PERCOLATION AND ABSORPTION OF WATER IN THE SOIL.

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In this paper I propose to give an account of recent developments in our knowledge of the physical conditions which determine the motion of water in soils, and to point out those aspects in which the hypotheses formed, or the experimental results which have been substantiated, have a direct bearing on the problems of irrigation. I would make it quite clear from the outset that many of the conclusions reached at the end of the paper are based solely on hypothetical considerations, which however, I hope to show, do not conflict with experimental results at present available. I have, moreover, attempted throughout the paper to make it clear how much rests on hypothesis and how much is substantiated by experimental evidence. Some of the conclusions may prove to be at variance with the experience of irrigation engineers, but any hypothesis is better than none when analysing such an excessively complicated problem as is, indisputably, that of the motion of water in soils ; in fact, I feel that it is useless to discuss the question except in terms of clearly defined physical principles. I have therefore attempted to summarise the essential points in the analysis of the problem, and later, in the light of the relations deduced, to apply them to practical considerations.

All the work here described has been the result of study or experiment carried out by me or under my direction at Lyallpur. Some of it has been published but much remains to be completed. I should have preferred to wait for more experimental results before committing myself to tentative conclusions, but my period of deputation with the Agricultural Service has come to an end and I am glad to take this opportunity of putting before the Engineering Congress the results at which I have arrived.

§ 2. **The ideal soil.**

The first hypothesis which must be framed concerns the nature of a soil. The idea that it may be considered as a collection of insoluble particles whose shapes and sizes determine the pore space, has proved insufficient. Beside the crystalline particles of which, for instance, a sand is almost entirely composed, we have matter in another physical state, colloidal. All recent work in agricultural chemistry has tended to show the extreme importance of the colloidal constituents of the soil in determining its physical and chemical properties. For our present purposes we may regard soil colloids as jelly-like matter capable of retaining water in very intimate connexion. Thus a colloid jelly such as gelatin retains its water with a definite force which is a function of the concentration of water in the jelly. This force can be measured experimentally by subjecting the jelly to pressure and determining the equilibrium moisture content. This force is usually termed "the swelling pressure" of the colloid, and when considering a soil, the

water so retained is usually called " bound ", in order to distinguish it from the " free " water.

Briggs [1] and Warrington many years ago pointed out that the sizes of the constituent particles of a soil will determine the hydrostatic pressure in the water retained therein ; but in order to arrive at any quantitative conclusions some hypothesis as to the sizes and shapes of the soil aggregate is needed. The simplest plan is to consider the soil as composed of a collection of uniform spherical particles whose *average diameter* will then be an important characteristic. This view is not unsupported by experimental evidence. As long ago as 1899 Slichter and King [2] in America showed the approximate coincidence of experimental results with theory. More recently, Green, [3] with better experimental methods, has shown that the average diameter is an accurate statistical constant for collections of unequal and irregularly shaped particles. The same constant, and the same methods for its determination, can be used for soils, when their colloidal properties are also taken into account. Thus in addition to tedious microscopical enumerations or somewhat inaccurate sedimentation methods, we have available a rapid and accurate practical method for the determination of the average diameter, which by means of the relation originally deduced by Slichter gives us a single valued constant for the characterization of soils. Green's improved methods have been repeated and modified at Lyallpur and the consistency of the experimental results with soils demonstrated. The method will probably replace mechanical analysis of soils for most physical purposes. We are therefore justified in picturing our ideal soil as composed of uniform spherical particles ; if, in addition, we consider these particles coated with a film of colloidal matter, we shall be able to explain most physical properties of the aggregate which are of importance in the problem before us.

§ 3. The free water of the soil.

Neglecting for the present the water held by the soil colloids, the free water held by a soil will, by virtue of the force of surface tension, be collected in drops at the points of contact of the particles. Before we can calculate the magnitude of this force we must have some means of estimating the number of points of contact in a given volume of soil. This will depend on the degree of packing of the soil. The maximum number of contacts per sphere in an assemblage of uniform spheres is twelve. Whether we ought to consider the possibility of a larger number of contacts when we have to deal with assemblages of irregular particles of varying sizes is a point for future investigation. For the present we may take it that the number of contacts represents another variable which will depend on the average diameter of the particles and their degree of packing, and is therefore calculable on the hypothesis of the ideal soil.

We are now in a position to calculate the hydrostatic pressure in the water of the soil. Since we know the number of contacts at which water

will collect, the volume of the drops will be defined for each moisture concentration. Since again the force of surface tension present at the liquid-air interface tends to reduce the surface to a minimum, it is possible to calculate the curvature of the liquid drops, and from this the hydrostatic pressure. An approximate solution is given in my memoir on soil moisture. The function is of the form

$$\phi = -\frac{2\gamma}{a} f(\theta)$$

Where $f(\theta)$ is a complicated function of an angle made by the liquid meniscus and the point of contact of the spheres, and γ is the surface tension of the water. γ will vary with the temperature and slightly with the concentration of salts in the liquid. It will thus be seen that the pressure varies inversely as the average radius of the soil particles for any value of θ. It is shown in the paper above quoted, that θ is a function of the moisture concentration which is independent of a but depends on the number of contacts (*i. e.* the degree of packing). Table 1 gives corresponding values of the moisture concentration, and the hydrostatic pressure expressed in atmospheres, for a soil whose particles have an average radius of 0·0002 cm. This last value has been chosen as representing the average value found for a light loam in the Punjab, and corresponds with the value determined experimentally.

TABLE I.

μ	ϕ (atms.)		h in feet $a = \cdot0002$.
	$a = 1{\cdot}0$	$a = \cdot0002$	
1	0·0180	9·00	305
5	0·00468	2·34	79
10	0·00180	0·90	31
15	0·00087	0·43	14·5
20	0·00036	0·18	6·1
25	0·00007	0·04	1·5
27	0·00000	0·00	0·00

It is obvious that, since the pressure varies inversely as the radius, the values for other types of soil can be calculated. It must be clearly understood that the pressures are negative ; *i. e.*, they represent the pull of the soil for water. It will be seen that these negative pressures become

very considerable at low moisture contents. Thus for a 5 % moisture concentration in the standard soil chosen, the pull exerted is equal to a pressure of as much as 84 feet of water.

§ 4. The influence of gravity.

The preceding treatment neglects the actual contribution to the pressure due to the weight of the drop, but under the conditions specified this is permissible, since we neglect a pressure of the order of 0·02 mm. of water in comparison with one of several feet. Nevertheless, as the moisture content of the soil increases, the pressure due to surface tension diminishes, and at the limit the weight of the drop should strictly be taken into account. As will be shown later in dealing with the dynamic aspects of the problem, the correction introduced by taking into account gravity is negligible for all practical purposes.

