WATER-LOGGING FROM IRRIGATION CANALS IN ALLUVIAL SOIL.

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Introduction—Water-table prior to irrigation—The effect of rainfall—How water is disposed of—Effect of canals on the water-table—Effects caused by varying permeability—Effect of smaller channels—Percolation—Percolation cones—Spring level observations—Sources of sub-soil water—Earlier methods of prevention of water logging—Drainage—Lining canal channels—Financial aspect of lining—Probable effect of lining certain Lower Chenab Canal channels—Lining material—Conclusions.

Introduction.

With the enormous increase throughout the world in the areas of land which have been and are being brought under cultivation by means of irrigation with water conveyed from rivers by gravitation through canals, the problem of preventing the evils of water-logging, which frequently make their appearance in such irrigated tracts, has become exceedingly prominent, while means of combating these evils which shall be at once effective and not excessively costly, have yet to be found, at any rate in India, the premier country in the world for the magnitude of its systems of irrigation canals.

In the Punjab, which of all parts of India has the most extensive system of such canals, an area of upwards of 10,000,000 acres of crops is irrigated annually from these channels, and it is therefore in no sense surprising that the soil has become water-logged in widely separated places all over that province. The total area so affected, it is true, is small by comparison with the area irrigated, but the relative smallness of the area damaged from this cause is poor consolation for the owners of the particular lands affected, and it is the duty of the canal engineer, who ensures to the people the benefits of irrigation, to do everything practicable to guard against the occurrence of any ill effects, which might detract from the value of this magnificent irrigation system.

In approaching the problem an investigator is to some extent handicapped at the outset by scarcity of data with regard to the conditions which prevailed before the commencement of cana irrigation, for, while water-logging has been for many years recognised as a result likely to follow the construction of canals, it is

only within the last few years that any really serious investigation of its causes has been attempted, and, while the causes of the trouble are now better understood than formerly, much misconception of the subject still exists, and a really effective and financially practicable remedy has yet to be evolved.

Water-table Prior to Irrigation.

In the plains of the Punjab, while exact data are generally not available as to the levels and movements of subsoil water before canals were constructed, observations made subsequent to their construction have made it possible to reconstruct fairly correctly what must have been the conditions of that period, and it has been found that for some reason not clear, the spring level in watersheds situated between confluent rivers was, and in some places still is, below the level of the rivers bounding the tract.

Thus, a cross section A B, as in Fig. (1), taken across from

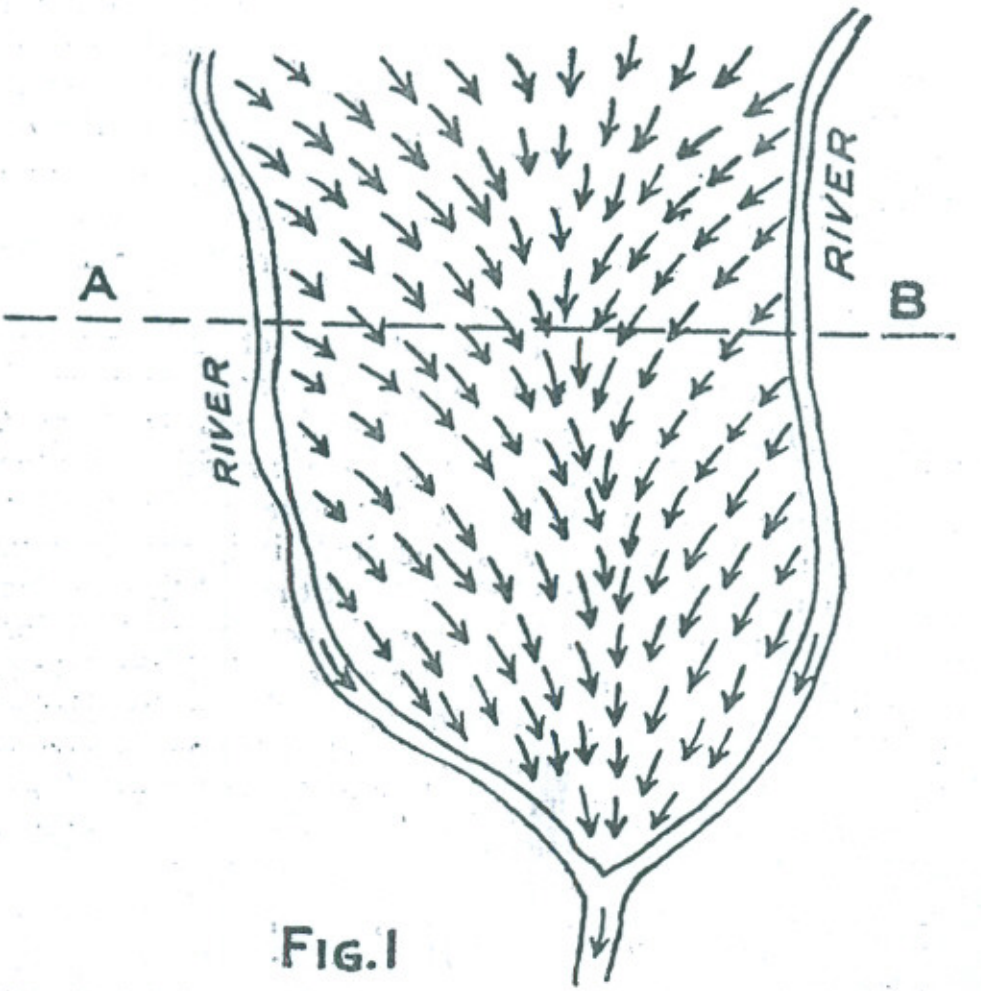


FIG. 1

river to river in one of the areas between rivers before the construction of the canals, would have shewn the water-table

to be in the form of a trough, subsoil flow being from the rivers towards the centre of the tract, as indicated in Fig. (2) by the chain, dotted line A C B.

