometimes as low as thirty-three inches ; but the rate of percolation loss, as indicated by the sinkage of water surface, was always approximately proportionate to the depth of the water.

The evaporation loss was measured by a metal pan, about ten inches square, floating in each tank and supported by wooden floats. It averaged a sinkage of 0·375 inch vertically of water surface daily for the period of 6½ months—the rate of daily evaporation varying from month to month as follows :—

March 0·28 inch per diem ; April 0·34 inch ; May 0·50 inch ; July 0·40 ; September 0·30 inch.

These results are far higher than the Roorkee results of Captain Cunningham ($\frac{1}{10}$ inch per diem) quoted by Mr. Kennedy in his Note of April 1883 ; but they are consistent with the Roorkee observations of Dr. Murray Thomson, (half an inch per diem in April and May, with a hot wind blowing), quoted in Mr. Beresford's Note of August 1875. As regards Captain Cunningham's low figures of evaporation loss, it is within the writer's knowledge that their lowness is due to the fact that certain engineer students, who helped Captain Cunningham with his experiments, indulged in the practical joke of surreptitiously replenishing his evaporation pans at night, thereby vitiating his results.

In the unlined tank at Amritsar the average rate of sinkage per diem, due to percolation and to evaporation, respectively, was as follows :—

Percolation 6·03 inches ; evaporation 0·36 inch. The rate of percolation loss was therefore seventeen times the evaporation loss, on the average.

The average depth of water in the tank during the observation was 4·2 feet. Its wetted surface of soil, for that depth, was 1,827 square feet; and its *reduced* wetted surface, under 4·2 feet head of pressure, was 1,257 square feet. A sinkage, due to percolation, of six inches per diem, was equivalent to a loss of 7·45 cusecs per million square feet of *reduced* water surface. Since this loss is proportionate to the water depth, we have a percolation loss of 1·77 cusecs per million square feet of wetted surface for each foot of water depth. Adding one seventeenth to this for evaporation loss, we get a total absorption loss of 1·87 cusecs per million square feet of wetted surface, for each foot of water depth.

Comparison of Tank with Stream Channel.

The capacity of the tank, for a 4·2 feet depth of water, was 5,107 cubic feet; so that its ratio of capacity to soil surface was, therefore, 2·8; or about the same as that of a unit length of a channel discharging 150 cusecs (bed width 18, depth 3·8, wetted perimeter 26·5 feet).

Lesson Drawn from Mexico Experiments.

An elaborate series* of experiments in evaporation on Lake Conchos in Mexico has shown that the rate of evaporation from pans floating on a lake is greater than that from the surface of the lake; and that the rate of evaporation recorded by two pans of different sizes, floating on the same sheet of water, varies inversely with some function of the sizes of the pans. This variation is evidently due to variation of the temperature of the water; the smaller the receptacle, the higher the temperature of the contained water.

The rate of absorption loss from the Amritsar unlined tank would be the same, presumbly, as that from an earthen channel having the same ratio of wetted soil surface to capacity in a unit length; *i.e.*, to a channel of bed-width 18 feet, and water depth 3·8 feet; discharging 150 cusecs. Such a channel, losing by absorption 7·89† cusecs per million square feet of wetted surface, would be losing 2·08 cusecs per million square feet of wetted surface for each foot of water depth. Or according to the formula

$$Q = c\,a\,d$$
$$= 2{\cdot}08 \times a \times 3{\cdot}8 = 7{\cdot}9a.$$

Where Q is the absorption loss, and a the unit area of one million square feet.

* Proceedings of the American Society of Civil Engineers, September 1915.

† $7{\cdot}45 + \frac{7.45}{17} = 7{\cdot}89$.

Ratio of Water Bulk to Soil Surface of a Stream.

The temperature of the water in an earthen channel must vary, *ceteris paribus*, inversely with some function of its volume ; or inversely with some function of the ratio of its volume, per unit length of channel, to its area of wetted soil surface.

It can be shown that for channels of similar section the ratio of their area of wetted soil surface to capacity per unit length varies uniformly, thus :—

TABLE II.