At a moisture content of about 23 % the pressure vanishes ; this therefore must represent the equilibrium moisture content of the soil, since it then has no tendency, either to draw to itself, or to expel, water. Experimentally, the figure 21 % has long been accepted as the average for all types of soil, water in excess of this amount being attributed to the colloid phase. We must regard this general agreement as satisfactory proof of the validity of our premises.

It is remarkable that although the limiting value for the moisture holding power of a soil has been recognised and measured experimentally as a routine process for a very long time, obvious deductions of a practical nature appear never to have been made. One important case is in the theory of lysimeters or drain gauges. In such installations a block of soil is isolated, and arrangements are made for the collection and measurement of the water which percolates through. This water is supposed to represent, and is actually still measured as representing, both in quantity and composition, the soil solution which would move through an unbroken column of soil. In order that water shall fall freely from the bottom of the gauge the hydrostatic pressure in the drop which is about to detach itself must be positive. This condition can only be attained when the soil contains approximately 21 % or more of free water. Yet in the undisturbed soil column, as long as there is a moisture gradient, there will be a pressure gradient, and water will keep moving from higher to lower concentrations until the gradient is flattened out. This motion can be detected experimentally in soils containing less than 5 % of moisture. I have elsewhere (*loc. cit.*) given reasons for believing that the composition of a drainage water must vary with the moisture concentration, or what is the same thing, the hydrostatic pressure. Both therefore as regards composition, and certainly as regards quantity, results obtained from the study of the soil solution from drain gauges must be accepted with considerable suspicion.

The same considerations apply both to drains in earth or tile. The water content of the soil must be greater than 21% before we can expect the drains to run. This was the fallacy which was at the root of the attempt, made some years ago, to apply mole draining to the reclamation

of saline soils." It was not to be expected that the drains would run unless they could be made in soil which was near the region of saturation, and, as can be shown experimentally, the pull of the dry soil for water is so large that even with a foot or more of water standing on the surface of the ground, the region of saturated soil extends only a few inches below. The only hope of utilizing a mole drainage plant is therefore in water-logged land, or land water-logged during part of the year.

The same objections apply in the case of the drain gauge which has been constructed under the bed of the canal at Lyallpur with the object of estimating the percolation.

§ 5. Distribution of water in a vertical column.

As I have shown in my memoir, knowing the hydrostatic pressure of the water in a soil as a function of the water concentration and constants depending on the fineness of the soil, its degree of packing, and the surface tension of the soil solution, we can advance a step further and determine the conditions of static equilibrium in a column of soil which is saturated at the bottom. As, owing to misprints, the deduction given therein is somewhat confused, it is reproduced below.

The fundamental argument is; that at equilibrium, the vapour pressure of the water drop must be the same as the pressure of the water vapour in the saturated column of air at the point considered. For the variation in pressure of water vapour (p) with the height (h) above a given datum line (h_o, p_o) we have

$$p = p_o - gh\int_{h_o}^{h} \eta\, dh.$$

where η is the density of the vapour and is of course a function of the pressure. This function is deduced by assuming the vapour behaves as a perfect gas, as follows :—

$$PV = R' T,$$

where R' is the universal gas constant R, divided by the molecular weight of water, P and V are volume and pressure respectively and T the absolute temperature. Since $\eta = \frac{1}{V}$ we have

$$p = p_o - gh\int_{o}^{h} \frac{p}{R' T}\, dh.$$

$$\frac{dp}{p} = -\frac{g}{R' T}\, dh.$$

$$\therefore -\lg \frac{p_o}{p} = \frac{g\,h}{R' T} \qquad (1)$$

From thermodynamical considerations it can be shown that if ϕ is the hydrostatic pressure to which the liquid of specific volume w is

subjected, the equation determining the vapour pressure is as follows :—

$$\phi w = R' T \lg \frac{p_0}{p} \qquad (2)$$

Equating this to (1) we have

$$\phi w = R' T \lg \frac{p_0}{p} = -R' T . \frac{1}{R' T} gh$$

$$\therefore -\phi w = gh \qquad (3)$$

If ϕ is expressed in atmospheres and h in feet, we have, if we assume that w never appreciably varies from unity,

$$\phi = \frac{30{\cdot}5}{1033{\cdot}2} h = 0{\cdot}0295\ h. \qquad (4)$$

No explicit relationship between the hydrostatic pressure and the moisture content (μ) has so far been obtained; the expression deduced in my memoir is too cumbersome for further calculation. However, an empirical equation of the form

$$-\alpha\phi = \frac{A}{\mu} - B \qquad (5)$$

is a sufficiently accurate approximation when values of μ are not too small. In Table 1, p. 3, which is calculated on the basis of the approximation formula, column 5 gives the heights at which the standard soil of 0·0002 cm. radius will have the moisture contents shown, when at equilibrium in an unbroken column the base of which is saturated.

The difficulty in testing this relationship lies in the fact that in order to demonstrate the equilibrium distribution with a fine soil a great height must be taken. Thus for a fall of 10% in the moisture content from saturation, a height of about 14·5 feet will be required in the case of our standard soil. By using a coarse soil in order to bring the experiment to more reasonable dimensions one must expect divergences from the theoretically calculated distribution on account of the greater effect of irregularities in the shapes of soil particles, and also, to some extent, from the influence of gravity. Moreover, as Buckingham[7] has shown, such experiments require a very long time before equilibrium is established, and during this time the soil columns must be kept under constant temperature conditions. The difficulties are by no means insuperable, and the experiment should be tried. The results of Buckingham already referred to, give the equilibrium distribution measured in this way, but unfortunately, we have no independent data for the calculation of the average diameter of the particles in the soils used. By assuming a radius it has been shown that the theoretical curves fit reasonably well on his experimental points, except in the coarsest sands. Moreover the figures for the radius obtained are of the order of magnitude to be expected. It may be mentioned here that the figures given for h in Tables 1 and 2 of my memoir are ten times too big.

§ 6. Variation in bound water content.

A further complication must be considered if we wish to deal with a soil (not a sand) and this is after all our primary object. Along with the variation of the free water, or, what amounts to the same thing, the equilibrium vapour pressure, there must be a concomitant variation above the saturation level, in the amount of bound water. This additional variable will not produce a serious error in the case of a sandy soil, but may have considerable importance in the case of a loam. The theoretical relationships have been worked out in my memoir, and preliminary experimental confirmations were obtained. A well-known empirical relationship exists between the so-called hygroscopic co-efficient of a soil and the moisture holding capacity. This is of the form

(Moisture holding capacity)=(Hygroscopic co-efficient)×4·2+21

where 21 is the experimental value of the saturation limit to be compared with the theoretically deduced value of 23 given in section 4 above. This factor 4·2 must represent the limiting value of a function relating the moisture concentration of the colloid phases with the vapour pressure, but has so far not been determined. Until more evidence has been obtained as to the nature of this function it will be impossible to take into separate consideration the bound and free water. In any case, in the light sub-soils which are general in the Punjab, the hygroscopic co-efficient is very low, so that, if we assume that the rates of change of bound and free water with change of vapour pressure are not very dissimilar, we shall not be far wrong in considering all the water as free. This assumption has been made throughout in what follows.