Evidence is not forthcoming to shew whether or not the

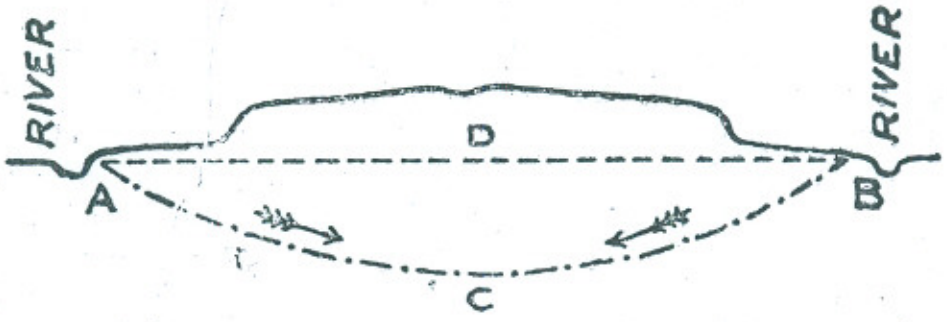


FIG. 2

water-table was at a fairly constant level, but it is clear that there must have been a constant flow from the rivers, and that, unless there were some outlet from this vast subterranean reservoir, the spring level must, in course of time, have risen to the level of the rivers, as shewn by the line A D B in Fig. (2), and at that stage, if the two rivers were at the same level, subsoil flow would have ceased except for a slow movement in the direction of flow of the rivers, sufficient only to remove water due to rainfall, while, if one were higher than the other, the lower river would change its role, and instead of contributing water to the subsoil, would begin to act as a seepage drain, carrying off water, which percolating from the higher river would cause a constant subsoil flow from the higher to the lower river. In neither case would water-logging result in the high lying lands, though the low lying lands bordering the rivers might become affected. In practice this state of affairs does not seem to have been reached anywhere in the Punjab, and it is only possible to conclude, therefore, that there must have been an outlet for the subterranean flow somewhere in the neighbourhood of the confluence of the rivers, so that the direction of subsoil flow would have been somewhat as indicated by the arrow heads in Fig. (1).

The Effect of Rainfall.

So far only that part of the subsoil water has been considered, which is contributed by the rivers, thus omitting entirely the principal direct source of water, the rainfall. Of the rain which falls on to the surface of the ground a part only

enters the subsoil. A considerable part is removed immediately by surface drainage, a part by evaporation, and part by transpiration through vegetation, the residue only passing down into the subsoil and raising the level of the water-table.

The exact proportion of the total rainfall which percolates into the soil in any particular locality must remain uncertain, depending as it does on several factors, such as the intensity of the rainfall, the slope of the ground surface, the nature of the soil, condition of the surface, etc., but there is no reason to suppose that, whatever the amount of percolation from rainfall, its effect is anything more than temporary. For, although during a rainy period the water thus added to the subsoil certainly raises the spring level, during a dry period this surplus of water will drain off by subsoil flow until the water-table is reduced to that normal level which has become established during a long period of time, so that there will be a seasonal fluctuation, varying from a maximum after a wet period to a minimum after a dry period, the minimum, provided that there is no artificial source of replenishment, hardly varying from year to year, though the maximum will vary according to the nature of the season.

In places where the minimum spring level is normally but a short distance below ground surface, rainfall may well cause water-logging to become apparent, but this condition will be purely temporary, and will disappear after a period of dry weather. Similarly the presence fairly near the ground surface of a stratum of impervious or only slightly pervious soil will also cause manifestations of water-logging to follow rainfall, since it prevents free percolation of the water downwards, and the spring level must therefore rise to a height sufficient to create a sub-soil gradient which will carry away the water laterally, by flow over the top of the impervious stratum. Another condition which will sometimes cause water-logging arises at the outcrop of an impervious stratum which has an extremely steep dip. In such circumstances the outcrop of impervious material forms a barrier which may, by preventing subsoil drainage, create a permanent marsh on one side of it.

How Water is Disposed of.

Water which is contributed to the earth's surface by rainfall or other means is, then, removed by two processes of

drainage; firstly, by means of purely surface drainage, surplus water flowing off down to the rivers, and ultimately to the sea, by means of surface drainage channels, such part of the rainfall never penetrating the subsoil at all. Secondly, by means of percolation into the soil and drainage by means of subsoil flow into the rivers which form the boundaries of the area concerned.

In order that water-logging shall not occur, it is necessary that these two processes of drainage, assisted by evaporation and transpiration, shall remove the whole of the water added to the soil from all sources, without requiring a rise of spring level which shall bring the water-table to within a certain limit of depth from ground surface. What this depth should be is open to question, and will probably depend on the nature of the soil and the nature of the crops to be grown, while considerations of the health of the population must also receive attention, for a depth which is quite suitable for the purpose of agriculture may, perhaps, be too little from the point of view of health. The soil will be damp to a height of several feet above spring level, water being drawn up into the interstices of the soil by capillary action to a height which will vary with the class and texture of the soil. Spring level may be defined as the level up to which the voids in the soil are completely filled with water, while above this level there will be a zone of capillary action throughout which the soil will be moist, but not completely saturated. For the preservation of health it is probably necessary that the capillary zone should never quite reach the ground surface, except perhaps for very short periods of time following heavy rainfall, while, in order that vegetation may best flourish, the capillary zone should perhaps be within reach of the roots of the plants, but still remain low enough to permit of the upper layers of soil keeping sufficiently dry to be porous to air.

The requirements of health and of cultivation are not inconsistent with each other, and will perhaps mean that spring level should not ordinarily be less than ten feet below ground surface.

The lines of flow of surface drainage are patent to all, and can be ascertained without the least difficulty. They must be left unobstructed in order not to cause surface accumulations of water, which, besides being directly detrimental to health, may also cause some rise of spring level, owing to the greater share of the rainfall which they will cause to pass into the subsoil by percolation.