Discharge (cusecs).	Bed width (b) (feet).	Water depth (d) (feet)	Ratio $\frac{b}{d}$	Wetted perimeter (feet) W.P.	Capacity (A) per unit length (square feet).	Ratio $\frac{\text{W.P.}}{\text{A.}} = \frac{1}{\text{R.}}$	Multiplier C^R	Co-efficient C in formula $Q = cad$.	Gradient one in	Mean velocity.	Kennedy's critical velocity ratio.
1	2	3	4	5	6	7	8	9	10	11	12
10,000	300	9·75	31·0	3·2	2,988	0·110	10·50	1·16	8,000	3·35	0·94
5,000	198	7·90	25·0	217	1,595	0·136	10·00	1·36	5,714	3·13	0 99
2,000	114	6·15	18·5	128	720	0·177	9 30	1·65	5,714	2·78	1·03
1,000	74	5·25	14·0	96	391	0·220	8·45	1·86	5,714	2·54	1 03
500	45	4·50	10·0	55	213	0·259	7 63	1·95	5,000	2·35	1 07
250	27	4·20	6·4	36·4	122	0·300	6 67	2·00	5,000	2·05	1·03
150	18	3·8	4·74	26·5	76	0·350	5·95	2 08	4,444	2·0	1·00
100	14	3·55	3 9	22·0	56	0·40	5·45	2·18	4,444	1·8	0 93
50	9	3·0	2·95	15·7	31·5	0·50	4·80	2·44	4,000	1·59	0 94
25	5·5	2·45	2·25	11·0	16·5	0·66	4·25	2·83	3,333	1·51	1·00
10	3·4	2·0	1·7	7·9	8·8	0·95	3·75	3·55	3,333	1·14	0 88
5	2·1	1·6	1·3	5·7	4·64	1·23	3 45	4·25	2,500	1·05	0·93
2·5	1·25	1·4	0·90	4·4	2·75	1·60	3·06	4·90	2,500	0·85	0·82
1·0	0·5	1·0	0·60	3·4	1·6	2·13	2·60	5·60	2,000	0 66	0 79
0·5	0·4	1·0	0·40	2·6	0·9	2·90	2·15	6·23	2,000	0·52	0 62

In Table II above it has been attempted to compare streams of different volumes, designed on similar lines ; *i.e.* with as uniform values as possible for Kennedy's critical velocity ratio, and with a uniformly varying ratio of bed width to depth. The figures of columns 4, 7 and 9 of the Table will be found plotted graphically in Plate 1, appended.

An inspection of the diagram shows that the ratios of the soil surface of the stream to the bulk of the water per unit length of channel vary only very slightly for channels discharging from 2,500 cusecs to 10,000 cusecs ; and not greatly for channels down to a thousand or even five hundred cusecs, discharge.

This suggests that we may, without serious error, ignore variations of the factor c, in the equation $Q = c\,\bar{a}\,d$, in the case of canals discharging over five hundred cusecs. At the point representing a stream of 250 cusecs, however, in Plate I, we notice a sharp change in the curve representing ratios of soil surface to water bulk ; and this is just the point which separates the definition of a "canal" from a distributary. Distributaries range, in discharge, from 5 cusecs to 250 ; and it is clear from Plate I, that the value of c in our formula must vary very greatly, according to the width and depth of each distributary.

Plate I shows also that c must vary very greatly between large watercourses, discharging four or five cusecs, and small ones, which discharge only one cusec, or less. This illustrates the value of the reforms advocated by Beresford and Kennedy, in the way of amalgamating petty watercourses into larger ones ; working distributaries in rotation, with full supplies alternately with complete closures, instead of with continuous driblets of low volumes, &c.

Kennedy's Watercourse Experiments.

The average dimensions of sixty-three watercourses measured by Kennedy in 1883 were as follows :—

Water surface width, 3·6 feet; length 4,000 feet ; discharge 0·48 cusec. Whence we may infer the following dimensions:— bed width, 2·9 feet ; water depth 0·35 ; reduced wetted surface 3·4 feet.

At the present date it is rare to find watercourses discharging less than one cusec. The average discharge of watercourses varies between 1·1 cusecs on the Upper Bari Doab Canal to 2·7 cusecs on the Sirhind Canal ; the general average for all Punjab perennial canals being 1·7 cusecs per watercourse. Let us get back to Kennedy's watercourses of 1883. He found their absorption loss to amount to 9·4 cusecs per million square feet of water surface (which in this case was very nearly the same as the "reduced" wetted soil surface). By the formula $Q = c\,a\,d$; if we take a as one million square feet, we get

$$Q = c\,a\,d = c \times 0{\cdot}35 = 9{\cdot}4.$$

Whence $c = 27$; an enormously high value. If the design and discharge of the watercourse had been as in the last line of Table II above ; then, even if the rate of absorption had been the same, we should have had :—

$$Q = c\,a\,d = c \times 1{\cdot}0 \times 1{\cdot}0 = 9{\cdot}4$$

Whence $c = 9{\cdot}4$ only.

Kennedy's Prairie Soil Experiments.

Kennedy measured a loss of 9·75 cusecs per million square feet on a plot of virgin soil. This was nearly the same as his observed loss of 9·4 cusecs per million square feet on watercourses ; and as a matter of fact the conditions, in respect of our formula, were nearly the same ; for the plot of land was kept flooded to a depth varying between 0·2 and 1·0 foot ; average say 0·5 or 0·6 foot, as compared with 0·35 in the watercourse.