§ 7. Laws of flow of water in soil.

Having a sufficiently well established hypothesis as to the statics, we may now attempt to form a theory of the dynamics of soil moisture. In the limiting case of saturated flow this has been done in the well known work of Slichter and King already referred to. It will be well to restrict the term percolation, which is now used indifferently with absorption, seepage, leakage, u.s.w., in discussing the losses due to motion of water through the soil from water courses, to *saturated* flow. Thus percolation, as in the case of movement of water through a filter bed, can only take place when the hydrostatic pressure is positive. Below the point at which the hydrostatic pressure is zero, we have to deal with *unsaturated* flow, and for this we may reserve the term absorption. Thus, as will be shown later, the motion of water leaking from a channel in a soil where the spring level is deep will be almost entirely determined by the factors governing absorption. In the case of seepage from a channel with a very high spring level, we may be dealing with conditions similar to those in a filter bed, and the term percolation would then be applicable.

If we neglect the influence of gravity, the pressure gradient in an unsaturated column of soil will be determined by the moisture gradient. In order to determine the velocity, we shall have to form some hypothesis as to the conductivity of the soil for water. In an early paper by Buckingham great emphasis was laid on this function, which was assumed to

vary with the moisture content of the soil. However, no definite evidence exists that this is the case. Gardner, on the other hand, who has considered the case of one dimensional flow in a soil, assumes that the conductivity is independent of the moisture content and varies only with the average radius of the soil particles and the viscosity of the moving liquid, according to the law of Stokes. Stokes' law states that the limiting velocity of a sphere moving relatively to a liquid is proportional to the impelling force and inversely as the viscosity and radius. As will be shown below, experimental evidence, at present available, is in accord with the second hypothesis, and in what follows, this assumption has been used. Since the equations for unsaturated flow must be continuous with those deduced by Slichter for saturated flow, we may take as the conductivity function the so-called transmission constant.

For the velocity of flow we may put therefore,

$$\frac{d x}{d t} = v = \lambda \frac{d \phi}{d x} \qquad (1)$$

But from § 5, (5)

$$-\alpha \phi = \frac{A}{\mu} - B$$

$$\therefore \frac{d \phi}{d \mu} = \frac{A'}{\mu^2} \text{ where } A' = \frac{A}{\alpha}$$

$$\therefore \frac{d x}{d t} = \frac{d \phi}{d \mu} \cdot \frac{d \mu}{d x} = \frac{A' \lambda}{\mu^2} \frac{d \mu}{d x} \qquad (2)$$

The flow in the direction of x will be equal to the velocity multiplied by the moisture concentration μ.

The equation of continuity may now be applied in the form

$$\frac{d \mu}{d t} = -\frac{d (\mu v)}{d x} = -\frac{d}{d x}\left(\frac{A' \lambda}{\mu} \frac{d \mu}{d x}\right) \qquad (3)$$

For simplicity in this and succeeding calculations it is more convenient to deal with a function σ such that $-\frac{d \sigma}{d x} = \mu v$

$$\therefore \sigma = A' \lambda \int \frac{d \mu}{\mu}$$

$$= k_1 \lg \mu + C \qquad (4)$$

At the steady state, $\frac{d \mu}{d t} = 0$, so we may write

$$\frac{d^2 \sigma}{d x^2} = 0$$

A solution of this is, $\sigma = B - Cx$

or $\sigma_1 - \sigma = Cx$

From (4), $\sigma_1 - \sigma = k_1 \lg \frac{\mu_0}{\mu}$

Therefore $$\lg \frac{\mu_o}{\mu} = \frac{C}{k_1} \cdot x \qquad (5)$$

This equation gives as good agreement with observed results as that of Gardner which was arrived at by using a different expression for the hydrostatic pressure. His equation expressed in our symbols is

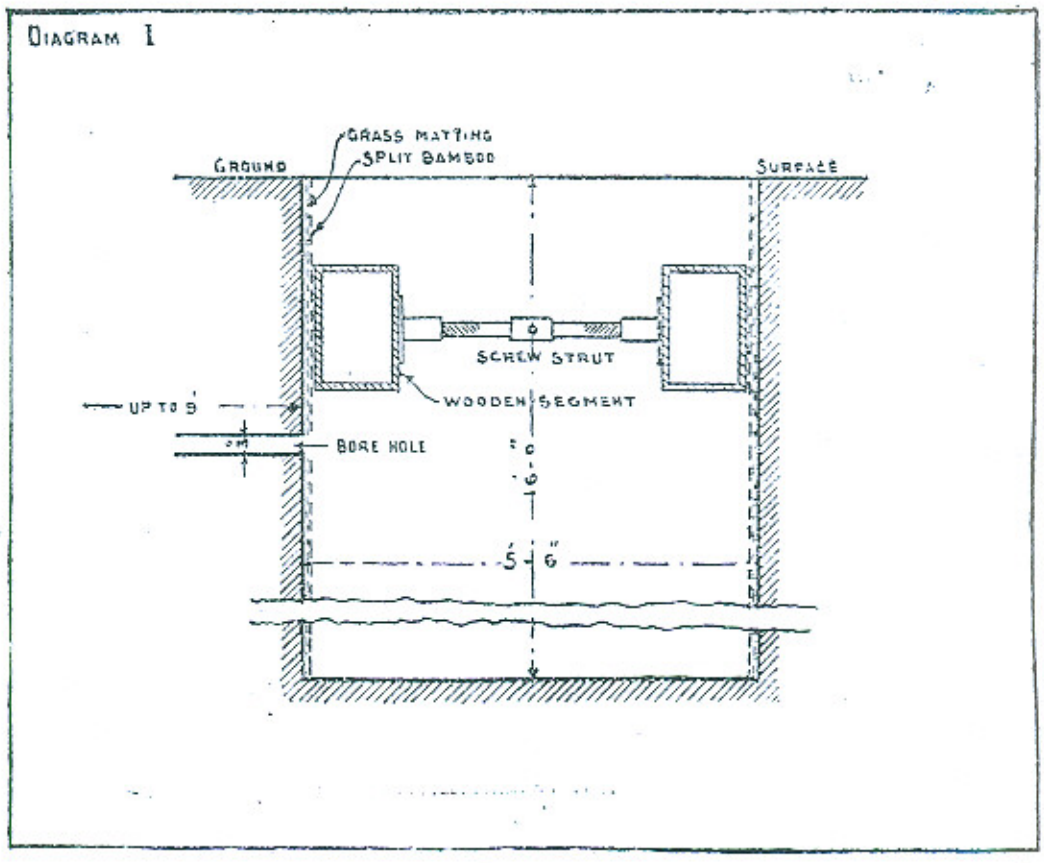
$$\mu = \left(M - N x\right)^{\frac{3}{2}}$$

but there is considerable doubt as to the correct magnitude of the exponent. It will thus be seen that when the range of μ is not large, both expressions will give approximate agreement. It is obvious that the expression will only hold for values of μ above unity. This is due to the fact that equation § 5 (5) is only an empirical approximation for the more complicated expression deduced theoretically.