The direction of flow of subsoil drainage is, on the other hand, obscure, and can only be ascertained by carefully mapping out the contours of the subsoil water-table by means of numerous observations of spring level, and, although it may happen by a coincidence that the lines of subsoil flow follow those of surface drainage, such an occurrence is purely accidental, the two systems of drainage being entirely separate, so that they must be considered as separate problems except in so far as surface drains having a permanent flow of water are concerned. Permanent surface water in any considerable quantity will be likely to influence the direction of subsoil flow, but even then the direction of subsoil flow may be very different from that of the flow in the surface channel. A glance at Fig. (1) will clearly illustrate this, for there, in the upper parts of the area sketched, the direction of subsoil flow is nearly at right angles to the direction of flow in the river.

Too much emphasis cannot be laid on the essential difference between the direction of flow of surface drainage and that of subsoil drainage, for it is a common misconception that subsoil drainage will be obstructed by the creation of an obstruction to surface drainage. Thus it is not uncommonly asserted that the alignment of a canal channel across a surfuce drainage will obstruct subsoil drainage and lead to water-logging. There could hardly be a more mistaken idea, for the relation of a canal alignment to surface contours can have no influence whatever on subsoil flow, which is entirely unconcerned with the configuration of the surface. It is necessary, certainly, that any surface drainages which are crossed should be left unobstructed, that is to say, that drainage crossings should be constructed for them of sufficient capacity to prevent any surface accumulation of water, but, subject to this one condition, which itself is often of only minor importance, from the point of view of subsoil drainage it is quite immaterial how many surface drains a canal crosses. Indeed, it may easily happen that for the avoidance of obstruction to subsoil drainage a canal alignment crossing surface drains is actually the best, though whether or not this is the case, can only be ascertained by a careful study of the canal alignments in their relation to the contours of the subsoil water-table ; a study which should take into consideration not only the existing conditions of the water-table, but also, and principally, the probable effect on it of the introduction of a system of canals

It is an axiom of irrigation canal construction that such canals should follow the watershed between surface drainages

but the true reason for this is, not that obstruction to subsoil, or even surface, drainage may be avoided, but the simple and obvious one that, since water will only flow down hill, a canal which has to irrigate the land by gravity must be on the highest available ridge, failing which either a great deal of land will remain uncommanded, or, in order to command it, the canal must be taken into very high embankment and a long way out of soil.

That this general principle has been wrongly attributed to the need for preventing water-logging is perhaps due to local water-logging having occurred in the neighbourhood of high canal embankments, which is very liable to happen in consequence of the great height of canal water surface above ground surface, but such water-logging will be purely local and easily dealt with by a local waterproof lining in the canal.

Effect of Canals on the Water-table.

The effect on the subsoil water-table of the introduction of a canal may next be considered. Fig. (3), represents a cross section similar to that in Fig. (2), A C B being the spring level

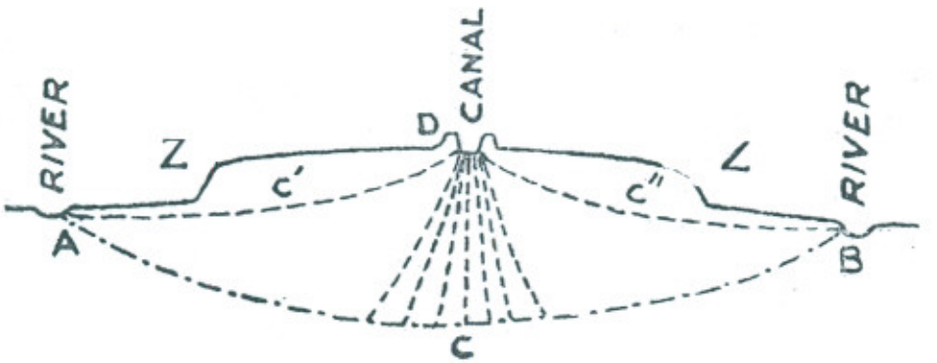


FIG. 3

line prior to the advent of the canal. The canal being introduced along the highest ridge of the central plateau, as shewn in cross section in the figure, water will percolate from it into the soil, adding to the total volume of water contributed to the subsoil, and creating a "percolation cone" as shewn by the dotted lines, while the smaller distributary channels, the water-courses, and the irrigation of the fields, will also add their quota to the total volume of subsoil water. If the spring level line, A C B, had formerly been in a state of equilibrium, apart from

seasonal fluctuations, it is clear that the addition to it of a large volume of water from the canal will disturb that equilibrium, and, though the level had formerly been sufficient to allow all inflow from the rivers and from rainfall to drain off by subsoil flow, it will no longer be sufficient when direct percolation from the canal and its distributaries and from the irrigated fields is added to the former flow. The result will be a rise of level to some line A C' D C'' B, which is of such height that the increased inflow can be balanced by the outflow. How high the level will rise before this new position of equilibrium is reached it will never be possible to say since it depends not only on the amount of extra water added to the soil, but also on the facility with which subsoil drainage can take place. The new line A C' D C'' B may still remain well below ground surface, or it may rise so high that the rivers, formerly contributing water to the soil, are converted into seepage drains, removing some of the water added by the canal. If any such considerable rise takes place, the spring level may rise above ground surface, particularly at points [illegible], and cause permanent water-logging. Even if it does not rise quite to this extent, it may approach so near to ground surface that seasonal fluctuations due to rainfall may bring it temporarily above ground surface, or, at any rate, so near to it as to constitute water-logging. Water-logging of this latter description will always manifest itself after rainfall has occurred, and may be, and in fact has in practice been, attributed to the rainfall only, overlooking the fact that the canal, by causing a permanent rise in the normal spring level, has brought the ground surface within range of seasonal fluctuations and is therefore the real culprit.

