SUBSOIL WATER IN THE PUNJAB PLAINS.

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Introduction—Principles and Laws—Variation of pressure and flow induced—Effect of the medium on flow—Velocity of flow of subsoil water—Flow in a trough—Percolation from the soil—Percolation drains—Percolation into the soil—Percolation through the skin of the soil—Conditions in the Sind-Sagar Doab—Subsoil storage—Conclusions—Appendices I to VI.

Introduction.

This paper has its origin in some notes made by the writer in 1918 in connection with the possibilities of water-logging in the Sind-Sagar doab on the introduction of an irrigation canal. They have hitherto remained buried in the appendices of a report, since pigeon-holed. Very little, if anything, original appears in the paper, which is a study of the subject in the light of existing knowledge. Accordingly previous papers dealing with the subject have been drawn upon, conclusions arrived at, sifted and examined, and, where considered necessary, fresh reasons deduced from research and experiments made by other writers before accepting or rejecting them. It is hoped by this means to be able to advance a non-contentious theory, which will be useful as a *pied-a-terre* for the further examination of the subject in its various branches, which are of immense importance in the Punjab.

If it has the effect of dispelling the very general impression that as one approaches this subject it is necessary to banish all accepted dynamic and static laws and deal with it as a matter obeying an entirely different and unknown set of laws, the writer will not be dissatisfied; but he also hopes that it will suggest directions in which further investigations should be undertaken so as to be able to utilize and control nature for the prevention of water-logging and obtaining supplies when most needed, more effectively than in the past.

Principles and Laws.

No advance can be made in any subject until certain laws and principles have been accepted. Later knowledge may show that some of the laws and principles formerly accepted are erroneous and a re-adjustment of conclusions drawn therefrom has to be made, but in the meantime they have permitted of conclusions, which even in the light of more recent knowledge, may not have to be entirely abandoned. It will be simple to state at the outset some of the more important laws and principles, which have been accepted by the writer, and give the reasons for accepting them later on—

(1) When the subsoil water is at rest, pressure is transmitted throughout and varies with the depth below the water surface.

(2) The rate of flow of the water in the subsoil depends on the gradient of pressure, in the case of lateral flow this will be the surface gradient $= \frac{h}{l}$.

(3) The rate of flow depends on the medium through which the flow occurs, and on the degree of consolidation of that medium.

(4) Under motion in excess of a very limited amount the pressure falls off very rapidly in the direction of flow.

(5) The rate of flow under ordinary conditions is of an extremely low order.

(6) There is no flow in a trough.

(7) Apart from lateral flow out of an area there is a loss throughout the area.

(8) The doab between two rivers may be looked upon as a large reservoir, in which the water is always trying to find its own level, but fails to do so, because the rate of flow is extremely small, while apart from loss by lateral flow out of the area, which may or may not exist, there is a general loss throughout the area and a continuous or intermittent inflow from certain sources.

Variation of Pressure and Flow induced.

The fact that water flows through the interstices of the soil, as demonstrated by its action at wells, shows that though small, there must be continuous passages, through which the water can flow, from which it follows that when at rest, the pressure of water at any place must be that due to the water overlying it. These passages, however, are so minute that the resistance to flow must be very large, and in excess of that of capillary tubes, for which Poisseuille ascertained that the velocity of flow was proportional to the gradient of pressure and $= cd^2 \frac{h}{l} \times \frac{1}{w}$

Where :— c=a constant.
d=diameter of the tube.
l=the length of the tube.
w=co-efficient of viscosity, depending on the temperature.

The adoption of this formula *en bloc*, by giving a value depending on the medium and the degree to which it is compacted, appears a reasonable first approximation to make. Of the above factors $\frac{h}{l}$, the gradient of pressure, is the most important, as this is the one that will be changed on the introduction of fresh sources of supply to the underground water in the doab.

Mr. F. W. Schönemann quotes observers' results in his paper on 'Absorption losses of canals*," and of these, perhaps the most important for the present purpose, are the experiments made by Colonel Clibborn, in 1917, at Roorkee, the results of which are recorded at page 13 of that paper. Two of the results are :—

(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.

These experiments were made with pipes, the sand being placed in a pipe placed in a vertical position and kept covered with water to certain depths. The two results show that the discharge of water through sand was proportional to the gradient of pressure through it. †Experiments with a drain gauge under the Rakh Branch, near Lyallpur, confirm result (1) for the soil below the bed of that channel. These experiments are certainly made on isolated portions of soil, and it can be argued that if such soil were surrounded with similar soil on all sides, the action would be different. This will be dealt with later, but a point to be noticed now is, that in these experiments the sectional area, through which flow took place, was constant, hence the rate of flow was found to be proportional to both the gradient of pressure through the soil and the head, the producer of that gradient of pressure, but if the flow through a portion only of the column of soil, lying between two adjacent areas of flow is considered, it is clearly due to the difference in pressure above and below that portion, or the gradient of pressure through that portion, and is only proportional to the head of pressure on the whole column of soil in so far that, under the conditions existing, the gradient of pressure through the part is proportional to the head of pressure at the surface of the whole column. It is known that water will percolate through soil under the action of gravity alone, so that had the experiments been carried out in expanding or conical pipes, the rate of flow per unit of sectional area would not, at some point, have been in excess of that due to gravity alone, whereafter any increase in the length of the column

* Absorption Losses of Canals, by F. W. Schönemann, pages 10 to 13, Volume V, 1917, Punjab Engineering Congress Proceedings.

† Page 34*l* of the above paper.

of soil at the larger end of the cone would have had no effect on the rate of flow ; if then, the head of pressure had been increased, the gradient of pressure would not have been increased proportionately, because the volume of flow reaching the section, which it formerly passed under the action of gravity, being greater, gravity alone would have been insufficient to pass it, and the distance through which there would be a gradient of pressure would be increased.

Part of the increased head of pressure being used to set up a gradient of pressure where there was no gradient of pressure before, the increase in the gradient of pressure, where there had been a gradient of pressure before, would not have been increased in proportion to the increase in the head of pressure, and likewise the discharge would not have been increased in proportion to the increase in the head of pressure.

A reference to the results recorded in columns 2 and 6 of the statement in Appendix I, prepared primarily for another purpose, to be dealt with later, will show that the rule that the quantity of flow is proportional to the gradient is not very far wrong, because, accepting that for a gradient of 1 in 1,000 the flow is 49 cubic feet per annum, for 1 in 275 it should be 178 ; for 1 in 73, 671 ; 1 in 45, 1,088 ; and for 1 in 28, 1,750. It certainly breaks down for the gradient of 1 in 28, but this is only 25 feet from the strainer, and in addition to any mistake that there may be in the gradient given, the soil in the immediate neighbourhood of the strainer will undoubtedly have been broken down, owing, firstly to the original bore being larger than the strainer and secondly to the material carried through the strainer. The marvel really lies in the fact that the figures support that rule to the extent that they do.

Effect of the Medium on Flow.

Results of observations on the effect of the differences in any degree of consolidation of the medium on flow have been recorded in Mr. F. W. Schönemann's paper already referred to. Captain Ashford has carried out researches to determine the rate at which different classes of soil, mainly sandy soil, give up their available water contents, and has evolved a method of obtaining an idea of the relative yield obtainable from different soils, described in his "Note on Tube Wells*," which relies on the fact that experiment has shown that soils containing larger spaces between the grains give up their available water contents more readily than soils enclosing a greater number of smaller spaces.

It is a well-known fact that the yield of an ordinary sand filter gradually diminishes, but that the yield can be practically restored by removing and replacing the top few inches of sand

* Note on Tube Wells by Capt. Ashford, pages 52 to 56, Volume VI, 1918, Punjab Engineering Congress Proceedings.

only. The percolation capacity of the sand below the top few inches not having been impaired, it follows that the gradient of pressure through it must diminish as the yield diminishes, a state of affairs which can only be the result of the gradient of pressure through the top few inches being increased. It is possible and even probable that due to the grading of the filter the water flows through the bottom portion of it under the action of gravity alone, but this only reduces the length of the path of the water through which there is a gradient of pressure. This is all that it is necessary to say to show that the rate of flow depends on the medium and the degree of consolidation of that medium, and that at the surface of a medium changes take place which decrease the permeability. For further data regarding the permeability of soils the reader is referred to a paper appearing in *Engineering.

Velocity of Flow of Subsoil Water.

Merely stating as a fact that the velocity of lateral flow of subsoil water is very slow, amounting to a few hundred feet in a year is not very impressive, yet the fact that it is slow is of importance as it accounts for certain irregularities in the gradients of the subsoil water in doabs which have been irrigated for many years; and is responsible for as much water not being returned to the rivers as ultimately will be. In order that the almost unrealizable slowness of lateral flow may be more fully realized, the writer has given figures of the rate of flow to a tube well in Appendix I. No great reliance can be placed on the figures obtained, depending as they do on obtaining the correct gradient at several points on a curve and on the correctness of the areas of the section of approach, but they will serve until more reliable figures are obtainable. Regarding the quantity of water in a soil, which is free to percolate under the action of gravity or gradient of pressure, figures† are available. These figures have been reproduced in Appendix II, for ready reference, and in accordance therewith it may be stated that the amount of water, different classes of soil varying from coarse sand to clay can contain, varies from 33 to 42 per cent. by weight of the soil, but of this 13 to 20 per cent. is retained by capillary action, leaving 20 to 22 per cent. by weight or 28 to 29 per cent. by volume free to flow under the action of gravity or gradient of pressure. Hence the rate of flow to the above tube well would be $\frac{100}{28}$ to $\frac{100}{29}$ multiplied by the figures in columns 4 and 6 of the statement in Appendix I, in feet per year, according as the soil is coarse sand or clay. Taking the last item in column

* Wells and permeability of soils, pages 856 to 857, "Engineering", Volume CX, No. 2870, dated 31st December 1920.

† Irrigation Engineering by A. P. Davis and H. M. Wilson, page 21.

6 the lateral flow under a gradient of 1 in 1,000 amounts to 175 to 171 feet only in a year according as the soil is coarse sand or clay.

For further figures of the rate of flow in soils, the reader is referred to the paper already mentioned, on "Wells and Permeability of Soils." In doing so it should be remembered that M is the volume of flow in cubic feet per day under a gradient of 1 in 1, therefore values of M of 30 to 70, correspond to an advance of about 43 to 91 feet in a year under gradient of 1 in 1,000.

The curve of pressure head in the case of the tube well referred to in Appendix 1, denotes how rapidly the pressure head falls off in the direction of flow when that flow is in excess of 10 cubic feet per day through an area of one square foot, which is equivalent to a velocity of advance of 35 feet per day and is that for a gradient of about 1 in 25, while it has already been shown that the quantity of flow for this gradient would probably be considerably less than here given, but for the fact that it is based on an observation of flow at some 25 feet from a tube well strainer, where the original condition of the medium has probably broken down.

Flow in a Trough.