§ 8. Distribution experiments.

During 1920 experiments were performed under my direction at Lyallpur with the object of determining the distribution of water in the sub-soil under various conditions. Two sets of conditions were investigated; the first, under a field irrigated at known dates, and the second under a water course which was kept full long enough to ensure that the water distribution in the soil below should have attained the steady state. The results of the experiments at present obtained are too variable to enable any definite conclusions to be drawn. In order to

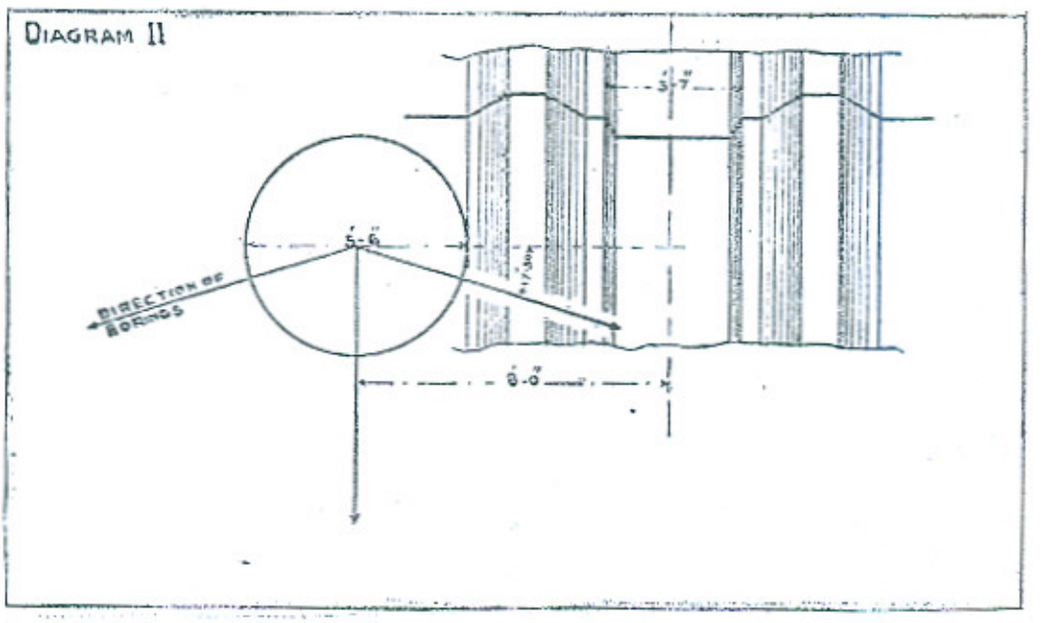
DIAGRAM I



reduce the experimental error of a single vertical boring, in which of course it is impossible to obtain any thing like simultaneous values for the moisture concentration at various depths, an "observation" well was sunk to a depth of about 36 feet. This was lined with grass matting (*chittai*) supported by a trellis of split bamboo, and shored by doubly acting screws as shown in Diag. I. Borings can be taken radially at any desired depth and a series of samples are thus obtained at each level. A clear idea of the accuracy of the experiment can be obtained by comparing the values of the moisture concentration obtained from a boring in a direction along which the value should be constant. The method of taking samples, and the experimental error involved, is described in a paper in the Indian Agricultural Journal.[9] As an additional method of estimating the moisture, in one of the wells a series of electrodes were inserted, so that by measuring the variation in electrical conductivity of the soil between successive electrodes, any variation in water content can be detected. Certain evidence as to the conditions under an irrigated field ought to be obtained if these experiments are continued, but work had not progressed long enough when I left Lyallpur to form any definite opinion.

The experiment in which the observation well was sunk near a water-course has given interesting results which it was hoped would enable a strict test to be made of the theoretical relations which have been deduced. While it has been found that the actual experimental conditions of the experiment are too complicated to use for the purpose of a rigid quantitative test, qualitatively the theoretical deductions are supported.

The well was sunk as shown in Diag. II at a distance of about 8 feet from the centre of the water-course. Samples were taken at each of



several depths by boring, (1) towards the water-course, (2) parallel to the water-course, and (3) away from the water-course. Diag. III shows the results of these observations plotted, and Diag. IV is a contour diagram