Absorption Losses, Upper Bari Doab Canal.

The writer has found that a value of $c = 1{\cdot}33$, in the absorption-formula, $Q = c\ a\ d$, accords well with the actual data of absorption of the principal Punjab perennial canals, as exhibited in our statistical records. Appendix A is a tabular statement, showing, reach by reach, the bed widths, full supply depths, reduced wetted surfaces, and absorption data (the latter calculated by the formula above stated) of the main line and branches (excluding distributaries) of the Upper Bari Doab Canal, throughout its course. The results, so calculated, compare as follows with published periodical statistical records :—

TABLE III.

Period.	Full capacity.	KHARIF DATA. According to Statistical Records. Average supply (cusecs).	Ratio of column 3 to column 2.	Average loss by absorption (cusecs).	Percentage ratio of column 5 to column 3.	Calculated by formula. Loss at full supply conditions.	Loss under average supply (column 7 × column 4).	Percentage ratio of column 8 to column 3.
1	2	3	4	5	6	7	8	9
1899-1909 ...	6,500	4,984	0·77	964	19·2	1,150	886	17·8
1899-1912 ...	6,500	5,032	0·77	936	18·5	1,150	886	17·6
1903-1912 ...	6,500	5,130	0·79	903	17·6	1,150	909	17·7
1906-1912 ...	6,500	5,039	0·775	785	15·6	1,150	891	17·7
Averages ...	6,500	5,046	0·776	895	17·7	1,150	893	17·7

RABI DATA.

		According to Statistical Records.				Calculated by formula.		
1899-1909	6,500	2,484	0·38	614	24·7	1,150	437	17·6
1899-1912	6,500	2,611	0·40	554	21·2	1,150	460	17·6
1903-1912	6,500	2,743	0·42	414	15·1	1,150	483	17·6
1906-1912	6,500	2,824	0·44	435	15·4	1,150	506	17·9
Averages	6,500	2,666	0·41	504	19·0	1,150	472	17·7

The aggregate loss by absorption suffered by the main line and branches of the Upper Bari Doab Canal, when that canal is in flow up to its full capacity (6,500 cusecs) throughout, would be, according to the formula, $Q = c\ a\ d$, 1,150 cusecs; as shown in column 9 of Appendix A, if $c = 1{\cdot}33$.

But the actual supplies flowing, on the average throughout the kharif and rabi seasons respectively, according to our statistical records, are those shown in column 3 of Table III above. And if we multiply the figure 1,150 by the ratio of average supply to full capacity, as shown in column 4 of the table we arrive at the figures shown in column 8. In this way we arrive at the result by the formula, that the absorption loss, in the kharif season, as well as in the rabi season, averages 17·7 per cent. of the average supply at canal head; whilst our statistical records indicate, as shown in column 5 of the Table that the said absorption loss averages 17·7 per cent. in the kharif season, and 19·0 per cent. in the rabi season. The variations of the percentages given in our statistical records for different periods indicate that the results of the calculation by the formula are more reliable than those of the statistical compilations; but in any case the results obtained by the formula agree as closely as could be expected with the statistics.

The statistics of four different periods of years have been tabulated above in order to get rid of accidental agreement in the figures of a single period.

Dyas' Results checked by the Formula.

From Appendix A it may be seen that the absorption loss calculated by the formula in the main line and main branch upper of the canal, in a distance of 151,000 + 124,000 = 275,000 feet, or fifty-five canal miles, comes to 251·4 + 196·8 = 448·2 cusecs. If we omit the last three miles of the main branch upper ($70{\cdot}6 \times \frac{1}{3} = 23{\cdot}5$), we get 448·2 — 23·5 = 425·7 cusecs in fifty-two miles. This is for a full supply of 6,500 cusecs.

On a supply of 3,000 cusecs only the loss would be $425{\cdot}7 \times \frac{30}{65} = 196$ cusecs.

Colonel Dyas, in 1860, found the loss, by observation and measurement, on a canal head supply of 3,000 cusecs, in this same reach of fifty-two miles, to be $156{\cdot}75 + 36 = 193$ cusecs nearly; a remarkably close agreement with the loss calculated by the formula.

Moreover Colonel Dyas estimated in 1863 that the loss on the main line and branches ot the Bari Doab Canal, out of a supply of 3,000 cusecs, would be one-sixth of the whole, and this also agrees remarkably well with the percentage 17·7 calculated by formula in Table III above.

Higham's Results checked by the Formula.