References to the flow in a trough are not infrequent. Persons using it must either have used this term to represent something rather indefinite or never given the subject a moment's thought. The sectional area through which flow takes place towards a trough is enormous, and how all this converging flow can be considered for a moment to find a means of escape through a comparatively limited sectional area that may be assigned to a trough, is beyond comprehension*†, unless it was thought that the medium forming the sectional area of the trough was more porous than elsewhere,—but now that the introduction of canals has filled up old troughs and formed new ones, this position is untenable. In theory a trough is merely a plane, the trace of which is the intersection of surfaces of the subsoil water of two opposing gradients. Thus the surface of a trough itself has a gradient, but not necessarily uniform, or all in one direction. Where the opposing gradients of a trough meet, there is a summit or sump. Such sumps are found towards the tail end of doabs in the Punjab, which are not canal-irrigated or only irrigated within a restricted area.

What evidence there is, denotes that they have shown no tendency to fill up over long extended periods. Hence these conditions point to the fact that there must be a general loss from the

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* Plate I, showing contours of the surface of the water-table in the Sind-Sagar Doab.

† Plates I and II, of Mr. C. G. May's paper, Subsoil Water Contours of the surface of the water-table in the Rechna Doab, Volume VI, 1918, Punjab Engineering Congress Proceedings.

subsoil water either into the bowels of the earth, out of our ken, or into the atmosphere as vapour, and the form taken of the contour of the subsoil water surface on the introduction of canals denotes that this is general and not purely local. A close examination of the gradients of the subsoil water on approach to a trough, shows that they become horizontal in a direction transverse to the plane of the trough, thereby denoting that there is no flow, into a trough, and it is evident that this must be so, otherwise the trough and sumps would fill up, and the steepest gradient be in the direction of the outlet for the subsoil water. The writer does not recollect ever having seen the occurrence of brackish water connected with the neighbourhood of subsoil water troughs of long standing ; in view of the foregoing the connection is obvious, and it denotes that the loss of part of the water, at least, goes on in such a manner that it cannot carry the salts it contains with it. It is understood that Mr. Wilsdon is investigating the subject of the loss of water from the subsoil as a vapour; the results of his investigations will be looked forward to anxiously as an important contribution to the scientific side of the subject, and it may be shown that though canal channels are the chief sources of the subsoil watersupply, the irrigation of fields is of more importance than it has been assumed to be in the past, owing to the blanketting effect on the escape of water vapour through the soil. In addition to the loss into the atmosphere, there is no reason why there should not be a subterranean loss. The alluvial deposits must rest on some class of soil, which term includes rocks, while all soils are permeable to a greater or less degree and in the same way as there are land springs, there will be springs in the bed of the ocean. It is, therefore, well within the realms of possibility that the subsoil water of the alluvial plains of the Punjab finds an exit in the course of time out of the soil where it is at lower levels than the subsoil water-table, which will be, in the majority of cases, at least, below the surface of the ocean.

This carries the subject down to the final guiding principle already enunciated, that a doab between two rivers may be looked upon as a large reservoir, in which the water is trying to find its own level, but fails to do so, because the rate of flow is extremely small while apart from the loss by lateral flow out of the area, which may or not exist, there is a general loss throughout the area and a continuous or intermittent inflow from certain sources.

More space than was intended has already been taken up on these preliminaries and the further deductions therefore, which will incidentally pile up evidence in their support, will have to be curtailed or held over for another paper.

Percolation from the soil.

A well-known case of percolation from the subsoil, is that of percolation into wells. Many experiments have been made on the percolation into wells, and two years ago Mr. C. B. Barrie* dealt with the supply of water from numerous wells sunk by the North-Western Railway, and from these he arrived at twenty gallons per hour per square foot of bottom area of a well or 888 cusecs per million square feet of percolation surface as the average safe yield through the subsoil at the bottom of wells of twenty feet diameter. Figures of the yield from a tube well in the Minto Park, Lahore, under different heads derived from the data supplied by Captain Ashford†, have been given in Appendix III.

These figures are certainly of percolation from a sandy subsoil, but even so it is worth while to draw attention to their difference in magnitude to figures of percolation into the soil, which in the case of large canals of about ten feet in depth, amounts to from eight to twelve cusecs per million square feet of wetted area, a large proportion of which is bed area. At first sight it might be assumed that the percolaton into a well or drain would be doubled by doubling the percolation surface, but this will not be so unless the succeeding percolation areas proceeding away from the percolation surface are all doubled, and this it is impossible to do in the case of a single well or drain. All that is actually done in enlarging a drain, is to remove a certain amount of soil, through which the gradient of pressure is very rapid; but before the increased surface can yield a greater supply than it was formerly passing, a larger quantity of water must approach that surface, and a large proportion of the head saved will be utilized in causing this additional supply to pass through the more remote percolation areas, only leaving a slight additional head to force the water through the final percolation area or surface. For instance, if the total depression head of a tube well is twelve feet, and it is replaced by a tube well of larger diameter, which entails the removal of soil through which the drop in pressure was two feet, the depression head used in forcing the water through the more remote sectional areas of approach was ten feet and now becomes twelve feet, hence the gradient of pressure towards the well is increased by one-fifth and the supply also by one-fifth only.

This explains why numerous small percolation drains distributed over a wide area, give a greater yield than a single drain with a percolation area equal to that of the aggregate percolation areas of the small drains.

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* Railway Water Supplies by C. B. Barrie, pages 21 to 28, Volume VIII, 1920, Punjab Engineering Congress Proceedings.

† Note on Tube Wells by Captain J. Ashford, pages 49 to 60, Volume VI, 1918, Punjab Engineering Congress Proceedings.

The cases of increasing the length of a strainer of a tube well, or the diameter of a well with bottom percolation area, are not quite on all fours with that of the case of increasing the diameter of the strainer of a tube well, as not only is the area of the percolation surface increased, but the succeeding areas of approach differ slightly from what they were before, though this difference becomes less and less for the more remote areas of approach, hence the result is very much the same. There is, however, another aspect, from which the question of enlarging a drain or diameter of a well with bottom percolation area should be viewed, and this is that the supply thereto can be increased by increasing the depression head, because one of the results of increasing the percolation surface, is the reduction of the steepness of the gradient of pressure in the neighbourhood of that percolation surface in proportion to the increase of that surface. Thus by increasing the percolation surface and the depression head, the supply can be doubled without increasing the likelihood of a breakdown owing to causes which will now be dealt with.

Percolation through a percolation surface is increased by an increase in the gradient of pressure through the soil, but this gradient of pressure will open up the structure of the soil and, if increased too far, carry the soil with it. In the case of bottom percolation wells, gravity is acting against this disrupting process, but this is not so in the case of open drains, the sides of which must slough in very readily under the combined action of flowing water and gravity. This opens up one aspect of the desirable treatment of percolation drains in the search for efficiency, namely, securing the stability of the side slopes; but before action on this line is taken, it is desirable to consider the other limitations of percolation drains.

Percolation Drains.

In the sketch below, N S is the ground surface and, A B the subsoil water-table with gradient in the direction, A B. C D E is the waterway of the drain, used to carry off the water percolating into it. At the very best the drain could remove the

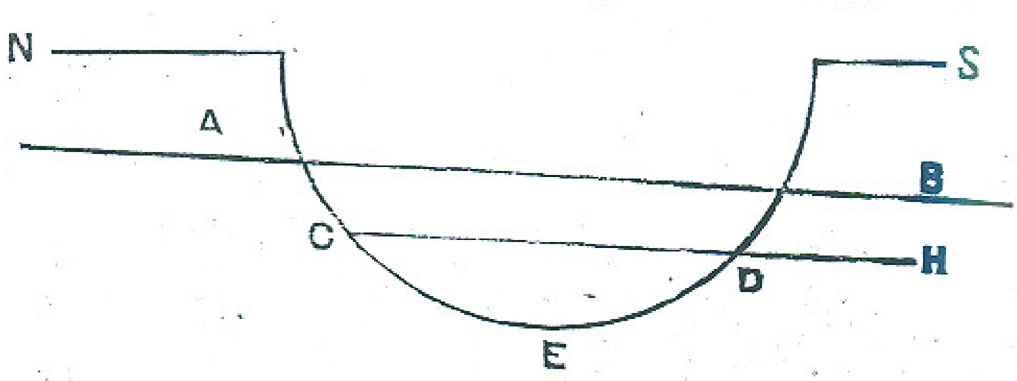


Fig. 1.

amount of water flowing towards it in the depth of soil, F C, and the subsoil water-table be lowered on the far side to D H; but it is well-known that a drain is not as effective as this and the reason is not far to seek. The flow into the drain is through the surface C E D, a gradient of pressure is set up in that direction and the pressure at any point in the soil below E is greater than the static pressure due to the water at the level C D, so that the water is continually passing under the drain in the direction of B, under a pressure in excess of the static pressure due to the depth below C D, and under that pressure continues to flow upwards as well as laterally and rises above the level of D H, to an extent which depends on the relation of the width C D, to the depth of soil below E, through which the water is percolating. In any drain that can be dug C D, will, except under special conditions, be very small compared with the depth of soil below E, through which percolation takes place, and unless C D, can be lowered fairly considerably below A B, the quantity of water withdrawn from the soil will be very small, the lowering of the water surface on the side A, very local, and the appreciable lowering of the water surface on the side B, also quite local.

The foregoing is far from being a recommendation of drains for preventing or curing waterlogging, but there are conditions of local configuration and nature of the soil which would render a percolation drain very effective. It will be sufficient to give one example of conditions which will often obtain in the neighbourhood of natural depressions or surface drainages.

In the sketch figure 2, N A D B S, is the natural surface D, a natural drainage depression and A D B C, the less permeable soil of that depression; usually the boundary, A C B, between the two classes of soil will not be well defined. G C H,

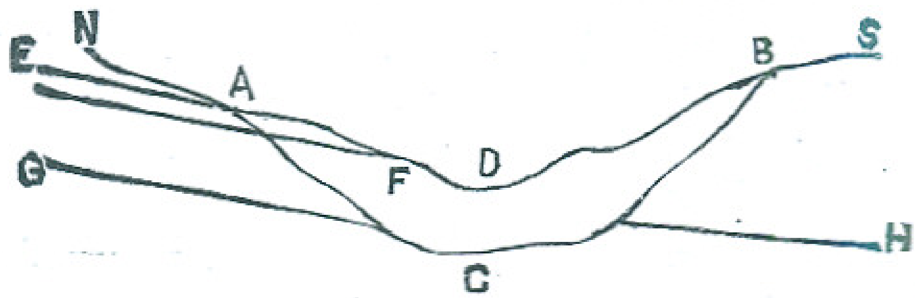


Fig. 2.

the surface of a sand strata, E F, the surface of the subsoil water-table, which would develop, if all the soil were uniform, and E A F, the one which will develop owing to the less permeable soil of the drainage. Water will be forced up through the less permeable soil of the drainage, but not fast enough to prevent the water-table at A, rising and overtopping it, under which conditions there may be extensive waterlogging, but a drain at D, piercing the less permeable stratum, would afford relief and lower the susbsoil water-table considerably. The less permeable stratum should be pierced throughout the length of the drain, although this means excavating below the final bed of the drain, as then such a drain would partake of the nature of one with lined sides.