This, in general terms, will be the result of the introduction of a single canal into an area bounded by two confluent rivers which are at nearly the same level. When there is much difference of level between the rivers, the final result will be very similar, but it will be attained slightly differently. Thus, considering Fig. (4), there will be under the canal alignment a subsoil flow in the direction A C. The percolation cone of the canal, extending down to the former spring level, will create an adverse head which will check the flow in the direction A C, and cause rapid ponding up of the subsoil water on the side of the canal nearest A, while on the other side of the canal no such ponding up will occur. The effect of this will be that the rise of spring level will be far more rapid in the part A C than in the part C B, and, even when a stable condition is reached, the spring level will probably

stand higher on the side towards A than on the side towards B.

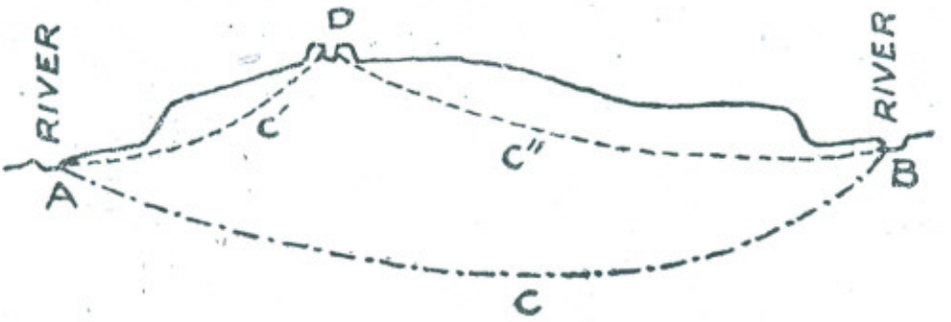


FIG. 4

The complexity of the question is very much increased when, as is generally the case, not one, but two or more parallel canals are introduced into the area, as shewn in section in Fig. (5).

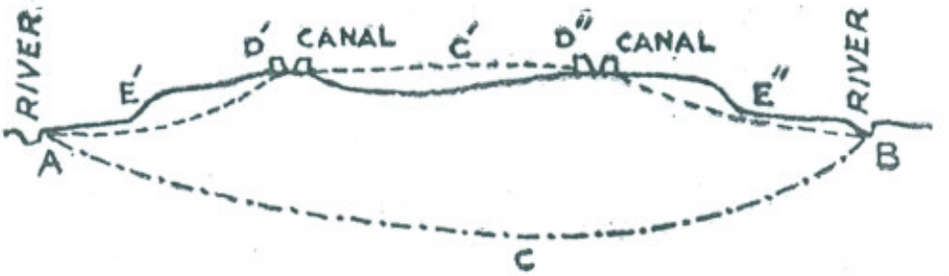


FIG. 5

In this case the percolation cones from the two canals will obstruct the subsoil flow from both rivers, and spring level in the portions A D' and B D'' may be expected to rise very rapidly until it reaches a level high enough to restore equilibrium between the water added to the subsoil by the canals and the water removed from it by subsoil flow and seepage into the rivers. A E'D' and B E''D'' illustrate this condition, which is evidently likely to cause water-logging at the points E' and E''. In the area between the two canals the position is much worse, for here there is available no short route through the subsoil to the rivers, this part of the area being completely cut off from them by the percolation cones of the two canals, so that the only possible route by which subsoil flow can remove the canal and rain water is a longitudinal one down the centre of the area between the rivers.

Fig. (6) shews this [illegible] in plan, and considering the section A C B, it is clear that if the shape of the spring level