Turning to Mr. Higham's observations of 1874, we see that he found the loss in the first fifty-two miles of the Bari Doab Canal to be 272 cusecs, or $12\frac{1}{2}$ per cent. of the canal head supply of 2,176 cusecs. Mr. Higham's figure of loss worked out to 9·78 cusecs per million square feet of *water surface;* whereas the figures in Appendix A give a loss of 425·7 cusecs on a reduced wetted soil surface of 35·62 million square feet. This means twelve cusecs per million square feet of reduced wetted soil surface of channel with a mean water depth of nine feet. Expressed in terms of water surface area the formula would give a loss of 11·5 cusecs per million square feet, on a discharge of 6,500 cusecs; whereas Mr. Higham's observations gave a loss of 9·78 cusecs per million square feet on a discharge of 2,176 cusecs only.

Referring again to Appendix A, we see that on the Main Branch Lower, the loss calculated by the formula, on the reach from R. D. 115,000 to 432,000, a length of sixty-three canal miles, would amount to 116·2 cusecs under full supply conditions. The loss of forty-six cusecs, reported by Higham, suggests that the canal was flowing with only forty per cent. of full supply at the time of measurement of that loss.

Absorption Losses, Sirhind Canal.

A tabular statement of hydraulic data, similar to Appendix A, has been prepared in detail for the Sirhind Canal; but is not reproduced here. Its principal data, however, abstracted by branches, are given on the next page.

TABLE IV.

Reach. From	Reach. To	Length (feet).	Average bed width (feet).	Average full water depth (feet).	Reduced absorption surface (millions of square feet).	Rate of absorption (col. 5 × 1·33).	Loss by absorption (col. 6 × col. 7).	Name of Branch.
1	2	3	4	5	6	7	8	9
0	130	130,000	200	11·5	28·21	15·4	434·4	Main Line.
130	195	65,000	200	11·5	14·11	15·4	217·3	Do.
Totals and averages.		195,000	200	11·5	42·32	15·4	651·7	
0	10·75	10,750	136	12	1·66	16·0	26·6	"Combined."
Head.	Tail	629,000	57	7 6	40·85	10·16	415·1	Abohar.
,,	,,	200,000	56	9·4	13·15	12·53	164·8	Feeders.
,,	,,	500,000	59	7·2	32·93	9·6	316·0	Bhatinda.
,,	,,	248,000	25	6·3	7·72	8·37	64·6	Ghaggar.
,,	,,	105,000	24	4·1	2·94	5 47	16·0	Choa.
,,	,,	31,000	30	6·9	1·15	9·2	9·5	Navigation.
,,	,,	490,000	32	7·0	19·21	9·4	180·0	Kotla.
Grand totals and averages ...		2,409,000	59	8·55	161·93	11·4	1,844·3	

Statistical records take no account of the discharge or of the absorption loss in the main line upstream of the gauging site at Garhi, mile 26 (R. D. 130,000). Downstream of this site the absorption losses in the main and branch canals, calculated by our formula, amount to 1,844 − 434 = 1,410 cusecs.

The absorption losses calculated by our formula compare as follows with those indicated by the published statistics :—

TABLE V.

Period.	Full capacity (cusecs).	KHARIF DATA. According to Statistical Records. Average supply (cusecs).	Ratio of col. 3 to col. 2.	Average loss by absorption (cusecs).	Percentage of column 5 on column 3.	Calculated by Formula. Loss at full supply conditions.	Loss under average supply (col. 7 × col. 4).	Percentage ratio of col. 8 to col. 3.
1	2	3	4	5	6	7	8	9
1899—1909	8,000	5,700	0·71	1,033	18·1	1,410	1,001	17·6
1899—1912	8,000	5,305	0·66	902	17·0	1,410	931	17·6
1903—1912	8,000	5,086	0·64	855	16·8	1,410	902	17·7
1906—1912	8,000	4,607	0·58	733	15·9	1,410	818	17·8
Averages ..	8,000	5,175	0·65	881	17·0	1,410	913	17·7
		RABI DATA. According to Statistical Records.				Calculated by Formula.		
1899—1909	8,000	4,515	0·56	696	15·4	1,410	790	17·5
1899—1912	8,000	4,531	0·57	633	14·0	1,410	804	17·7
1903—1912	8,000	4,576	0·57	568	12·4	1,410	804	17·6
1906—1912	8,000	4,558	0·57	528	11·6	1,410	804	17·5
Averages ...	8,000	4,545	0·57	603	13·3	1,410	801	17·5

We see that the kharif loss averaged seventeen per cent. of the average canal head supply according to our statistics, whilst it averaged 17·7 per cent. as calculated by the formula. This is a very close agreement. It might have been closer still if the statistics for the three years 1909-1912, which are obviously erroneous, had been excluded from consideration. Thus, the statistics for kharif 1910 show the average supplies delivered at distributary heads (2,814) as very much greater than the average supply at canal head (2,345). And the statistics for kharif 1909 and 1911 show the difference between supply at the canal head and that at the distributary heads as only 600 cusecs ; whereas the statistics for the ten preceding years show this difference to be as much as 1,045 cusecs.