The gradient through the less permeable stratum would naturally be steep and not much head would have to be killed at the percolation surface: the main percolation would be through the sand which would fill up the low places in the bed until such drain worked under conditions similar to those of a bottom percolation well.

The series of percolation areas of approach to a bottom percolation well are the curved surfaces of hemispheres, $2\pi r^2$, and those of a drain per unit length, half cylinders, πr, hence the more remote percolation areas of approach in the case of a well are greater than those of a drain and will use up less of the available head, from which it follows that such a drain should be capable of working under a greater head than has been found to be safe in the case of a bottom percolation well and its safe yield should be as great as that of such wells. Undoubtedly the conditions sketched out above are ideal, but it is under such conditions that waterlogging is most likely to occur, and careful surveys should enable somewhat similar conditions to be ascertained.

It will be seen that though the indiscriminate use of percolation drains is of little value as a preventive or cure for waterlogging, there will be conditions under which such drains can be constructed and prove efficacious.

Percolation into the soil.

In the case of percolation out of the soil it has been seen how water percolates through successively smaller percolation areas, and the medium through which the percolation takes place is saturated, only $\frac{2}{3}$ to $\frac{1}{2}$ of the water in the medium according as it is coarse sand or clay* flowing, the balance being retained by capillarity. Percolation may take place into soil which is already saturated, in which case there has to be a flow in the medium to make room for the new supply and a gradient of pressure is set up in the direction of flow. If water percolates into soil containing less water than it can retain by capillary action, flow will take place under the action of gravity and capillarity alone until the water contents has reached that limit. Figures of the rate of flow under the action of gravity and capillarity alone in various classes of soil are not at hand, but figures of the rate of rise against the action of gravity have been given by Davis and Wilson, † and have been reproduced in Appendix II.

*† Irrigation Engineering by Davis and Wilson, pages 21 to 118.

The greatest rate of rise is that given for the first fifteen minutes and amounts to $\frac{1}{4}$, to $\frac{1}{12}$, of a foot in that time, from which it follows (see Appendix IV) that 2·75 to 4·5 hundredth of a cubic foot of water can be disposed of by this means in soil containing no capillary held moisture per square foot of area or 30 to 50 cusecs per million square feet of area. This figure is astounding in view of the fact that the loss by percolation from a large canal is in the neighbourhood of 8 to 12 cusecs per million square feet of percolation area only.

The medium between a source of a water supply and the water-table will rapidly become water laden up to its capillary capacity, and additional water which percolates from the source will travel downwards under the action of gravity and laterally under capillary action, but, if the supply from the source exceeds what can be disposed of in this way, the soil below the source will become saturated and pressure will be set up, which will reduce the percolation from the source and increase the percolation through the medium.

It is necessary to turn to the further consideration of what the lateral flow due to capillarity can amount to. The references already quoted show that the rate of capillary rise from a saturated surface, against the action of gravity, diminishes as the thickness of soil containing capillary held moisture increases, that the rate of decrease varies with the nature of the soil and that the extent of the rise also varies with the nature of the soil. Capillary action causes the flow of water from the soil charged more highly with capillary held water to a soil less highly charged, from which it may be assumed that the force producing capillary flow depends on the gradient of capillary held water.

Clay has a greater capillary capacity than sand, and in consequence, the limit of capillary rise may be expected to be greater in the case of clay than in the case of sand. This is so, but the limit of capillary rise in clay as compared with that in sand is greater than what would be due to its greater capillary capacity, while the rate of rise in dry soil adjacent to a saturated surface is greater in the case of sand than in the case of clay, which can only be explained by assuming that the finer the soil, the greater is the resistance to capillary flow, and the greater the force causing capillary flow. Certain figures* which have now come to the notice of the writer, do not entirely support this theory of capillary flow. Reference to this article shows that the soil immediately above a water surface,, which has become charged by capillary action, is less heavily charged than the soil about one foot above the water surface, the charge increasing with the distance from the water surface

*Capillary Moisture and its effects on Highway Subgrades, by W. McLaughten, pages 1037 and 1038, Engineering News—Record, Volume 86, No. 24, 16th June 1921.

up to some point, whereafter it diminishes more or less uniformly. Capillary action is a dual force, which retains water, passive, and causes flow, active, into adjacent dry soil. It is a case of two forces acting in opposition to one another, and it is not inconceivable that a water surface creates a larger passive force in its neighbourhood reducing with distance therefrom than capillarity causes at some point beyond the influence of the passive force of the water surface.

However this may be, it is clear that in the case of lateral capillary flow where gravity is not opposing water movements, there will be no limit to the distance to which it will extend, but as the gradient of the quantity of capillary-held water will soon become very small, the rate of movement will be very small and the distance to which it extends will be limited by the rate at which the water is removed from the soil in the form of vapour.

If the case of percolation into the soil from a source or channel which has contained water for a long period is considered, it is clear that a very small amount of the water supply from the source flows under capillary action, and for all practical purposes the problem is reduced to the consideration of percolation under the action of gravity or gravity and pressure. This being so, as soon as the supply entering the soil is in excess of that which can be disposed of under the action of gravity alone, the soil will become saturated, pressure will be set up, which will reduce the supply from the source, cause lateral percolation and assist gravity in causing percolation vertically downwards. Percolation vertically downwards being aided by gravity will be the more rapid, but the lateral percolation will result in the area of percolation increasing to such an extent that a point will come at which the supply of water is insufficient to saturate the increased volume of soil, into which it is percolating, thereafter the water will percolate vertically downwards under the action of gravity alone, but in doing so it will tend to spread laterally owing to the soil and imprisoned air diverting the direction of flow. If the water source is a narrow channel the gradual growth of the volume of saturated soil, as percolation goes on, will drive the air before it and it will escape laterally, but if the channel is a wide one, pockets of air will be liable to be enclosed and the lateral movement of the percolating water increased thereby. The final limit of the saturation of the soil below a source of water supply will not be capable of exact calculation, but will largely depend on the rate at which water enters the soil from the source and the dimensions of the area through which the water enters, as it depends on how soon pressure can be eliminated by the increase of the area of percolation to such an extent that the water can pass without the assistance of pressure.

The limit of saturation will often be where the soil changes from one of less percolation capacity to one of greater percolation capacity, but in the event of a stratum of less percolation capacity being encountered, the water will percolate laterally over that stratum until it extends over a sufficiently large area for the whole of the supply, under the conditions set up, to percolate into it. If the pressure is dissipated before the water-table is reached, the flow of the subsoil water is uninterrupted, but if it extends down to the water-table a gradient of pressure is set up in the water-table to either side, which must be overcome by an opposing gradient before lateral flow under the channel can take place. In the above will be found the germs of the explanation of what Mr. Elsden referred to as solid and dispersed cones in a paper presented to the Congress last year.*

Figure 3, exclusive of the lines B A C and X Y, shows the

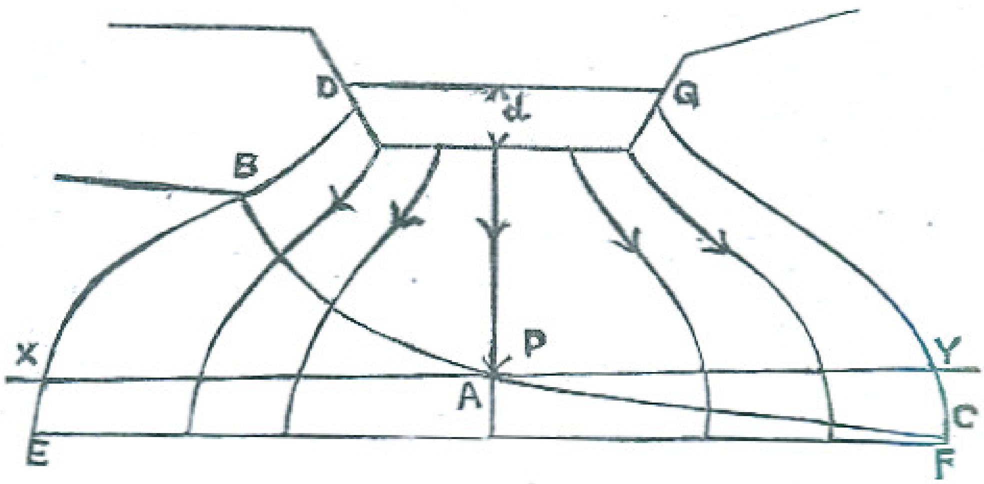


Fig. 3.

conditions in the case of a channel which has been in flow for some considerable period. Below the channel there is a region of saturation, in which there is a gradient of pressure, varying from that due to a depth of water at the bed of the channel to nil (atmospheric) at the boundary of the region of saturation.

The conclusions which may now be drawn therefrom are :—

(1) The sectional area of the region of saturation and the depth to which it extends are functions of the nature and compactness of the soil, the bedwidth of the channel and the depth of water therein.

(2) If the medium is uniform, the gradient of pressure will be greater in the neighbourhood of the bed of the canal than at a site more remote therefrom owing to the increase in the percolation area at the sites more remote.

* Waterlogging from Irrigation Canals in Alluvial Soil by F.V. Elsden. Punjab Engineering Congress Proceedings, Vol. IX, 1921.

(3) The percolation from the channel will not vary directly as the depth in the channel, but as the gradient of pressure through the skin of the channel. Under certain conditions, such as in a drain gauge*, the gradient of pressure varies directly as the depth in the channel, hence the percolation from the channel varies directly as the depth of water in the channel.

(4) If the surface of the water-table, as raised by the supply from the channel, is below the region of saturation and there was originally a flow of subsoil water from one side to the other of the channel, that flow can continue.

(5) If the surface of the water-table cuts the region of saturation and the original direction of flow of the subsoil water was from one side of the channel to the other, it will be possible for flow to continue in that direction by heading up on the side from which the flow is, to an extent, less than the supply level in the channel.

Conclusion (5) will require some additional proof. It is a point which the writer has pondered over for some considerable time past, because, if it was not so, two small high level channels on either side of a lower level large channel would effectually prevent percolation from that channel. Assume that flow does take place under the channel from left to right and that the surface of the water-table is some such line as B A C, (see figure 3) through A under the centre of the bed of the channel, draw a horizontal line X Y. From the bed of the channel down to B A C, there is a gradient of pressure; the resultant of this pressure on any point on the line B A C, will be referred to as the superimposed pressure. The pressure at any point below B A C, will be that due to the depth below B A C, plus the superimposed pressure. If the superimposed pressure at A is P, it is clear from the figure that the superimposed pressure at any point A C, decreases at sites more remote from A.

Therefore there is a gradient of pressure in the subsoil water below A C, in the direction A C. The pressure at any point on A X, is that due to the height above that point to the line B A, plus the superimposed pressure on B A, and it is possible to locate B A, so that there is a gradient of pressure along X A, in the direction X A.