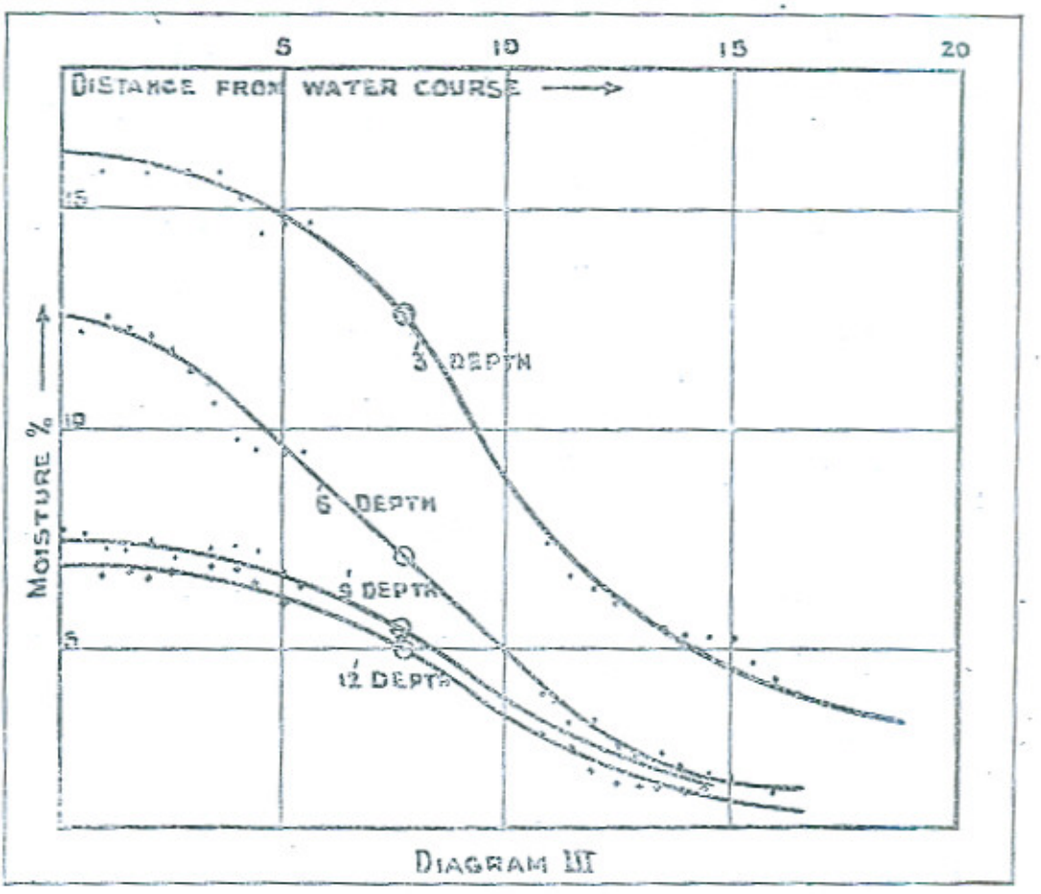
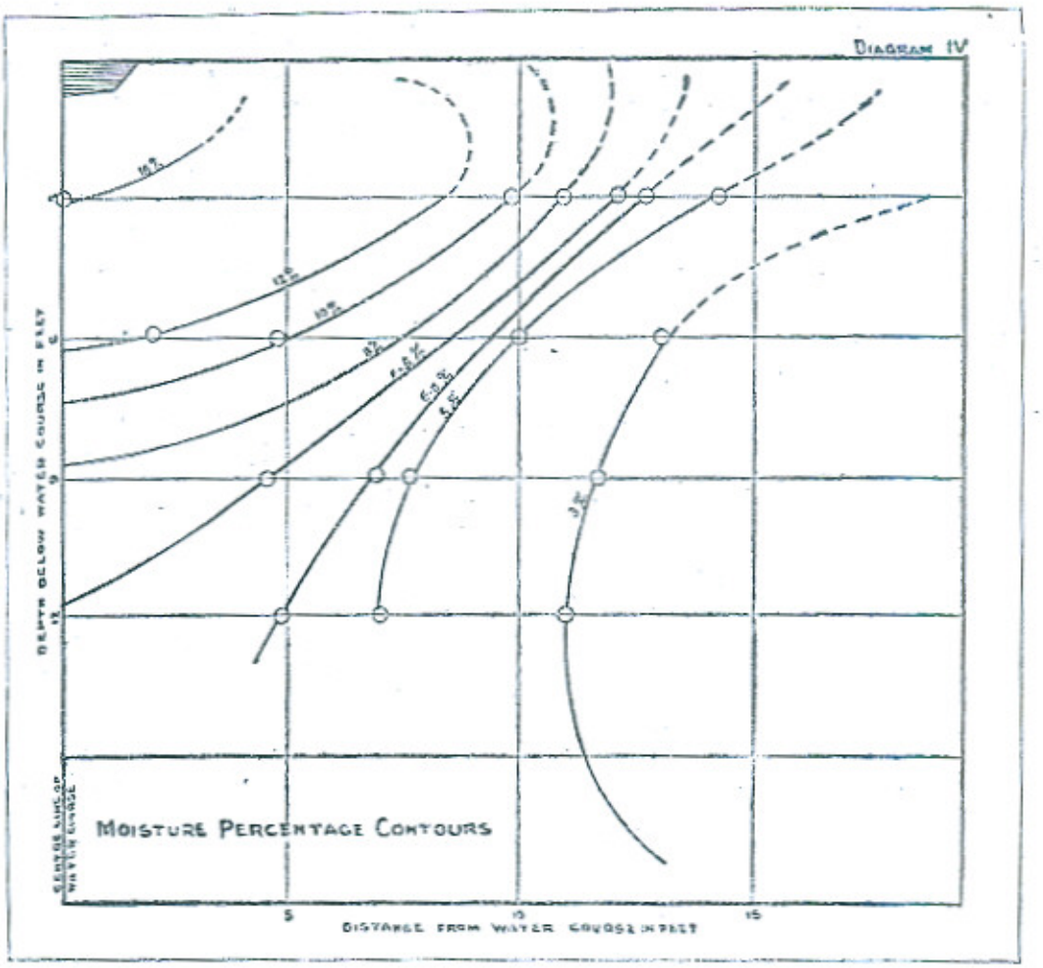


DIAGRAM III

obtained by interpolation on Diag. III. It will be seen that the contours of equal moisture concentration are distorted ellipses. Near the origin the contours are approximately parallel to the bed of the channel, as would be expected if the effect of gravity were negligible. At greater distances it is obvious that other moisture gradients are superimposed. Thus if we take into account the water gradient arising from the water table (the "ground water gradient"), we see that there must be a point somewhere beneath the centre of the channel where the concentration reaches a minimum, increasing until it attains saturation, above, at the bed of the channel, below, at the spring level. The combination of the two gradients will give a distribution something as shown in Diag. (5 a.). Another gradient probably interferes near the surface due to increased draught of water on account of evaporation and the action of plant roots. In addition we must allow for changes in the texture of the soil which in the most uniform soil is bound to occur near the surface where decomposed vegetation increases the colloid content.

The possibility that the distribution had not yet attained the steady state was not neglected and experiments were made to test the point.

Fresh borings were made about a month after the first ones were made but no change outside the experimental error was detected.



The differential equations obtained by introducing the unsymmetrical factors described above, which will affect the distribution, become very complicated and I have been unable to obtain satisfactory solutions. In order to crystallise the underlying ideas it may be as well to write down the equations, as also in the hope that they may attract a solver. A solution will not however be of great use until further experimental evidence has been obtained. Moreover, the main practical utility of these considerations will be in the dynamical equations it may be possible to construct, since, both from the points of view of irrigation engineering and agriculture, it is of the rates of movement of water that we need information.

§ 9. Boundary conditions in two dimensional cases.