ine, prior to the introduction of the canal, was as shewn in

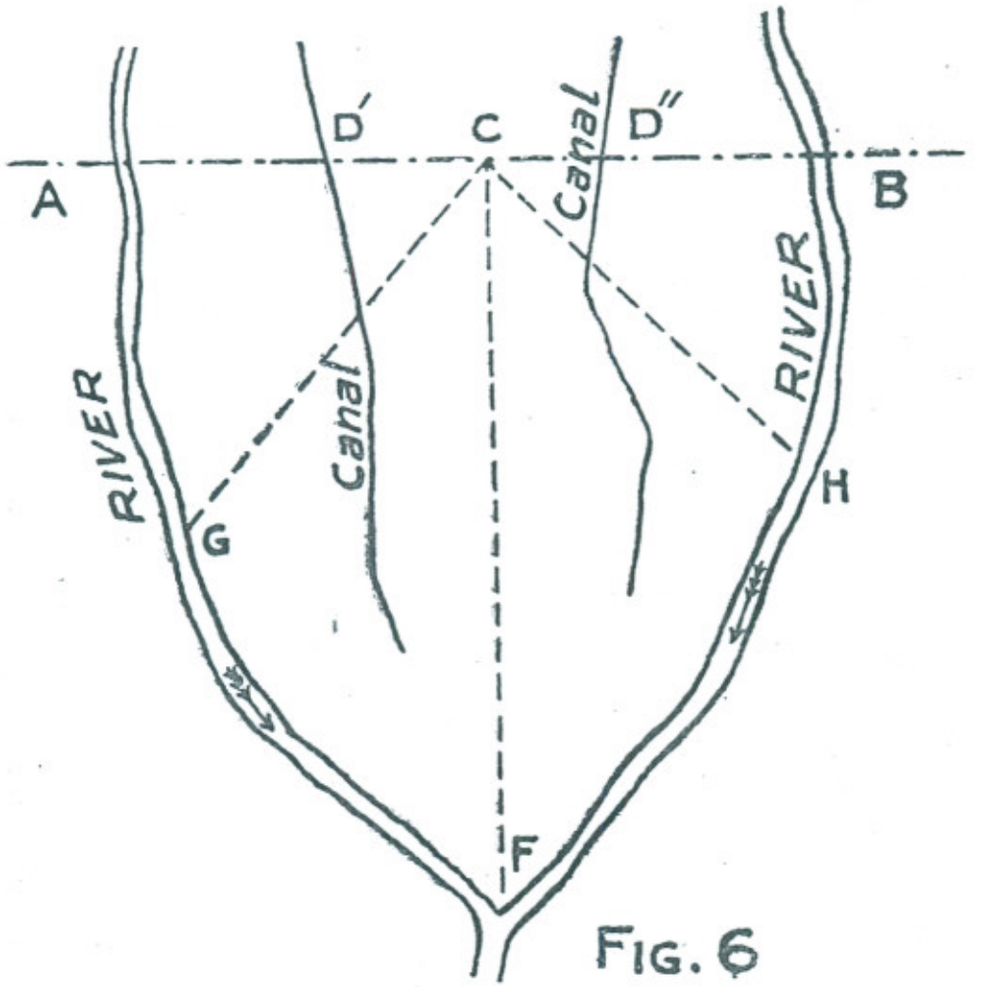


FIG. 6

Fig. (5), the direction of flow of the main subsoil drainage must then have been along the line C F. The canal, however, by causing a very considerable increase in the volume of water added to the subsoil, will cause a rise in spring level line A C B, and, if this rise is sufficient to bring the spring level line wholly above the levels of the river, the shortest and best natural line of subsoil drainage will be changed, and will now be transverse to the rivers, along some such lines as C A and C B, or else along oblique lines somewhat as C G and C H, depending on the river levels, the increase in quantity of subsoil water, etc.

It is clear that when any such direction of subsoil flow becomes the shortest natural route of subsoil drainage, the percolation cones of the canals will assume a new and sinister importance, for they will then begin to act as barriers, obstructing this shortest route, and compelling all subsoil flow to continue to use the old and longer line C F. On this line, not

only will its greater length call for a higher spring level at C than would be needed on the shorter lines C A and C B, but in addition to this, the area of flow on this longer line will actually be far less than that along the shorter lines, and both these causes will require a very great rise in the spring level in the tract intercepted between the two canals. This rise will become more and more pronounced on going upstream, and, in course of time, the spring level throughout the upper part of the tract may even become horizontal, as shewn by the line D'C'D" in the section shewn in Fig. 5.

This is a condition which will be likely to arise first in the angle formed by the bifurcation of a large main canal, and thence to spread slowly downstream. An example of this action is perhaps afforded on the Lower Chenab Canal, in the angle between the Main Line Lower and the Kot Nikka Branch, where water-logging has been complained of, but the information available is not sufficient to assign it definitely to this cause, while the fact that the Kot Nikka Branch has been lined with cement in its first seven miles has now materially changed the conditions and perhaps caused some improvement.

Effects Caused by Varying Permeability.

The subject has so far been treated as though the soil throughout the whole width and depth of the tract considered were homogeneous and of uniform porosity. This of course will not be the case, and in practice the permeability of the soil will vary from place to place and from stratum to stratum. Such variations do not, however, affect the general principles which have been enunciated, and, so long as the soil is permeable at all, the ultimate results of the construction of a canal will be those indicated, though local variations in permeability will cause considerable irregularities during the period immediately following the introduction of the canal, when things are adjusting themselves to the changed conditions, and will always produce changes of subsoil gradient from place to place, according as the soil is more or less permeable.

An absolutely impermeable stratum or outcrop will, of course, entirely change the conditions, and its effect can only be gauged after it has been mapped out. A completely impervious surface layer so deep that the canal does not penetrate through it, will of course entirely stop percolation, but the presence of such a stratum at a short distance below the canal bed, even though it is not completely watertight, but merely

of reduced permeability, will create a most dangerous condition, for, by preventing or checking percolation downwards, it will necessitate a very considerable rise of spring level before percolation from the canal is balanced by subsoil drainage, and this rise is almost certain to reach ground surface, or, at any rate, sufficiently near to it to constitute water-logging and cause damage to the land. The very rise of spring level will, of course, tend to reduce percolation from the canal, but serious damage to the land may nevertheless result unless the percolation is entirely stopped by some artificial means.

This effect of an impervious stratum underlying a canal at no great depth has been actually exemplified in the Punjab, on the Upper Jhelum Canal, where complaints of serious water-logging have arisen in lands adjoining some reaches of the canal within three years of the canal being first opened. Such an early appearance of water-logging is attributeable wholly to the presence of a stratum of soil of low permeability some ten to twelve feet below ground surface, and some six to eight feet below the bed of the canal.

Effect of Smaller Channels.

In considering the effect on the subsoil water-table of the introduction of a system of canals, only the main canals have so far been taken into account, and the network of smaller tributary channels and watercourses has been ignored, as also has the water which is spread on the fields, though, as will appear later, both these agencies also contribute to the rise of the spring level. Ordinarily these smaller channels are of importance only by reason of the volume of water which they add to the subsoil, and they take little or no part in the obstruction of subsoil flow, a function which, in the majority of cases, is the sole prerogative of the larger channels. This somewhat sweeping statement appears to be justified by the results of spring level observations, and an investigation of the process of percolation will reveal a working hypothesis which also supports it, and which is not in conflict with observed facts.

Percolation.

It is common knowledge that water escapes from earthen channels by percolation through the minute interstices of the soil, and so finds its way down into the subsoil, but how this action takes place is less well known, and the causes which lead to water-logging of the soil by this process, whereby considerable areas of land are rendered valueless and unhealthy, are also not so well understood as they should be. A canal in earth

may be considered as a conduit full for water, the bottom and sides of which are perforated with minute holes which permit part of the water passing down the conduit to escape. Underlying the canal at some depth is the spring level, the surface of the subterranean reservoir of water which is found almost everywhere at a greater or lesser depth below ground surface, which is indicated in Fig. 7 by the line S S. Were there no