* Drain Gauge under the Rakh Branch, at Lyallpur, discussion on paper on "Absorption Losses from Canals". by F. W. Schönemann, page 341, Volume V, 1917, Punjab Engineering Congress Proceedings.

In the paper by Mr. F. W. Schönemann referred to above, that officer put forward a formula Q =cad, for calculating absorption losses, *i. e.*, percolation plus evaporation losses from canal channels.

It is not very clear how he arrived at the values of c, adopted by him, but he drew curves connecting the coefficient c with the capacity in cusecs for a series of channels of standard sizes selected by him, and it does not seem unlikely that the curve was drawn to fit the accepted losses for the set of channels selected, and that the coefficient c, for each size of channel was selected accordingly. However this may be, on examination of the coefficient c, he found that it varied in some way with the size of the channel to an extent greater than that justified by the varying viscosity of water, due to assuming that the temperature of the water varied within limits inversely with the size of the channel, and he connected it with the reciprocal of the hydraulic mean depth by means of a multiplier, which varied in some way with the size of the channel, which he did not explain.

The writer considers that he has by his analysis of percolation into the soil shown why the coefficient c, varies with the size of the channel, as according to his analysis, the larger the channel the greater the distance, in which the head producing the percolation has to produce a gradient of pressure. The analysis also shows that the percolation on any given channel does not increase as rapidly as the depth in the channel is increased, because the whole increase in depth is not utilized in increasing the gradient of pressure through a length of soil, in which there was formerly a gradient of pressure, but is partly utilized in setting up a gradient of pressure in a portion of the soil beyond the limit where the pressure was originally nil (atmospheric). This is all fairly obvious as long as the local zone of saturation under a channel is above the subsoil water-table, but is not perhaps so obvious when the local zone of saturation of the channel is cut by the surface of the water-table, but the change in gradient of pressure down to the subsoil water-table depends on the extent of the increase in the percolation area at the point at which the water from the channel merges into the subsoil water-table.

Turning to the quantitative analysis of the percolation from canals, it will be seen that the absorption per unit length of the channel will probably vary as the product of functions of the reduced wetted perimeter and the depth. If there is no pressure, but merely a film of water over the percolation area, the percolation will obviously be proportional to the percolation area, or wetted perimeter; when there is a definite depth of water, it will probably be more accurate to take the reduced wetted perimeter instead of the wetted perimeter.

Let Q=absorption in cusecs per unit length of the channel.
W_p=reduced wetted perimeter.
d=full supply depth in the channel.

Then $Q = W_p d$.

But for convenience in figuring make

$$Q = \frac{W_p d}{1{,}000{,}000}$$

Vide appendix V, and plate II, $Q = \frac{6\ W_p d^{0 \cdot 3}}{1{,}000{,}000}$

$d^{0 \cdot 3}$ is small compared with d, and the loss by absorption from a channel under full supply conditions with a full supply depth of 1·0 feet is not so very much less than that of a channel of full supply depth of 10 feet. It is probable that the back pressure set up by the additional pressure required to cause the extra supply from deeper channels to percolate through the soil cannot entirely account for the power of d in the above equation being so small, from which it must be concluded that the soil once subjected to a pressure of 10 feet head of water is less permeable than that which has only been subjected to a head of pressure of 1·0 feet. This can easily be tested by an experiment, in which the loss in a new tank under small heads is observed, and again observed after the tank has been subjected to a considerable head of pressure over a long period. It is for this reason that the formula $Q = \frac{6\ W_p d^{0 \cdot 3}}{1{,}000{,}000}$ is only put forward as a formula for ascertaining the absorption loss (average over a large number of channels to get rid of differences of soil in which excavated) of channels under full supply conditions, and not for ascertaining the loss in a channel for different depths of supply less than full supply. The presumption is that in any one channel the loss will vary according to some function of d less than d, but greater than $d^{0 \cdot 3}$.

Percolation Through the Skin of the Soil.

The main factor determining the amount of percolation from a water channel or reservoir is the permeability of its skin.

The standard figures* of loss are still those given by Mr. Kennedy in 1883; the figures include loss from evaporation and are as follows in cusecs per million square feet of percolation surface :—

Flooded virgin soil	..	8
Cultivated land	..	9·75
Watercourses	..	9·4
Distributaries	..	3·3
Branch Canals	..	2·2
Main Canals	..	9·75

* The Absorption Losses of Punjab Canals by F. W. Schonemann, page 7, Volume 5, 1917, Punjab Engineering Congress Proceedings.

Many of the main canals have much in common with cultivated land; in the one case the surface is disturbed and broken by percolation into the canals during closures and in the other the surface is broken and disturbed by cultivation, yet the loss through one covered with several feet of water is the same as the loss from the other covered with only a few inches of water. If the cultivated soil were enclosed within banks and covered with a depth of 10 to 12 feet of water, the loss therefrom would, in the course of time, be very much the same as it was under a few inches of water and this can only be explained by a change taking place in the top soil on subjection to pressure, but something more than this appears to take place in the case of branches and distributaries, which is more effective in reducing losses in the case of branches than in the case of distributaries. A possible explanation of the absorption losses from branches being less than that from distributaries per unit of area, is that the observations of absorption losses from branches were made when they were running with less than full supply; but this does not explain why the loss from distributaries and branches is so much less than that from main canals and watercourses. The skin of the latter two classes of channels is subject to more disturbance than that of the former as watercourses are dry for long periods and subject to damage by cattle, etc., while in many main canals water percolates into them during closures, which breaks down the skin, or erosive action is severer than in branches or distributaries. It is possible, then, that this skin may have something to do with the amount of absorption losses, and that the formation of a skin of varying permeability does not depend only on the pressure under which the fine particles are driven into the pores of the soil, but on other causes.

Mr. J. Albert Holmes, in his paper on "Hydraulic Fill Dams"*, besides mentioning that pressure increases impermeability also refers to the fact that there is a greater resistance to percolation at the surface of a material than within the material and states that the presence of vegetable matter in the soil reduces percolation, in proportion to the quantity of vegetable matter in the soil. Again it has been found that the clogging of sand filters is largely due to colloidal matter: the writer has not been able to ascertain much about the properties of colloidal matter, but one class of colloids will precipitate another† and it is possible that use can be made of this in obtaining a less permeable skin.

The absorption experiments in tanks at Narwala are a striking illustration of how rapidly a skin begins to form when the necessary

* Hydraulic Fill Dams by J. Albert Holmes, Water and Water Engineering, Volume XXIII, No. 269, 20th May 1921, page 179.

† Water and Water Engineering, Volume XX, No. 236 (new series), 20th August 1918, pages 187 to 189.

material is present. In these experiments the absorption losses of two tanks were compared, one was unlined and the other lined with open jointed slabs : to ensure that the results were not due to inherent differences in the tanks, the two were interchanged, the lined tank of the first series of tests becoming the unlined tank of the second series and the unlined tank of the first series of tests the lined tank of the second series, yet on both occasions the absorption from the lined tank was the greater. In the lined tank much of the fine material, which would otherwise have been carried down into the pores of the soil, was deposited on the slabs, while the water had a free passage through the joints between the slabs and between the slabs and the soil on which they were seated, with the result that the pressure on the soil was very much the same in both cases, while in the lined tank self-tamping was interfered with. It may be claimed that the slabs were well bedded on the bed and sides but however carefully this may have been done, there would be little resistance to flow between the soil and the slabs compared, with the resistance to percolation into the soil, and it is obvious that any skin that was formed in the unlined tank during the first series of tests would have been completely broken when placing the slab lining therein before the second series of tests were made.

There is no reason why in the case of canal channels this less permeable skin, when once formed, should remain for all time the skin of the channel : it could be covered up by introducing works to flatten the gradient, or formed at a level, which can be protected, subsequently, by a covering of soil or silt. The severe erosion, which often occurs in main canals, could be stopped by the exclusion of more of the heavy silt at the head works and flattening the gradients of the canals.

If, on the average, the amount of absorption loss from canals is as given above, it must be considerably less in some channels, and if this can be traced to the formation of a less permeable skin and its subsequent security from damage, it will be quite worth while to see what more can be done to direct the forces of nature to form and protect a less permeable skin. The formation of an impermeable skin in the soil itself has the advantage over any independent lining laid on the soil, that if it is damaged, the increased percolation will be confined to the area of the damage only, while if an independent lining is faulty or damaged, the water will flow between the lining and the soil and percolation will take place through a large area of soil surface, prevented by the lining from developing a less permeable skin from natural causes.

Previous efforts at lining have resulted in an independent lining except in the case of clay puddle or oil spraying, the latter of which has not proved to be lasting as the oil itself is volatile.

The incorporation in the soil of waste vegetable matter, rolling with a heavy roller with a suitable pattern of tread and inoculation or chemical treatment of the soil, have possibilities which should not be ignored.

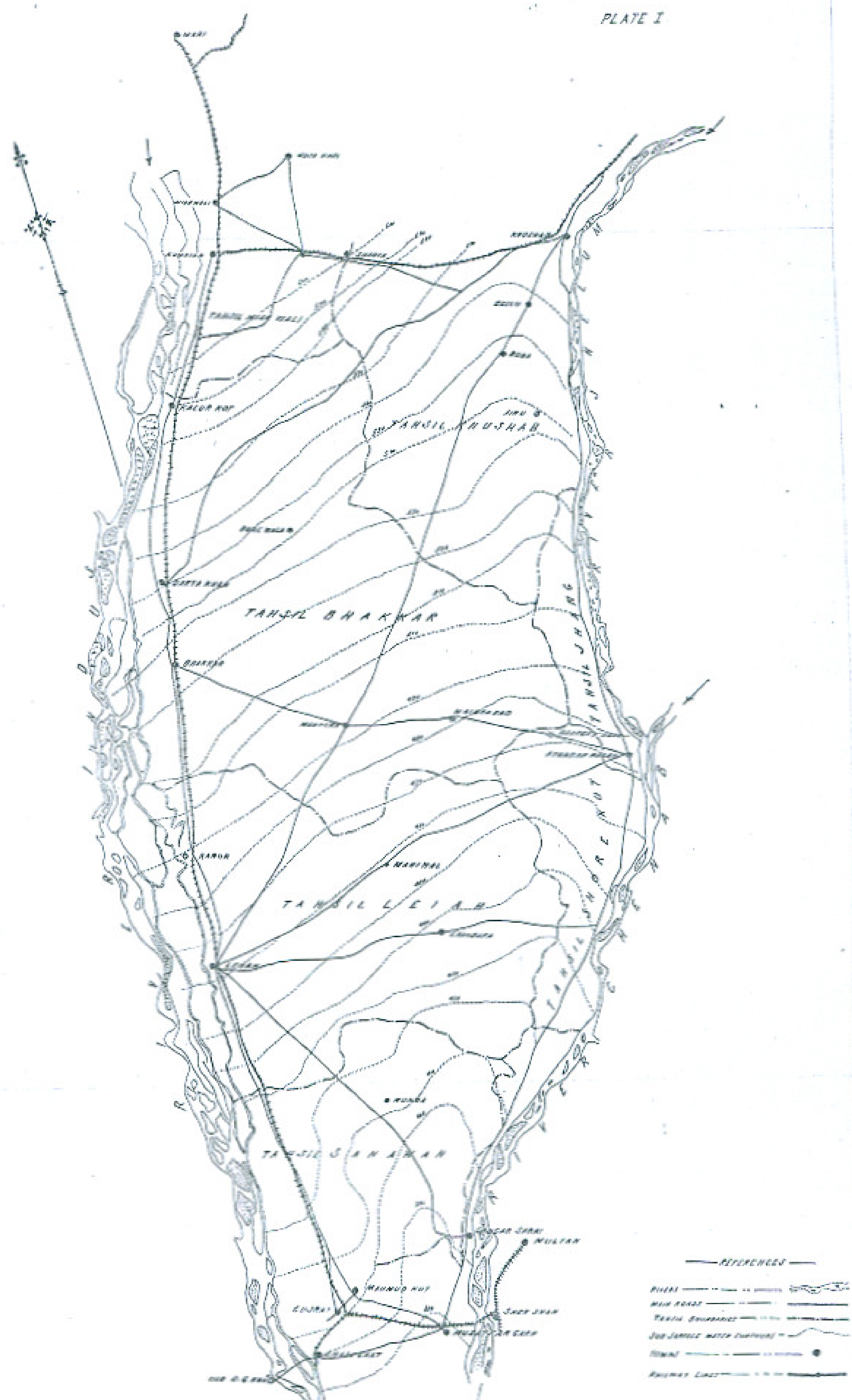
Conditions in the Sind Sagar Doab.