The first factor to introduce is the hydrostatic pressure of the water in the channel. For simplicity, instead of dealing with a channel of

trapezoidal section in rectangular co-ordinates, we may use polar co-ordinates, assuming that the channel has an elliptic section. The equation to the bed of the channel may thus be written,

$$\rho_\circ = r - a \sin \theta \tag{1}$$

The head of water at any point on the perimeter will be given by $\rho_\circ \sin \theta$ and the radial component will be $\rho_\circ \sin^2 \theta$

The pressure gradient will now be determined by the difference in the apparent and ground water gradients, *i. e.*,

$$\frac{d\phi}{d\rho} = \frac{A}{\mu^2}\left(\frac{d\mu}{d\rho} - \frac{d\mu_s}{d\rho}\right) + F(\theta)\frac{d\theta}{d\rho} \tag{2}$$

where μ_s represents the static moisture concentration and

$$F(\theta) = \frac{d(\rho_\circ \sin \theta)}{d\theta}$$

Equations § 5 (4 & 5) give the value of μ_s in terms of D, the depth to spring level, as

$$\mu s = \frac{1}{K(D - \rho \sin \theta) + B} \tag{3}$$

Equation (2) may therefore be written

$$\frac{d\phi}{d\rho} = \frac{A}{\mu^2}\left\{\frac{d\mu}{d\rho} - \frac{1}{K}\frac{\sin \theta}{(D - \rho \sin \theta)^2}\right\} + k F(\theta)\frac{d\theta}{d\rho} \tag{4}$$

and, as before,

$$\mu v = \frac{k_1}{\mu}\left\{\frac{d\mu}{d\rho} - \frac{1}{k}\frac{\sin \theta}{(D - \rho \sin \theta)^2}\right\} + k_2 \mu F(\theta)\frac{d\theta}{d\rho}$$

whence,

$$\sigma = k_1 \int \frac{d\mu}{\mu} - \frac{k_1}{k}\int \frac{\sin \theta}{(D - \rho \sin \theta)^2}\phi + k_2 \int \mu F(\theta)\, d(\theta) \tag{5}$$

Of these terms, the first is the absorption term, the second is the ground water correction term, and the third the percolation term. The difficulty in using these equations for determining the distribution lies in applying the condition of continuity in such a way that the boundary conditions are obeyed. These are (1) that the range of y shall be D the depth to spring level, (2) at the perimeter of the channel $\sigma_\circ = f(x, y)$, and (3) when y = D, σ shall be determined by the gravity term alone, or,

if we neglect this term, $\sigma = o$. Diag. Vb gives the contours for a case in which the ground water gradient is not considered, *i. e.*, it represents

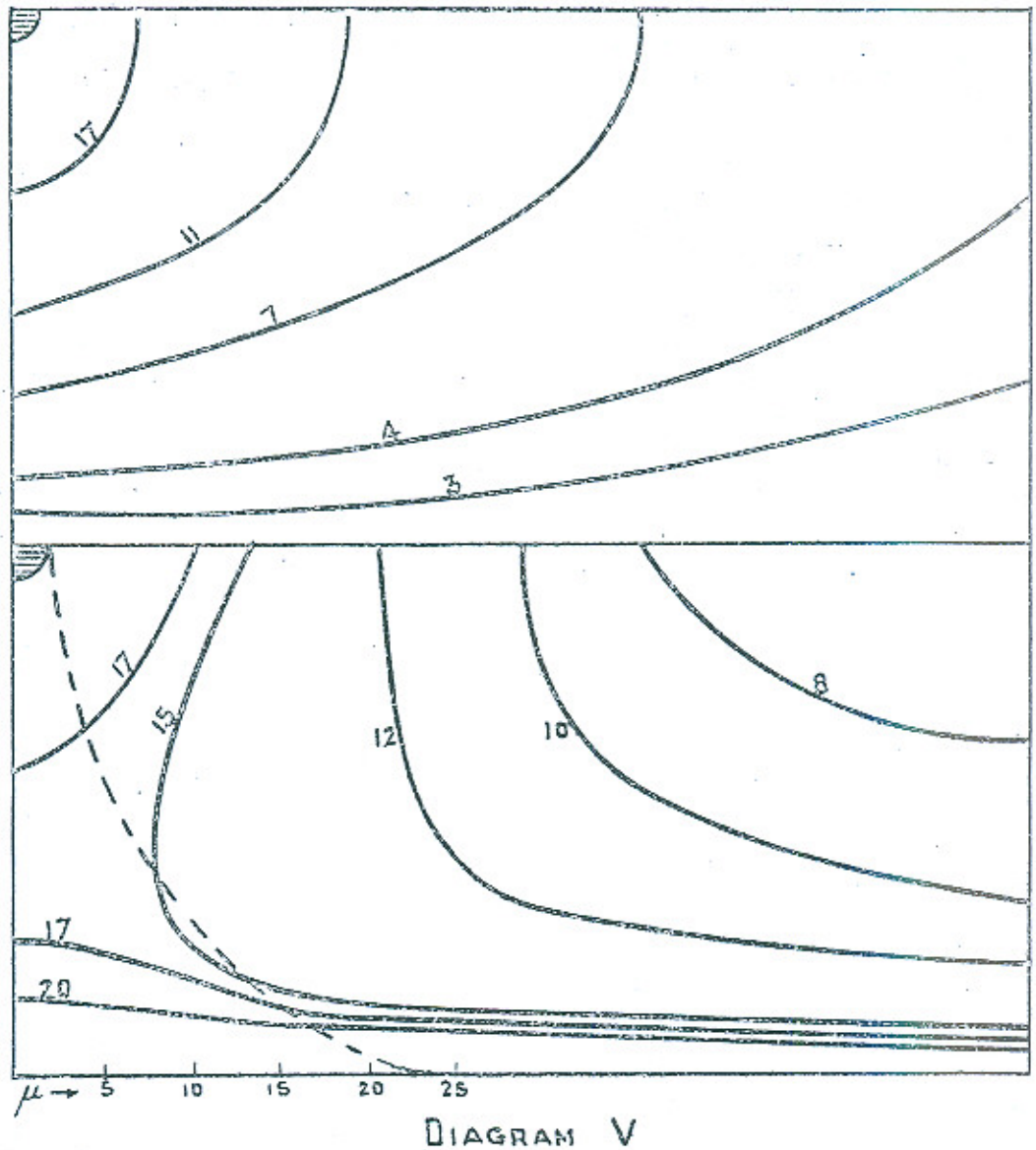


DIAGRAM V

THE DOTTED LINE REPRESENTS STATIC MOISTURE DISTRIBUTION WICH IS SUPERIMPOSED ON THE VALUE OF μ CORRESPONDING WITH THE Σ CONTOURS IN THE TOP DIAGRAM

the contours due to absorption from a channel into a uniform soil with an impervious layer at $y = D$. These curves were calculated by means of a Fourrier series, the derivation of which would be of no interest here.

If the ground water gradient were introduced, the μ contours would be approximately as shown in Va ; it will be seen they are similar to those observed.