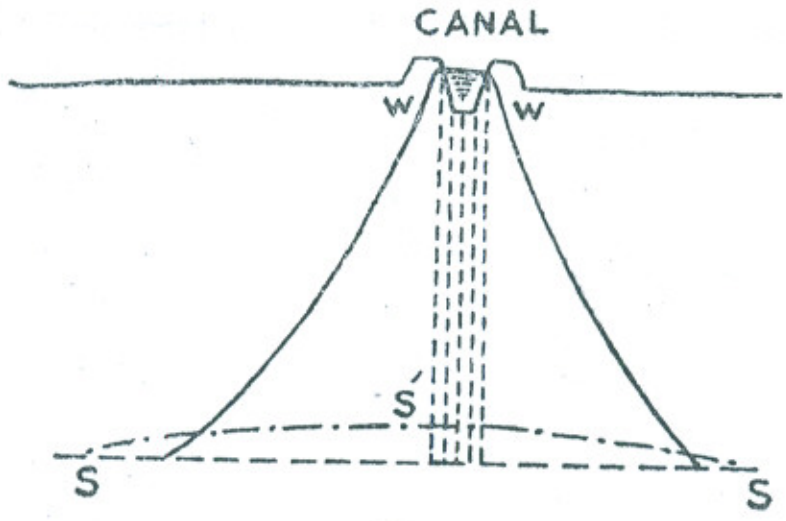


FIG. 7

direct substance between the bed of the canal and the spring ., it is clear that leakage from the canal would fall vertically every n until it reached the spring level line S S, as is dispe n by the dotted lines in Fig. 7, where the increase benea lume of water would cause the spring level to rise to a size o line SS'S, such that its slope is sufficient to carry appar his extra water. Actually the whole space is filled with The p having in it interstices which form paths, through which lar r can flow under the action of both gravity and capillary quit tion, and the effect of the presence of this soil is to modify esc ay in which flow takes place from the canal down to passed level, capillary action causing flow to take place in a there is for l as well as a vertical direction so that the water fans the size of the shape, roughly speaking, of a truncated cone, as causing ob the curves W S, W S in Fig. 7. Throughout the limit will ded by these curves there is both downward and the car surface low until spring level is reached, when downward after means, es, and, as before, the spring level rises to the height a the st e water which has percolated down from the canal.

Percolation Cones.

The existence of such percolation cones beneath large canals will be demonstrated by the examples which are given later from observations of spring levels, but in all these examples, although the spaces between the large channels contain numerous smaller channels, no trace of percolation cones beneath these smaller channels has been recorded. That this should be the case requires explanation, and it seems to be explicable only on the grounds that, for some reason, the percolation flow from these smaller channels becomes broken up, so that it does not completely fill the voids in the subsoil within the cone, the soil therein being moist, but not saturated, so that, although downward flow continues throughout, the spring level line will not follow the boundaries of the shape of the cone, as would happen were the voids completely filled, but will pass below it, unaffected by it except to the extent of the rise needed to carry off the extra water reaching it through the cone from the canal.

It is unlikely that such a "dispersed percolation cone," as it may be termed, will cause obstruction to subsoil flow, though there can be no reasonable doubt that a percolation cone, in which the voids of the soil are wholly filled, which may be termed a "solid cone," will do so, since it creates an adverse hydraulic gradient which cannot fail to stop flow towards it. The factor which seems likely to determine the formation of a "solid cone," or of a "dispersed cone" seems to be the quantity of water which passes from the canal to the subsoil, which, in the absence of any lining to the canal, will depend on the size of the canal, and it will be of interest to consider whether some limit of size cannot be found below which the formation of a "solid cone" becomes unlikely.

At any depth below a canal, the quantity of percolation water necessary for the formation of a solid cone will be a function of the percentage of voids in the soil, the area of the cone at that depth, and of the velocity of percolation flow. At any depth, if A is the horizontal area of the cone, V the velocity of subsoil flow, and P the percentage of voids in the soil, then the volume of water which passes per second past the plane considered, is $\frac{P \times A}{100} \times V$ cusecs and the cone will be solid only if percolation from the canal above can replace this quantity. It is clear, then, that the vertical velocity of

percolation flow in a solid cone must decrease as the depth increases, since, by reason of the spread of the cone, the area of flow increases as the depth increases. In a solid cone, therefore, the velocity must vary inversely as some function of the depth from ground surface.

Let it be assumed that the angle of divergence of a percolation cone will be constant in the same soil for canals of all sizes, and for the sake of simplicity, that its side is a straight line making an angle θ with the vertical. Assume also that the percolation velocity, so long as the cone is solid, is constant at the same depth for all canals. By making these two reasonable assumptions it becomes possible to explain the apparent absence of percolation cones beneath small channels in the following manner. The quantity of water which enters the soil is proportional to V, the percolation velocity at canal bed level, and to W, the width of bed. At any level D below bed level the percolation velocity will become V' and the area of the cone per foot run of the canal will be $W+2D \tan \theta$. The cone will remain solid only to such a depth that $V'(W+2D \tan \theta)$ is equal to $V W$, that is to say, only so long as $D=\frac{W(V-V')}{2V' \tan \theta}$, which gives us a limit of depth which is directly proportional to W, the width of the canal.

It is probable, then, that there is a limit of depth below every earthen channel below which its percolation cone becomes dispersed, and ceases to offer obstruction to transverse subsoil flow beneath the channel, this limit of depth being proportional to the size of the channel, and this hypothesis would amply explain the apparent absence of percolation cones beneath small channels. The percolation cones are there, just as they are in the case of large canals, but, except in their higher portions, which being quite close to the canal where no observations were made, have escaped detection, they are dispersed cones, and have therefore passed unnoticed. If this hypothesis is correct it indicates that there is for every soil and for every depth of spring level, a limit to the size of canal which can be constructed without danger of causing obstruction to subsoil flow beneath the channel, and this limit will depend, not on the spring level which existed before the canal was constructed, but on that which is likely to prevail after the canal has been in flow for a long period of time.

This means, if correct, that the considerations it follows that every canal in each tract, having been constructed that its size, will have a percolation cone some-

what as sketched in Fig. (8). Down to a certain depth D, the cone will be "solid" (indicated by continuous lines), and, if the spring level is at or above that depth, the percolation cone will cause obstruction to subsoil flow. Below the plane A A, at depth B, the percolation cone will be "dispersed" (indicated by broken lines), and will not be capable of causing stoppage of subsoil flow.