In plate I the contours of the water-table in the Sind Sagar Doab have been given.

The plan shows that the sectional area through which the water enters the doab is many times greater than any sectional area obtainable towards the south of the doab, through which there can be a flow from the doab into the river, which hypothecates a loss within the doab. The river Indus opposite Kundian is at a higher level than the river Jhelum opposite Khushab by some fifty feet, but this difference of levels diminishes towards the south till at the junction of Chenab and Indus they are the same. Under these conditions the main source of the supply of water is the river Indus; there is a certain amount of supply from the Salt Range to the north, but certainly not in excess of that from the Indus, and owing to the high level of the Indus the subsoil water trough is some ten to twelve miles from the Jhelum and the loss from the Jhelum is checked by the height of the water-table along it. Towards the north the supply from the Indus is so copious that a supply passing a unit length at right angles to the steepest gradient passes through more than a unit length before the trough is reached, thereby increasing the area over which loss can take place from the supply entering that unit length. At Leiah, where the height of the river above that of the river Chenab is less, the reverse is the case in spite of the doab here being narrower than further north. As far as observations have been made when sinking wells, the subsoil throughout the doab, except perhaps towards the south, is uniform, consisting of a yellow sand covered by some twelve feet depth of soil, also of a sandy nature, but to the north to somewhat south of a line across the doab from Kundian to Khushab the depth of covering soil is greater on account of hill washings. Under such conditions the subsoil flow will always be in the direction of the steepest gradient, and the writer would suggest that the volume of flow from any source dictates the superficial area under which that volume will distribute itself but, perhaps, it would be preferable to state the case by saying the superficial area available for the distribution of the supply from any portion of a source controls the volume of that supply. If this were not so, the level of the water-table would rise until the supply from the source were diminished by the back pressure. Under these circumstances the conditions in any one isolated area are so dependent on the conditions in adjacent areas that it is difficult to denote more than the general results of the introduction of fresh sources of water supply. If the loss from the sub-

CONTOURS OF THE SUBSOIL WATER TABLE
IN THE
SIND SAGAR DOAB

PLATE I



soil reservoir is in the form of vapour escaping into the atmosphere, it would be natural to expect that its amount varies as some function of the depth, not necessarily to the water-table itself, but to the limit of capillary rise, and that as soon as the limit of capillary rise reaches the ground surface, this loss would increase. This being so, one would expect the surface of the water-table when near the ground surface to conform to some extent to the ground surface contours as noticed by Mr. Colyer. The result would be the same even if the loss from the reservoir into the air was supplemented by a loss into the bowels of the earth or through some subterranean channel.

In the Sind Sagar Doab the depth to the water-table increases towards the trough as the ground surface contours run more or less across the doab, and diminishes towards the south of the doab as the ground surface slopes more rapidly in that direction than the subsoil water-table. Another point which can be observed from plate I is, that if cross sections are taken roughly parallel to the Kundian-Khushab Railway, the gradient on them, speaking generally, flattens out in the neighbourhood of the trough. In the north this is due to the gradient at the trough, at right angles to the sections, being flatter than on parallel lines more remote from the trough; further south it is due to the subsoil water contours making loops of larger radius. Below the Leiah and Sanawan tahsil boundary a change is introduced by the inundation canals from the Indus, the practical effect of which is to move the virtual position of the river further inland, and here again the gradient along the trough is flatter than at lines more remote, and the gradients along cross lines are flatter as the trough is approached. Accepting the conclusion that the supply from a source is balanced by the loss from the superficial area under which that supply flows up to the trough, it is possible to obtain a ruling gradient. The ruling gradient when the flow in the subsoil is parallel is the most important, and may be termed the key gradient for the medium in question, and from it the remaining ruling gradients when the lines of flow are no longer parallel but diverging or converging can be derived. With the aid of these ruling gradients it will be possible to some extent to forecast the configuration of the surface of the subsoil water on the introduction of fresh sources of supply and say in which direction the subsoil water should be given free access to the natural drains.

Thus in the case of the Sind Sagar Doab the subsoil drainages into the Jhelum and Chenab rivers should obviously be kept open, while a large channel down the western side of the doab would do no harm, as it will convert flow from the river Indus into the doab into a flow from the doab into the Indus without adding very materially to the supply already entering the doab. The general direction of the surface drainages is from north to south, so that aligning channels on this principle would entail the crossing of some of them, but ample waterway could be left for these. On the other hand, alignment of canal channels on these lines precludes the use of channels along the drainages as percolation channels to any useful extent, and a more north to south direction of the channels fits the configuration of the ground surface better. Though it is probable that the major portion of the doab will remain unaffected by waterlogging, the conditions in the south of the doab, where waterlogging already exists during parts of the year, will, in the course of years, become worse and the area affected likely to extend some distance further north.

To remedy this drains will have, in time, to be constructed, or, as the gradients into the river here are insufficient, pumping on a fairly-large scale will have to be resorted to.

Subsoil Storage.

It has already been shown that the amount of water which can be recovered by percolation from a saturated soil amounts to from 28 to 29 per cent. by volume of the soil.

If the soil can be made to give up its supply at will, an enormous reserve of water supply would be available. Prior to the construction of canals in the Punjab, the winter supplies were only augmented to a very small extent by storage in the plains, the storage reservoir being confined to a narrow strip along the rivers where the direction of subsoil flow changed according as the river was at a high or low level. Since the introduction of canals the early winter supply has been considerably increased thereby, but many of the large canals have not filled these reservoirs, particularly at the downstream end of the doabs, to the extent that they ultimately will, and a considerable increase in supply from this source may be anticipated, and as further canal extensions fill up the subsoil reservoirs in the high ground alongside rivers.

As it is some of the creeks along the east bank of the Indus flow throughout the winter season with water obtained from percolation from the reservoir filled by the Indus in its higher stages, but not much of this water finds its way back into the river, as it is utilized by means of jhallars placed along its banks.

There are possibilities in impounding water in the riverain tracts and drawing on it during the winter, as by so doing the water in the soil besides the surface water would be available for drawing on.

Conclusions.

In the course of this paper the writer has made but a few passing references to the subsoil consisting of strata and pockets of varying permeability. No doubt such do exist throughout the plains of the Punjab, but they merely introduce complications into the subject, which in an initial examination it is desirable to avoid as far as possible, and by so doing it is hoped that a simple and reasonable theory of flow in, into and out of the soil has been built up, which does not transgress the commonly known laws of nature and that it is not, in consequence, necessary or justifiable to think that the subject entails the introduction of a number of new rules peculiar to itself.

It should not be difficult to visualize the fact that resistance to flow through a uniform medium of constant area is constant, that in the case of flow out of the soil in a restricted area the resistance to the flow increases as the area through which it takes place diminishes, but that near the exit it is modified by the texture and the consolidation of the soil being broken down, and that in the case of flow into the soil the action is reversed, the surface of the soil through which the water enters becoming clogged and consolidated. To reduce percolation from channels the natural effort would be in the direction of assisting the clogging and consolidation of the skin and the protection thereof, but so far efforts have been mainly directed to the addition of an artificial skin, instead of to the examination of nature's methods of staunching leaks and supplying the constituents needed for the purpose. The chief sources of trouble from subsoil water in the Punjab are that in certain localities it rises too near to or even above the ground surface, rendering the locality unfit for cultivation and unhealthy. Apart from local differences of the soil being responsible for this, the rivers are insufficient drainage channels, due to their high level, which again is due to the amount of detritus carried by them. If this were reduced, the river levels would retrogress and the rivers become more efficient drains. Under certain circumstances artificial drains can remedy the conditions, but not only must be the percolation surface of such drains or their collecting grounds be large, but the areas of approach to the percolation surface must be large, a state of affairs which is attained better by a number of small drains distributed over the area than by a single drain with an area of percolation surface equal to the aggregate of those of the smaller drains through the area. Where waterlogging is local and due to differences in the permeability of the medium, drains scientifically aligned to obtain their supply under considerable pressure by piercing a less permeable but more stable stratum will be effective; but if it is the case of a uniform medium, which cannot get rid of its supply before it reaches too near or percolates through the surface owing to the gradient obtainable in the direction of the river or sump being insufficient, reduction of the supply from the source is the obvious remedy, but none of the remedies should be carried to excess, otherwise the full benefit of storage of water in the subsoil, which will naturally add to the supplies in the rivers as the supplies from the hills diminish, will not be obtained, and now that the number of weir controlled canals from the hills is increasing this becomes a very important source of supply.

APPENDIX I.

Rate of Lateral Flow of Subsoil Water.

The following data have been calculated from the "depression curve" of a 10 inch tube well given in figure 8 of Captain J. Ashford's paper "Note on Tube Wells", which appeared in Volume VI, or the 1918 volume of the Proceedings of the Punjab Engineering Congress. This well had 95 feet of strainer, and the area of section of approach at the various distances from the well have been taken, in the one case as the area of a cylinder of radius equal to the distance from the well, on the assumption that the bottom of the strainer was sunk to the bottom of the water bearing stratum and in the other of a cylinder plus the area of half a sphere both of radius equal to the distance from the tube well.

The yield of the well was 1·93 cusecs=60,864,480 cubic feet in a year.

Distance from tube well in feet.	Gradient of depression curve.	*Water bearing strata of depth equal to the length of the strainer*		*Water bearing strata of considerable depth.*	
		Area of section of approach in square feet.	Quantity in cubic feet passing per square foot of area per year.	Area of section of approach in square feet.	Quantity in cubic feet passing per square foot of area in a year.
1	2	3	4	5	6
0	..	249	244,435	249	244,435
25	1 in 28	14,929	4,077	18,857	3,228
50	1 in 45	29,857	2,039	45,570	1,118
100	1 in 73	59,714	1,019	122,570	496
200	1 in 275	119,429	509	370,857	164
400	1 in 1,000	238,857	265	1,244,570	49

APPENDIX II.