§ 10. Calculation of leakage.

Of more practical importance is the study of leakage from channels; also, it is probable that the dynamic treatment of the problem may afford better opportunities for experimental verification of the hypotheses involved than do the distribution experiments.

The leakage will obviously be estimated by integrating σ over any path which encloses the source. We may write therefore

$$L = \int_o^{\pi} \rho \, \sigma \, d\theta. \qquad (1)$$

In the simplest case we may put $\rho = \rho_o$, and $\sigma = \sigma_o$, thence from section 7, (4), putting $C = o$ and $\mu = \mu_o$ we get

$$L = k_1 \int_o^{\pi} \rho \lg \mu_o \, d\theta$$

$$= \pi k_1 \rho_o \lg \mu_o \qquad (2)$$

if ρ is independent of θ.

This represents the absorption from a circular channel of radius ρ_o, and neglects the initial pressure due to head of water. Since $L/\pi\rho_o$ is proportional to the absorption per unit area, it will be seen that under these simple conditions, this magnitude is a constant depending only on the properties of the soil and the viscosity (temperature) of the water.

If we consider any other section we may put

$$L = k \int_o^{\pi} \sigma_o (r - a \sin\theta) \, d\theta$$

$$= k_1 \lg \mu_o (\pi r - 2a) \qquad (3)$$

As before, the leakage per unit area will be a constant.

In order to introduce the effect of the head of water in the channel we may use the expression for σ_o deduced in § (5) neglecting the middle term which represents the correction for the ground water gradient. Putting $\rho_o = r - a \sin\theta$ in equation § 10, F (θ) becomes

$$2r \sin\theta \cos\theta - 3a \sin^2\theta \cos\theta,$$

and the values for σ from equation 3, substituted in the leakage integrals give

$$L = k \int_o^{\pi} \int_{\mu}^{} \rho \frac{d\mu}{\mu} d\theta - \frac{k_1}{k} \int_o^{\pi} \int \rho \frac{\sin\theta}{(D - \rho_o \sin\theta)^2} d\rho . d\theta$$

$$+ k_2 \int_d^{\pi} \int \rho \, \mu \, (2r \sin\theta \cos\theta - 3a \sin^2\theta \cos\theta) \, d\theta \qquad (4)$$

Neglecting the middle term and putting $\rho = \rho_0 = r - a \sin\theta$, where $\mu = \mu_0$, we get

$$L = k_1 \lg \mu_0 \left(\pi r - 2a\right) + k_2 \mu_0 \left\{\frac{3\pi a^2}{8} - \frac{8 a r}{3} \frac{\pi r^2}{2}\right\} \quad (5)$$

As regards the middle term of (4) if ρ is small compared with D it is obvious that the value of the integral will vary inversely as D^3 and may be neglected.

§ 11. Evaluation of constants.

The following table gives the values of the constants in the last equation for particles of various sizes. The transmission constant λ has been calculated for a temperature of 12° C according to Slichter's formula, the necessary correction being made to convert the pressure to atmospheres. The value of the constant in the middle integral is independent of the size of particle, and equal to 0·005.

TABLE 2.

a (cm)	·005	·0025	·0005	·00025	·0001	·00005
λ	0·0004	0·0001	0·000004	0·000001	0·00000016	0·00000004
k_1	0·00025	0·00013	0·000025	0·000013	0·000005	0·0000025
k_2	0·000011	0·0000028	0·00000011	$0\,0_7 28$	$0\cdot 0_8 44$	$0\cdot 0_9 11$

Taking μ_0 as 21 and the average radius as 0·0001 cm. we can calculate the absorption per million square feet from § 10 (2). This comes to 11·5 cusecs, which is of the right order of magnitude. This value would of course be reduced if the second term, due to the ground water gradient, were included. In order to estimate the effect of the percolation term we may substitute βr for a ; d, the depth of water in the channel then becomes equal to $r(1-\beta)$. In this way we find for the percolation correction to the absorption per unit area (Λ_p)

$$\Lambda_p = k_2 \mu_0 d. \left(\frac{\frac{\pi}{2} - \frac{8\beta}{3} + \frac{3\pi\beta^2}{8}}{\pi - 3\beta + 2\beta^2}\right) \quad (1)$$

We may simplify the expression for the total leakage by writing

$$\Lambda = \Lambda_a + \Lambda_p = C + c\,d$$

Here C is a constant for any particular soil and c is a function of both soil and the section of channel. Since $k_2 = \frac{k_1 a}{A \times 36}$ this may be written.

$$\Lambda = k_1 \left(\lg \mu_o + \frac{a}{A \times 36} \mu_c d. f(\beta). \right) \quad (2)$$

Thus since k_1 varies as the average radius, the percolation correction will vary as the square and becomes more negligible as the soil becomes finer. Table 3 shows the values of the percolation term for a channel where d = 10 and β=0·5, (*i. e.*, 40′ × 10′) for various soils, expressed as a percentage on the absorption term.

TABLE 3.

Av. radius (cm.).	0·0025	0·0005	0·00025	0·0001	0·00005
$\Lambda_a \times 10^6$	300	57	30	12	6
$\Lambda_p \times 10^6$	290	12	3	0·5	0·02
$\frac{\Lambda_p}{\Lambda_a} \times 100$	·97	21	10	4·0	0·3

The coarsest sandy soil yet measured at Lyallpur has an average radius of not greater than about 0·001 cm., and, as has been pointed out, the average is about 0·0002. We must conclude therefore that the percolation correction even in a very deep channel never amounts to more than about 10%. The absorption certainly does not vary directly as the depth under any conditions which would be met with in practice, as is assumed in Wood's formula.*

The method of treatment adopted above is necessarily approximate but I believe that the results are certainly qualitatively correct. It may be well to summarise the reasoning which has been followed in arriving at these results. If we consider the absorption, without taking into account the percolation term due to the effect of gravity on the water in the channel and in each individual drop in the soil, we find that so long as the depth

* Q = c a d where Q = the rate of absorption,
c is a constant under particular conditions,
a is the wetted perimeter,
d is the depth of the water.

to spring level may be considered infinite, a pressure gradient establishes itself which will depend only on the texture of the soil, the temperature, and the saturation value of the soil.

If we now add the percolation term, still assuming the spring level to be infinitely deep, the same gradient will establish itself outward from a contour where the effective hydrostatic pressure is zero and above which it is positive. Equation § 9 (5) assumes that the increase in (negative) pressure is brought about by decrease in moisture content alone. A small correction should however be introduced for the loss of energy due to decrease in velocity which may take place without alteration of moisture content. As the velocity must be very small we are justified in neglecting this correction.