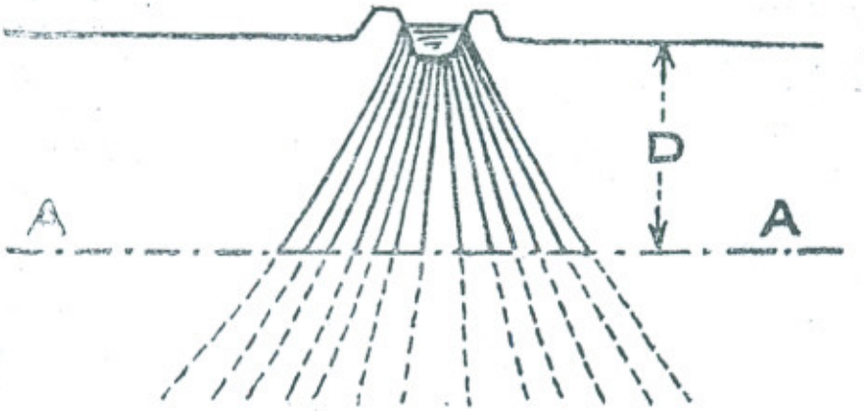


FIG. 8

The sketch in Fig. (8), assumes that the soil is homogeneous throughout, which is never likely to be strictly true, and variations in the permeability of the soil will modify the shape and character of the cone. Should there be a more permeable stratum underlying the upper stratum and above the level of the critical plane A A, the effect will be to cause the cone to become "dispersed" at a higher level, while if the reverse is the case the percolation cone will flatten out until its area at the plane of junction between the two strata is such that all the water reaching that plane can pass away through the less permeable soil. In the extreme case of a completely impermeable stratum, the sides of the cone will flatten until the whole of the water can escape laterally over the top of that stratum, a condition which, as has been before noted, may easily result in very early and very serious water-logging.

The foregoing hypothesis is not one which is readily susceptible of observational confirmation, but it is in complete conformity with observed facts so far as the subject has yet been investigated, and would justify leaving all small channels out of consideration so far as concerns questions of subsoil flow except where spring level is very near ground surface. What should be the limits of size for each depth of spring level it is not possible to ascertain by any theoretical means, though working rules could no doubt be evolved from the study of a

large number of careful observations made for the purpose of detecting percolation cones and of gauging the depths at which they cease to be "solid."

Spring Level Observations.

For a number of years past observations of spring levels in the canal irrigated tracts of the Punjab, have been made regularly twice a year, once in June, immediately before the rainy season, and again in October, after the end of the rains. These observations have been made by selecting wells situated along lines lying transversely to the alignments of the canals, and roughly ten miles apart, the wells being some five miles apart along the lines. There is thus a vast mass of information available which will shew the general tendencies of the subsoil water-table when influenced by canals, and though these results have many defects, due to the observation points not having been properly chosen, and to other causes, they convey, even so, a great deal of most valuable information. The sketch in Fig. (9) is an early example of such an observation, shewing the spring level as observed along a line across the Western Jumna Canal tract in 1881, before the regular observation of spring levels was started. This section shews very well the percolation cones beneath the Delhi and Rohtak Branches, and the spring level line suggests the probability of water-logging having been present in the low-lying riverain lands bordering the Jumna river.

Figs. (10) to (14) are a series of modern observations of spring levels on the Lower Chenab Canal, and are of much interest. They show the observed spring levels of 1905 and 1919, intermediate years having been omitted for the sake of clearness. The positions of the section lines along which these spring levels were observed are shewn in Fig. (15), a plan of the Lower Chenab Canal shewing the principal canal channels, the rivers bounding the tract, and the well lines along which observations are made regularly.

These sections will now be studied one by one, in doing which it must be borne in mind that the spring level lines shewn are likely to be defective in the neighourhood of the large canals owing to the absence of observations close to the canals, the nearest being seldom less than a mile distant. Extraordinary drops in spring level are also occasionally to be noticed, the reason for which is doubtful, but they may well be due to false values for the spring levels having been obtained owing to the wells under observation having been heavily worked only a short time before the

observations were made ; for these spring level observations have all been made by measurement of the depth to water surface in village and field wells, most of which are in regular use, and not in wells or bore holes sunk for the purpose and reserved solely for the observation of spring levels. The chances of error are therefore very considerable, and irregularities are not surprising.

Fig. (10) is more or less typical of the case of a single canal of considerable size passing down the area between two rivers. In this instance the canal has been working for upwards of thirty years, and it seems likely that a more or less permanent spring level, subject only to seasonal fluctuations, has been reached on the right hand side of the canal. It will be noticed that the apex of the percolation cone does not coincide with the main canal, an observational error which is due to there being no well within nearly a mile of the canal on one side and nearly four miles on the other side. At well No. 19 the line shews an extraordinary drop in 1919, probably an error of observation, since all other years are nearly the same at this point. The true shape of the curve at the main canal is probably as shewn by the shaded line. On the left bank the levels in intermediate years all lie between the 1905 and 1919 lines, shewing a constant rise, which probably had not yet reached its limit. On the right bank this is not the case ; some of the intermediate years rise above the 1919 line, and here the rise has perhaps reached its limit, fluctuations being now due only to variations of rainfall and of river level. Water-logging is a subject of complaint here, as can be well understood from the spring levels, which in some years have even risen above ground surface in the depressions.