Flow under capillary action, and amount of water in soils which is free to percolate.

Chapter III, pages 16 to 21, 7th Edition, Irrigation Engineering by Davis and Wilson.

TABLE I.

Extent and rate of capillarity.

Kind of soil.	*Capillary rise in inches.*							
	15	1	2	1	3	8	13	19
	min.	hr.	hrs.	day.	days.	days.	days.	days.
Silt and very fine sand.	2·7	4·7	7·0	20·0	30·0	45·0	52·0	56·0
Very fine sand...	7·6	10·0	12·4	21·0	23·0	26·0	27·5	28·5
Fine sand	9·0	9·5	10·0	11·6	13·0	14·3	15·2	16·0
Coarse and medium sand	5·8	6·0	6·3	7·5	9·0	10·0	11·5	12·5
Fine gravel ..	4·0	5·0	5·3	6·4	8·0	9·0	10·0	10·8

TABLE III.

Percentage by weight of moisture capacities for various soils.

Type of soil.	*Water contents.*		
	Total.	Retained by capillarity.	Free to percolate.
Coarse sand	33	13	20
Fine sand	34	14	20
Sandy loam	35	15	20
Fine sandy loam	37	16	21
Loam	38	18	20
Clay loam	40	19	21
Clay	42	20	22

APPENDIX III.

Rate of Percolation from a Sandy Subsoil.

The following figures give the rate of discharge for different heads from the tube well in the Minto Park, at Lahore, illustrated in figure 1 of Captain J. Ashford's paper "Note on Tube Wells", which appeared in Volume VI, or the 1918 volume of the Proceedings of the Punjab Engineering Congress.

This tube well has 120 feet of 10 inch strainer, which gives a seepage area of $120 \times 2 \times 22/7 \times 5/12 = 314$ square feet.

For the present purpose the curve of relation of head to discharge has been assumed to be a straight line through the origin and the point, head 24 feet, discharge 2·94 cusecs.

The gradient of this line is head/discharge $= 24/2{\cdot}94 = 1/{\cdot}12$ whence the discharges for various heads are :—

Head in feet.	Discharge per 314 square feet of percolation area, in cusecs.	Discharge per million square feet of percolation area, in cusecs.
1	0·12	382
2	0·24	764
3	0·36	1,146
4	0·48	1,528
5	0·60	1,910
6	0·72	2,292
7	0·84	2,674
8	0·96	3,056
9	1·08	3,438
10	1·20	3,820
24	2·88	9,172

APPENDIX IV.

Rate of Flow under the Action of Capillarity.

The data used have been taken from Irrigation Engineering, Seventh Edition, by Davis and Wilson.

Page 18.—Rate of rise under capillary action from a saturated surface.

Silt and very fine sand, 2·7 inches, say $\frac{1}{4}$ foot in 15 minutes.

Coarse and medium sand, 5·8 inches, say $\frac{1}{2}$ foot in 15 minutes.

Page 21—Capillary capacity of soils for holding water.

Fine sandy loam, 16 per cent. by weight, say 22 per cent. by volume.

Coarse sand, 13 per cent. by weight, say 18 per cent. by volume.

In soil containing water due to capillary action, assume that the soil adjacent to the saturated surface is charged to its capillary capacity, and that the charge of water gradually diminishes to nil at the limit of capillary rise.

Then the rates at which water is removed by capillary action are by :—

Fine sandy loam (silt and very fine sand),

$\frac{1}{2} \times \frac{1}{4} \times 22/100$ cubic feet in minutes per square foot of area.

$= \frac{1}{2} \times \frac{1}{4} \times 22/100 \times 1,000,000/15 \times 60$ cusecs per million square feet of area.

$= 30{\cdot}6$ ditto.

Coarse sand (coarse and medium sand),

$\frac{1}{2} \times \frac{1}{2} \times 18/100$ cubic feet in 15 minutes per square foot of area.

$= \frac{1}{2} \times \frac{1}{2} \times 18/100 \times 1,000,000/15 \times 60$ cusecs per million square feet of area.

$= 50$ ditto.

As a general figure 30 to 50 cusecs per million square feet of area may be taken as the quantity of water which will be disposed of by capillary action in soil containing no water held under capillary action adjacent to a saturated soil.

APPENDIX V.

RELATION OF LOSS BY ABSORPTION IN CHANNELS OF DIFFERENT CAPACITY UNDER FULL SUPPLY CONDITIONS.

Channel.			Coefficient c in the Q = cad formula. Per million square feet of wetted surface.	Reduced wetted perimeter.	Absorption in cusecs × 1,000,000 per foot run of the channel.	Col. 6 divided by Col. 5 = Col. 3 × Col. 4.	Log. of Col. 3.	Log. of Col. 7.
Discharge.	Bed width.	Full supply depth.						
1	2	3	4	5	6	7	8	9
10,000	300	9·75	1·16	311	..	11·31	·9890	1·0535
5,000	198	7·90	1·36	207·5	..	10·74	·8975	1·0310
2,000	114	6·15	1·65	121·0	..	10·15	·7889	1·0065
1,000	74	5·25	1·86	80·0	..	9·76	·7202	·9895
500	45	4·50	1·95	50·0	..	8·78	·6532	·9435
250	27	4·20	2·00	31·7	..	8·40	·6232	·9243
150	18	3·8	2·08	22·2	..	7·88	·5798	·8965
100	14	3·55	2·18	18·0	..	7·74	·5502	·8887
50	9	3·00	2·44	12·35	..	7·32	·4771	·8645
25	5·5	2·43	2·83	8·25	..	6·95	·3892	·8439
10	3·4	2·0	3·55	5·65	..	7·10	·3010	·8513
5	2·1	1·6	4·25	3·90	..	6·80	·2041	·8325
2·5	1·25	1·4	4·90	2·825	..	6·80	·1461	·8363
1·0	0·9	1·0	5·60	1·950	10·92	5·60	·0000	·7482
0·5	0·4	1·0	6·23	1·500	9·35	6·23	·0000	·7943

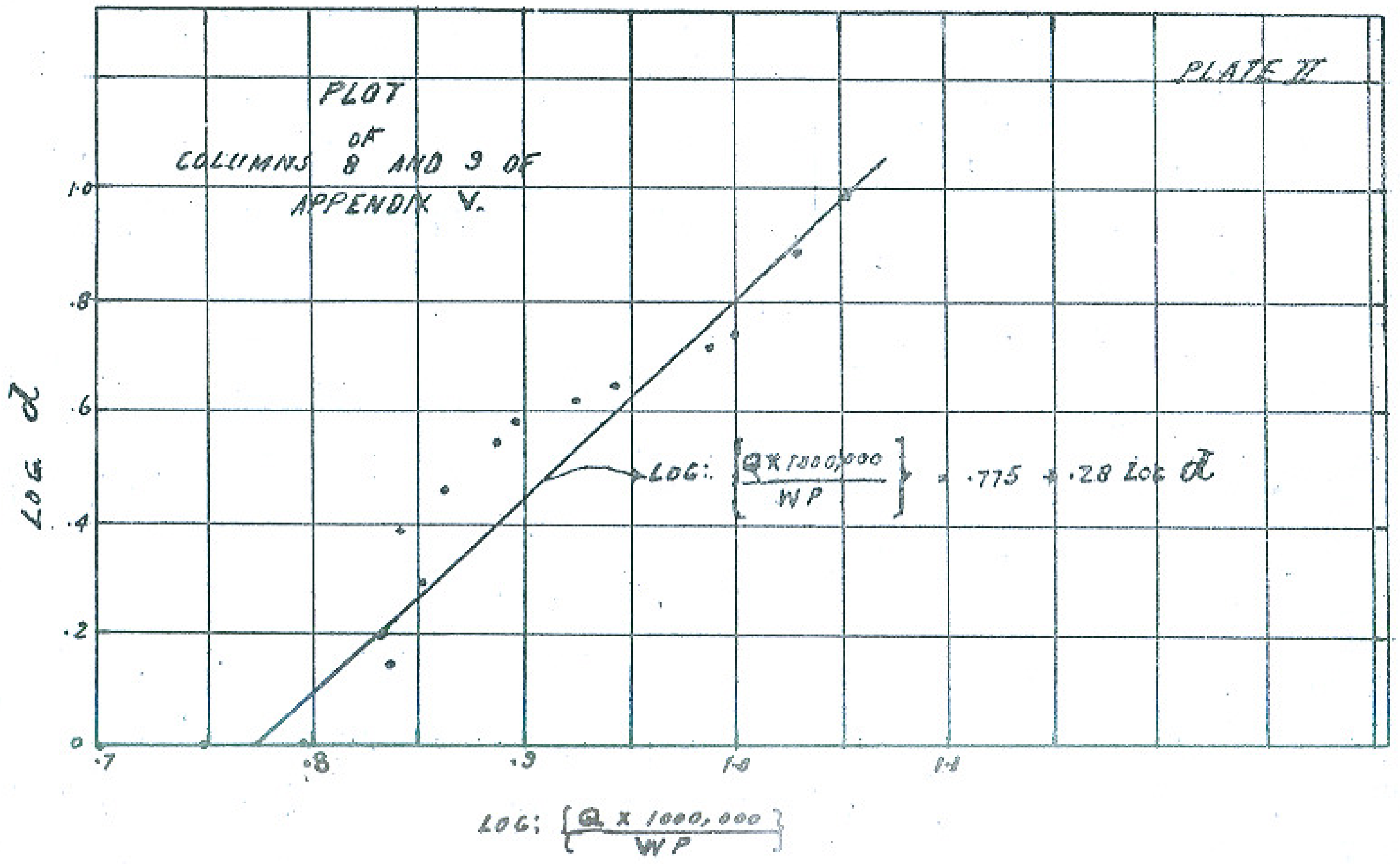


PLATE IV
PLOT
OF
COLUMNS 8 AND 9 OF
APPENDIX V.
LOG: {Q x 1000,000 / WP} = ·775 + ·28 LOG α
LOG α
LOG: {Q x 1000,000 / WP}
0
·2
·4
·6
·8
1·0
·7
·8
·9
1·0
1·1

Columns 1 to 4 have been taken from Table 22, of Mr. F.W. Schönemann's paper on "Absorption Losses of Canals," page 19, Volume V, 1917, Punjab Engineering Congress Proceedings, and it has been assumed that his Q=cad formula gives the correct absorption losses for the channels under full supply conditions.

Let Q=absorption in cusecs per unit length of the channel.

W_p=reduced wetted perimeter of the channel.

d=full supply depth.