Fig. (11) is another section, taken below the bifurcation of the canal, and crosses the main canal and two branches, the Kot Nikka Branch, and the Gugera Branch. Here again there is lack of coincidence between the apex of the percolation cone under the main canal and the canal itself, due almost certainly to the absence of observations, while the Gugera Branch and the Kot Nikka Branch shew no cone at all. In the case of the Gugera Branch, which is a large branch, this is probably due to the absence of observations close to the branch, while at the Kot Nikka Branch it is, perhaps, due to the cone being " dispersed," this being only a small branch which, moreover, has a thin concrete lining in its head reach. At the main canal and at the Gugera Branch the shaded lines probably represent the true state of affairs. On this section, as can well be understood, water-logging has

appeared between the main canal and the Kot Nikka Branch, but there has, as yet, been no complaint in the area situated between the main canal and the Gugera Branch. It would seem to be merely a matter of time, however, for it to occur there also, for the spring level shews a constant rise in the past, and does not seem yet to have reached its limit of height, at which fluctuations will arise only from seasonal causes.

Fig. (12) is a section taken still further down the canal. Conditions here are very much the same as in Fig. (11) on the right bank. On the left bank the observations do not reach the Gugera Branch, but shew spring level rising up to it, there being a trough between the two canals. The years intermediate between 1905 and 1919 shew a constant rise of spring level which is of nearly equal magnitude every year, and there is as yet no sign of finality.

Fig. (13), a section taken still further downstream, still shews the same characteristics on the right side, but on the left side the spring level has apparently fallen away from the Gugera Branch

This may be due to it having fallen below the "dispersion" level of the Gugera Branch percolation cone, but the shape of the spring level line suggests that it is perhaps due merely to lack of observations, there being a distance of four miles unobserved on the right bank of the branch. On the other hand, the levels at well No. 36 suggest a "dispersed cone," which perhaps offers some obstruction, but does not completely block subsoil flow. The 1919 line rises on the left to meet the river Ravi, which lies outside the section on that side and at a higher level than the spring level line on that side. Here again the spring level shews a steady rise, and there is reason to fear that it may soon reach the "solid" zone of the Gugera Branch percolation cone, after which a very rapid rise of spring level may be looked for between the Rakh and Jhang Branches, which may be sufficient to cause water-logging in this tract.

Fig. (14), a section taken still lower down the canal tract, shews a state of affairs not yet very different from the pre-canal condition, that is, the spring level forms a huge trough, well below river level, which is being slowly filled up by the combined action of canal, river and rainfall. The spring level seems as yet to be far below the "solid" zone of the percolation cones of any of the canal channels, but, as the yearly lines (not given in the section reproduced) shew, a constant rise is taking place which may continue for many years, and in course

of time bring the spring level near enough to the ground surface to cause water-logging. Between the Jhang Branch and the river on the right, and between the Burala Branch and the Degnala on the left, water-logging at the foot of the escarpment seems to be inevitable, and has, in fact already formed a subject of complaint in the former area.

In addition to subsoil flow outward from the canals, there is also flow parallel to the canals, so that water percolating from the upper portions of the canal will, some part of it, move gradually down the canal tract and add its own effect to that of the local channels. Subsoil flow is exceedingly slow, its velocity being of the order of one mile per year, and it may be that in the Lower Chenab Canal tract no percolation water from the upper reaches of the canal has yet reached the lower reaches.

Fig. (16) is a cross section on one of the well lines on the Lower Bari Doab Canal, which was opened only in 1913 and has even yet not attained its full development or its maximum discharge. In this section the spring level lines are shewn, on one side of the canal only, for the years 1915 and 1917. In the short period during which it has been in flow, the canal has already caused a very distinct rise in the spring level, but that level still remains far below the level of the river, and of the percolation cone of the canal. An instructive comparison may be made between this section and that shewn in Fig. (10). The line A R has been plotted to the same slope as has been attained by the spring level line on the L. C. C., shewn in Fig. (10), and if we can assume that the same slope will be required on the Lower Bari Doab Canal also in order to carry off percolation water, it is clear that it can be but a question of time for the whole of the depression between the main canal and the Gugera distributary to become water-logged. In fact, even though a far flatter slope should suffice, this result seems certain to follow after about another twenty years, unless some effective remedial measures are taken in the meantime. Such measures would probably take the form of some form of waterproof lining applied to the canal, but the study of this one section is far from being sufficient to determine the extent of the danger or the best way to avert it.

Fig. (17) is another section on the Lower Bari Doab Canal, but a section of a very different character. Here also the Chenab gradient line has been plotted, and comes well within soil everywhere. There is here little danger of water-logging unless the Gugera distributary should later on be found to

obstruct subsoil drainage beneath it, and as it is a channel of fairly large dimensions, this always remains possible. Further careful investigation of the subject of percolation cones can alone determine whether or not it is probable.

These few examples will suffice to shew the nature of the information which is available, the deductions which can be made from it, and how it may be possible to make use of it for the detection of danger zones on other canals. They also shew how incomplete is the information that has so far been collected. The system of spring level observations, now in use, has provided us with a mass of useful information, from which a general view of the subject may be obtained, but the points of observation are too far apart, too subject to accidental fluctuations and not correctly placed for any exhaustive examination of the subject to be possible. In the writer's opinion, what is now needed is a series of careful observations in a selected area, made at special observation wells or bore holes, sunk and reserved for that purpose only. The location of the lines of wells should be done with great care, and there should be an observation point on each side of every channel as close as possible to the toe of the outer slope of the bank. Careful observations of this nature would either confirm or refute the writer's hypothesis of "solid" and "dispersed" percolation cones, and should give us much other valuable information also. A series of such observations might make it possible to determine the gradients needed in various soils to carry off percolation water, and though these would no doubt vary with other factors also, and in particular with the size of the canal, it might become possible to establish some working rule which would be a most useful guide in dealing with areas not yet affected by water-logging.

Sources of Subsoil Water.

In the foregoing pages reference has been made to the various sources from which water enters the subsoil of a canal irrigated tract, but these have not yet been clearly defined. They may be classified as follows :—

(*a*) Percolation from the rivers and hills bounding the tract.

(*b*) Rainfall.

(*c*) Percolation from main canals and branches.

(*d*) Percolation from distributaries.

(*e*) Percolation from watercourses.

(*f*) Percolation from water spread on the fields.