In plate 11 $\log.\left(\frac{Q \times 1,000,000}{W_p}\right)$ *i.e.* log of figures in column 9 of the above table have been plotted as abscissae and log d, *i.e.*, log of figures in column 8 as ordinates, and a straight line has been drawn through the locus of the points thus obtained, which is satisfied by the expression $\log\left(\frac{Q \times 1,000,000}{W_p}\right) = \cdot775 + \cdot28 \log d.$

$$\text{Therefore } \frac{Q \times 1,000,000}{W_p} = 5.957 d^{0.28}$$

$$\text{Therefore } Q = \frac{5{\cdot}957 \times W_p \times d^{0.28}}{1,000,000}$$

$$= \text{say } \frac{6 \times W_p \times d^{0.3}}{1,000,000}$$

APPENDIX VI.

REFERENCES TO RECORDS MENTIONED IN THE PAPER, OR FROM WHICH INFORMATION HAS BEEN OBTAINED.

"Absorption Losses from Canals," by F. W. Schonemann, pages 1 to 34, Volume V, 1917, Punjab Engineering Congress Proceedings.

"Note on Tube Wells," by Captain J. Ashford, pages 49 to 60, Volume VI, 1918, Punjab Engineering Congress Proceedings.

"Wells and Permeability of Soils," pages 856 to 857, Engineering, Volume CX, No. 2870, dated 31st December 1920.

"The Subsoil Water-table under the Tracts Irrigated by the Lower Chenab Canal," by C. G. May, Volume VI, 1918, Punjab, Engineering Congress Proceedings.

"Railway Water Supplies," by C. B. Barrie, pages 21 to 28, Volume VIII, 1920, Punjab Engineering Congress Proceedings.

"Irrigation Engineering," Seventh Edition, by Davis and Wilson.

"Colloidal Solutions and their Practical Significance," pages 187 to 189, Water and Water Engineering, Volume XX, No. 236 (new series), dated 20th August 1918.

"Hydraulic Fill Dams," by J. Albert Holmes, page 179, Water and Water Engineering, Volume XXIII, No. 269 (new series), dated 20th May 1921.

"Waterlogging," by Iqbal Hussain, pages 127 to 138, Volume VII, 1919, Punjab Engineering Congress Proceedings.

"Capillary Moisture and its Effects on Highway Subgrades," by W. W. McLaughlin, pages 1037 to 1038, Engineering News-Record, Volume 86, No. 24, dated 16th June 1921.

DISCUSSION.

Mr. F. V. Elsden said that Mr. Middleton having gone on long leave was unavoidably absent from the meeting of the Punjab Engineering Congress, and had asked him to introduce his paper on the sub-soil water in the Punjab plains. He had sent him some introductory remarks which he would read out :—

"Perusal of my paper after a lapse of time has dulled the pictures in mind, brings out the fact that a few more words may be desirable before the discussion begins. Thus in commenting on the conditions in the Sind Sagar Doab, I see I have recommended aligning channels across surface drainages. I had in my mind drainages which seldom have water in them and have little to no effect in shaping the surface of the sub-soil water.

Should they contain water for as long periods as canal channels, they will have as much effect on the surface contour of the sub-soil water as a canal on that alignment and must be treated with equal respect.

I have referred in the course of my paper to drains and though I have particularly mentioned percolation drains, it may not be inadvisable to emphasize this point, as surface water drains, the object of which is to minimize the water supply to the sub-soil water reservoir from one source, are a matter apart and have no place in this paper except in the aspect of themselves being a source of water supply to the sub-soil reservoir. In this aspect drainages should not be ignored in designing a canal system, if there is any prospect of their becoming a source of sub-soil water supply of any moment."

In undertaking to introduce this paper he felt that he was in rather a false position since he did not see the paper until after Mr. Middleton's departure on leave and so had not had the advantage of discussing it with him and was therefore no better equipped than any other member of the Congress to appreciate fully Mr. Middleton's point of view. It was unlikely therefore that he would be able to reply usefully to any questions which might be raised, or further to elucidate any doubtful points, but he took this opportunity to remark on a few points in the paper which had particularly struck him.

Mr. Middleton's remarks at the bottom of page 55 and the top of page 56 regarding percolation through soil in a conical expanding pipe were practically an alternative statement of the theory of solid and dispersed percolation cones which the speaker advanced in the paper which he presented to the Congress last year. Mr. Middleton's point at which flow was due to gravity alone was the point at which complete saturation ceased, that was, at which the solid percolation cone ended and the dispersed cone began. No extension of the soil beyond this point would affect the percolation flow in such an expanding pipe, but, as an increase in the head of pressure was accompanied by an increase in quantity of flow it was evident that when the head was increased the point at which complete saturation ceased would become more remote from the source, or, taking the analogy of flow through a pipe, not only had resistance to flow increased owing to the increase of velocity, but the length of the pipe had also been increased. Thus the increase in percolation flow would be less than ought otherwise to result from the increase of head. This principle was evidently applicable in cases in which complete saturation ceased before the water table was reached, but the speaker was not sure that Mr. Middleton was entirely justified in applying it to other cases, as he did on page 68. It might be noted that this principle formed a powerful argument against the validity of Mr. Woods' formula for percolation loss from a canal, which made the loss vary directly with the depth of water in the canal.

He was not been able to follow readily Mr. Middleton's reasoning concerning flow in a trough, which he gave on pages 58 and 59, but he gathered that he was here arguing against a somewhat widely accepted fallacy that the bottom of the valley or trough which occurred in the watertable of a *doab* acted in a manner analogous to a main drain and carried away the whole of the sub-soil water which flowed into the *doab*. This of course was not what happened, and while he could not support Mr. Middleton to the extent of saying that there was no flow at all in a trough, he agreed that there could be no concentrated flow there, such flow as there was being no more than the general flow which took place throughout the width of the doab in a direction towards its downstream end.

The mysterious disappearance of sub-soil water to which Mr. Middleton referred on page 59 might perhaps, as he suggested, be capable of a perfectly simple explanation. It was probable that the alluvium of the Punjab rested ultimately on rock of low permeability, and that the sub-soil water flowed away over the surface of this rock, finally reaching the sea, for, at the junction between alluvium and a rock surface percolation flow would take place much more freely than it would through the mass of the alluvium, and, if they might suppose that such a rock surface existed and had a general gradient, or had in it valleys having a general gradient seawards, their explanation was complete. This was, he took it, the explanation hinted at by Mr. Middleton when he spoke of sub-soil water finding an exit beneath the surface of the ocean.

Mr. Middleton was to be congratulated on having drawn attention, on page 60, to the limited effect which could be obtained by increasing the area of the percolation surface of a well or drain, an important point which had not, the speaker thought, been fully appreciated in the past.

In dealing, on the top of page 64, with the rate of percolation into the soil, Mr. Middleton appeared to have overlooked the fact that the rate of flow calculated from the figures given by Davis and Wilson was into an unsaturated soil, whereas the figure which he quoted for rate of loss from canals was into saturated soil. If allowance was made for this difference in the state of the soil the difference in the rates of flow did not seem in any sense extraordinary.

Mr. D. A. Howell speaking as a waterworks engineer remarked that it had been proved long ago in Great Britian from tests made on waterworks wells in fairly homogeneous strata such as soft sandstone or sand beds that when water was pumped from such wells, "Cones of depression" were formed in the surface of the sub-soil water around the wells and the slope of the sides of the cone and the extent of the base area of the cone depended on the drop of water level in the well due to pumping (*i.e.*, depression head) and to the resistance of the strata to the passage of the water.

This agreed with Mr. Middleton's conclusions as to flow through homogeneous strata.

At the bottom of page 56 an analogy was drawn between the action of an ordinary sand filter and natural sub-soil flow through beds of strata of varying consolidation and the author argued from the specific case of the action taking place at the surface of a slow sand filter that "at the surface of a medium changes take place which decrease the permeability". The speaker did not quite understand what was meant by this. As a matter of fact an ordinary sand filter which was built up of successive layers of sand or gravel each layer being made of gradually finer material until the highest bed was reached which was composed of the finest material, the only change which took place was at the upper surface of the top medium and no change took place at the upper or lower surfaces of any of the other mediums.

The change which took place at the upper surface of the upper medium consisted of the clogging of the medium to a depth of a fraction of an inch and generally to renew the filter it was only necessary to scrape say $\frac{1}{4}$ of an inch of sand away and replace it with clean material. Moreover this change was the result of bacteriological action to some extent at least, if not entirely so, and the author was certainly, in the speaker's opinion, not justified in concluding that at the surface of each medium changes took place which decreased the permeability of soils. The sand filter, if it proved any thing at all, shewed that clogging action only took place at the surface of the top medium and no changes took place at the surface of the other mediums.

M. Iqbal Hussain said that the most important point brought out by Mr. Middleton in his paper was the principle that there was no flow in a trough. How desirable it would have been, that he should have given some direct instances to prove that principle was true that the sectional area through which flow took place was enormous, but in the dry Punjab all the water which could find its way from the beds of rivers and ponds, etc., hardly reached the trough. In the irrigation boundary of the Upper Jhelum Canal there were 590,000 acres ; before the advent of canal there used to be 3,200 wells, and *chahi* area=35,000 acres. These wells if worked in an ordinary way could cause a drop of 5·2 inches, in the sub-soil of the whole area. This extraction of water controlled the rise of water in the sub-soil, but after the canal was opened, the inflow into the soil grew tremendously, and water level in the trough started rising by jumps. Now it was urged by Mr. Middleton that this extra supply could not escape from the limited section, of the trough, existing below the confluence point of the Doab. And it was here where the mistake was made. This main trough had its branches also, and all that could escape from those branches did so, and it was the balance only which had to pass through the trough below the confluence point. So long as there was a slope in the water line of the trough, the flow must continue in it.

On page 63 Mr. Middleton had desired to know figures of the rate of flow of water in various classes of soil. This information could be had from the book "Use of water in irrigation" by Fortier.

Main figures were :—

Kind of soil.	Diameter of soil in m. m.	Velocity in feet per day.
Silt	0·01	0·0038
Fine sand	0·10	0·3690
Medium sand	0·25	2·305
Coarse sand	0·50	9·224

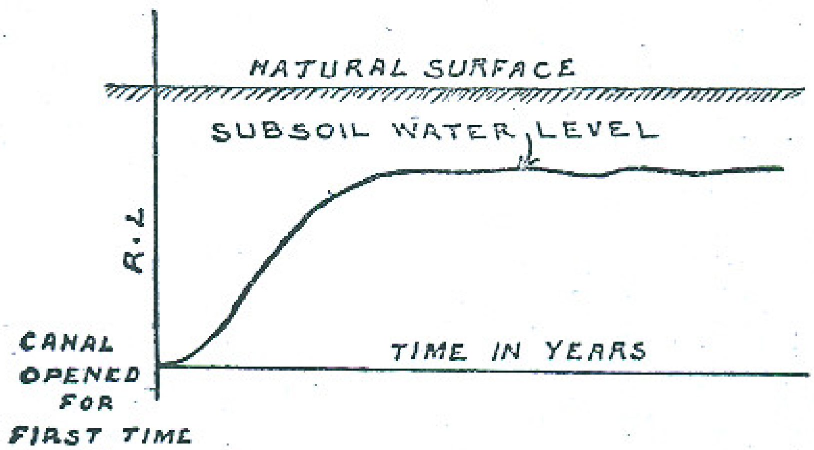
Sir John Maynard pointed out that in addition to the improvements in technical knowledge contributed by papers read before this Congress, the Congress had to its credit in the Punjab two important pieces of permanent machinery. The first was the Communications Board which had been brought into existence as a result of papers read on a former occasion before this Congress, and was now doing a large amount of useful work which had been outlined by the President in his address. The second was the Drainage Board, with its Drainage Engineer also originating in suggestions put forward in papers on sub-soil drainage and water-logging read before the Congress, and culminating in the lucid and cogent essay for which he had just had the pleasure of presenting the Society's Medal to Mr. Elsden. He added that there was yet a third matter regarding which suggestions had on a former occasion been made before this Congress, but which had not yet borne fruit. He referred to Mr. Carne's proposal for an institute of Research. Although this particular proposal had not yet been adopted, he said that every good suggestion put forward in these meetings might be trusted in the long run to bear fruit.

Mr. Colyer remarked that although Mr. Middleton's paper dealt chiefly with the effect of new canals upon an existing main watertable, executive engineers on running canals were more directly interested in the local effect of seepage, which caused damage to land or buildings by out-cropping. He read some notes written in the North-West Frontier Province during investigations into the cause of several houses in a village collapsing owing to the sudden rise in the sub-soil water level some years after the Upper Swat Canal was opened.

Longitudinal section along two lines of trial-pits approximately at right angles to the canal, and parallel to the ridge between two drainages, showed the sub-soil water gradient in such close conformity with the natural surface gradient, as to leave no doubt that the so-called 'hydraulic gradient' was eventually governed by evaporation, and was not a 'flow' gradient.

The outcrop was due to a sudden change in the natural surface gradient.

The idea that the sub-soil became filled up to a certain limit dependent upon the effect of evaporation upon different classes of soil was remarkably supported by the well measurements of the Lower Swat Canal, which when plotted as a diagram with level of sub-soil water against time in years, showed a rapidly rising curve which settled down to an almost horizontal line, the undulations in which were accounted for by years of abnormally high or low evaporation.



The general conclusions drawn from the investigation were as follows :—

(*i*) The waterlogging of land adjoining a new canal passing through country with a low sub-soil water-level, appeared to depend upon the porosity of the sides and bed of the canal, upon the porosity of the adjacent tract of country, the slope of the natural surface, the existence of natural drainages, the construction of drains, the existence of impermeable sub-strata, and the nature of the local climate as regards evaporative power.

If the canal and water-course banks and beds were impermeable waterlogging would not occur, as it had been proved by agricultural experts that practically the whole amount of water used to irrigate a crop, was used in developing the plant, after deducting evaporation losses, leaving practically none for percolation.

If the wetted perimeter of the canal was permeable, water would escape through the interstices.

(*ii*) In the extreme case of a channel passing through shingle soil, allowing water to seep out both in cuttings and fillings, the power of this seepage to waterlog, depended upon the depth of unsaturated soil between canal supply level, and the first impermeable stratum of considerable area, or the depth to existing sub-soil, water-level whichever was less. For waterlogging to occur, this unsaturated layer had first to be filled up, the rate of filling-up depending upon the porosity of soil and the existence of means of drain-off, *e.g.*, drains, or further areas of unsaturated permeable strata to act as drains.

When these dry strata became saturated, and sub-soil water-level near the canal rose to near bed-level, water would begin to flow at right angles to the axis of the canal, through the adjoining soil,

If frictional resistance of the soil were the sole controlling factor, flow would occur at the 'surface-slope' of 'Hydraulic-gradient' necessary to overcome friction. This gradient of free drainage was observed to be 1 in 6 for shingle and 1 in 20 to 1 in 30 for river sand. The quantity of discharge would depend upon this gradient, and upon the interstitial area.

So long as this gradient was 'free' *i.e.*, not headed up by back-water from other sources, and the interstitial area was sufficient to pass the discharge due to the head of water in the canal, stable uniform flow would obtain ; but if, owing either to a rise of subsoil water-level, or a local elevation of the impermeable stratum, the gradient was flattened, or the interstitial area reduced, then the supply would adjust itself to the new conditions by filling up the dry soil until the 'free-drainage' gradient due to that soil reformed.

If the natural surface slope was steep, this adjustment might result in the sub-soil water cropping-out, and waterlogging would occur unless the evaporation was active enough to keep with the seepage.

(*iii*) Thus, if the sides and bed of a canal were permeable, waterlogging was almost bound to occur in time, subject to control by evaporation. A draw-off such as a river or seepage drain, while it delayed the date of waterlogging, would not do so perpetually, and as soon as the soil above the impermeable stratum had filled up sufficiently to establish the 'free-drainage' gradient of the soil the sub-soil water would rise to such a level as would give enough interstitial area to pass the discharge. The logical deduction was that with canals of the Upper Swat, Lower Swat or Upper Jhelum type, which followed high contours transverse to the drainages, a time was almost certain to come when the unsaturated strata filled up, and if the drain-off was insufficient, the flatter tracts near the river would waterlog and springs would crop out in local depressions even in the steeper-sloping parts of the tracts.

(*iv*) The only real remedy for waterlogging was to render the channels impervious. Sub-soil drains might control the height of waterlogging but required such close spacing as to render their cost prohibitive.

On the other hand, an efficient system of surface-drainage was often found effective, because by rapidly removing surplus rainfall it allowed the process of evaporation to get to work with the minimum delay, thus controlling the outcrop of sub-soil water.

Mr. Curry remarked that Mr. Middleton had quoted the absorption experiments in tanks at Narwala and the results thereof. The experiments were repeated, because the results of the first series of experiments were not accepted and there was some difficulty in accounting for the fact that the absorption losses from the tank lined with slabs with open joints were greater than the losses from the unlined tank.

He thought Mr. Middleton's explanation was the correct one, namely that the extent to whch the slabs interfered with the self tamping of the tank in the areas covered by the slabs led to greater absorption than if the tank had been left unlined.

The Punjab Canals carried sediment which if conditions were favourable would form a partially impermeable "skin".

He did not consider however that it would be feasible to induce such a skin to form uniformly along the whole length of a channel, and, even if such a skin were formed, to protect it adequately and permanently by silt deposit.

The speaker expressed the opinion that the only effectual and practical way to prevent such losses from a canal was to line it.

CORRESPONDENCE.

Mr. Dhody wrote that there could be little doubt that water-logging was due to the advent of canals, a cause which obviously could not be removed outright, when they saw the other good sides of it.

The remedies might be put into two general heads :—

(*i*) Those carried inside the channel with an intention of stopping percolation.

(*ii*) Those carried outside with a view to reduce the evil of water-logging.

It might be well to define waterlogging. It was that condition of land in which it was so charged with water as to render it unfit or less useful for purposes of raising of ordinary crops or inimical to health. As long as water-table was sufficiently low that capillary action did not bring water up to surface or quantity rising was so small that evaporation from soil surface had power to keep it dry to a sufficient depth so as to admit of cultivation of all ordinary crops, there might be no strong fears but it was a bad admonition. Experiments so far had shown that conditions aggravate and what was just outside the pale of water-logging soon drifted into it and where water-logging started, conditions soon became inimical to health and crops,

Of the remedies they might deal with the second first.

These might be classed under heads :—

(1) Pumping.

(2) Drains.

Both depended on lowering the water-table and as such could have no effect in reducing the percolation from rather a forced draw through them should be in the nature of a suction which would open out any clogged veins that had seepage water from a canal coming under the soil. Their action again would depend on the proximity of the infiltrations of depletion cones, and in any case the result would be somewhat as shown in figures 1 and 2.

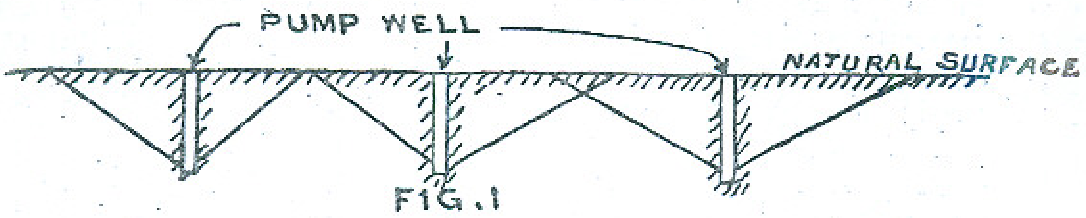


FIG. 1

FIG. 2

If wells or drains were further apart there might lie a saturated part between, or the cones of depression might overlap and render soil dry.

Obviously then while depending on the formation of the substrata, wells or drains had to be very close, the distance to be determined for each tract and part of it to be effective at all. While wells had a large depth and cone of depletion. the drains had a gain in their length and effective area.

Both then were cures and not preventive steps in any sense. By creating a greater draw they might help to dry the crust to some extent but the loss by seepage from the canals would be large owing to the forced suction and thus the loss in canals would be more.

A true remedy should therefore be such as would reduce seepage and just as in the first instance the water-table rose upwards gradually ; it should gradually fall down by stoppage of the feed. To achieve this the remedy must be effective and must be inside the canal.

Here again the remedies might be put under two main heads :—

(1) Various artificial devices of lining, and

(2) Natural and chemical lining.

Under 1, would fall all sorts of linings from oiled paper to concrete or bituminous slabs. Leaving out the question of cost for the present, these had the great disadvantages that any flow or deterioration rendered the whole ineffective as the contact between the two surfaces could not be so complete and water would find its way in between, rendering the whole useless. While therefore there might be differences of usefulness amongst the class, they could not be the ideal process. They were left therefore with any form of natural or chemical lining.

So far no experiments had been made to determine the effect of natural side silting on the amount of seepage which might be measured and compared in the rise of spring levels in long reaches of canals with and without such natural linings. If these figures should show that a good silt berm in a long length of canal had an appreciable effect on the rise of subsoil as compared with non-silted reaches the direction in which the remedy lay would be easily investigated. Such observations had been ordered on Lower Bari Doab Canal but having been on leave he had not seen the results. If the sides of canals could then be set back in all reaches sufficiently to allow of a good thickness of silt berms as time went on, there should be deposited an effective layer to control loss from the sides. For bed of canals where such silt deposit was not quite so easy the remedy would lie in finding such a substance which when dissolved in a low depth of standing water would with the water soaking into the soil penetrate and form a hard surface which when covered with a further layer of silt or clay would prevent or greatly reduce seepage losses.

Such actions both for the slope and the bed would be the cheapest way of dealing with the problem of saving water losses and reducing waterlogging.

It should be remembered that if large sections of canals designed as earth channels were lined with artificial lining the cost would be enormous owing to their large size. If on the other hand steeper gradient and narrow channels were adopted because of these artificial linings such as concrete, etc., there would be great difficulty of keeping up command all along the way. An irrigation canal must ideally follow the slope of the country and that could be done only with an earthen channel.