It is not yet possible to apply the ground water correction as the second term in section 10 (4) has not yet been integrated. It will be negative and must reduce the absorption. The correction will tend to vanish as the depth to spring level increases.

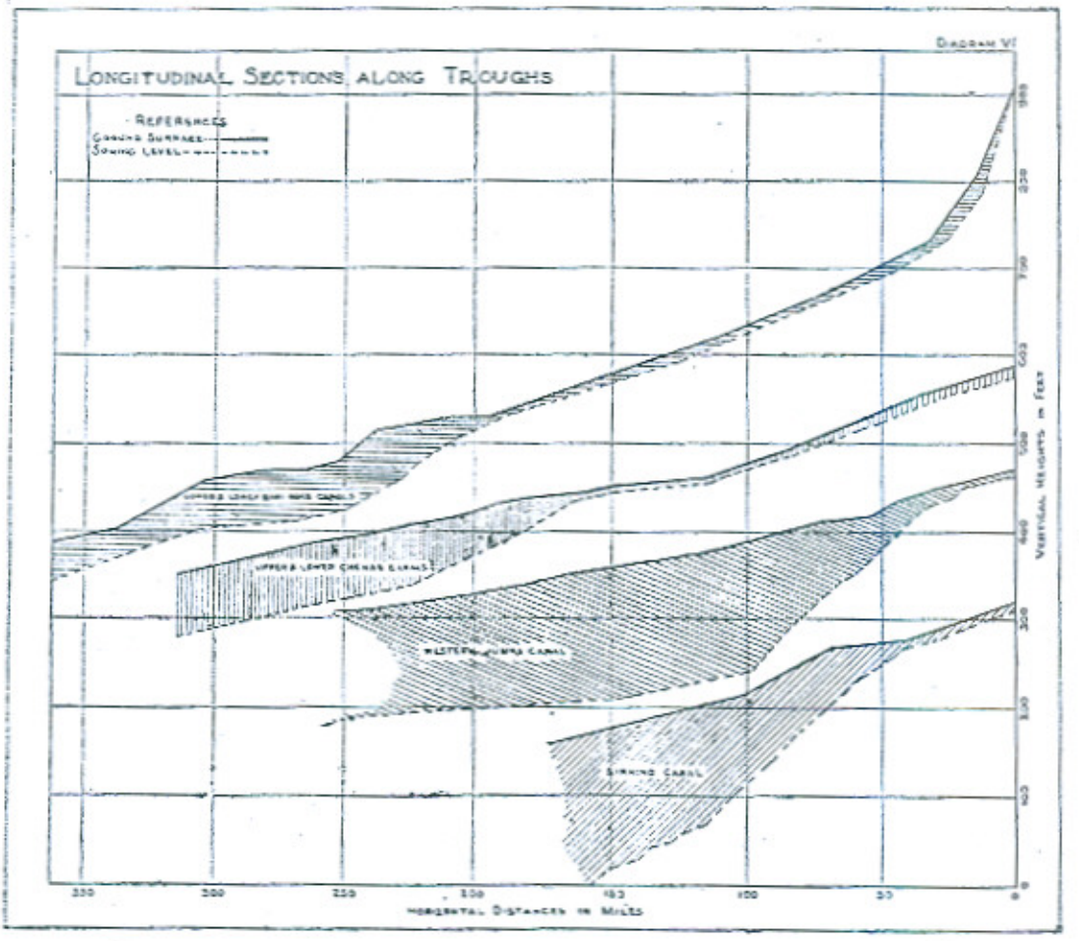
It may be objected that the figures in Table (3) give values for the absorption much greater than any that are met with in practice. Against this it should be remembered that the average diameter of soil does not vary between very wide limits; moreover, experimentally determined values for the absorption in channels depend on observations carried out over long distances which must comprise a considerable variation of soils, so that their horizontal and vertical distribution will tend to make the observed results approximate to a mean.

Experiments designed especially to test these relations would undoubtedly give interesting results; a few points may be mentioned in connexion with the choice of the best conditions. Tank absorption experiments will of course be the most easy to conduct. In order to interpret the results another dimension has to be included in equation (4) of § 10, and the integration carried out over the surface. Careful measurement of sinkage in tanks shaped as ellipsoids of revolution should then be directly applicable. It is possible however that the turbulent motion of the silt at the bottom of a running channel may have some effect on the rate of percolation by preventing the choking of the surface with a film of organisms and colloidal material. The growth of organisms might be prevented by adding a suitable antiseptic to the water in the tank. It is improbable however that this cause will have much effect when the losses depend almost entirely on the absorption factors. It is obvious that the most interesting results will be obtained by performing identical tank experiments in soils which differ as widely as possible, and with the spring level at varying depths.

§ 12. Practical applications.

The equations developed in the preceding sections show that in an average fine soil the influence of the depth of a canal on the absorption losses is slight. Economy in design will thus be determined by other considerations. It is only in the case of a very open soil that the influence

distributaries can only partially check the rise of the sub-soil water table. By actual measurement of the spring level contour maps of the Lower Chenab Canal it has been shown, that below Sangla, the average annual additions to the sub-soil are approximately constant over the whole area and represent a discharge from the surface of about 0·62 cusecs per square mile. This represents about 38% of the total water taken in at the head works during the year. Of this, according to statistics published by the Irrigation Department, 17·5% is lost in the main line and branches; 20% must therefore be accounted for by losses from distributaries and water-courses and fields. Averaged over the annual irrigated area this represents a discharge of about 0·5 cusec per square mile of irrigated area throughout the year. Kennedy[13] places the losses from distributaries at 6% of the canal head discharge. If we accept this figure we see that the losses from water-courses and fields, which waterproofing measures will never be able to touch, amount to 14%. The most perfect lining applied to all canals, branches, and distributaries will at the most only prevent about 60% of the rise.



Diag. VI.

The vertical scale for all four sections is the same but each section is to be referred to a different datum-line.

Waterproofing as a practicable proposition has appealed to many as it appears to go to the root of the evil. If, as is maintained, the most that can be hoped for is only a partial cure, it will be as well to consider if other and less heroic methods are not better, as well as cheaper. When it is possible to design a lined canal *ab initio* the saving of water and economies in design may be found to pay for the increased capital charges. In this case criticisms based on the probable inefficiency of linings in preventing the rise of the subsoil water table do not apply.

Diag. (VI) shows longitudinal sections along the trough of the water table in four doabs, drawn to the same scale. It will be at once remarked that in the case of the Sirhind and Western Jumna canals we have a very different state of affairs to that obtaining in the Rechna and Bari Doabs. In the former there are remarkably steep gradients while in the latter the gradients are flat, and for over 200 miles from the headworks, the water table is dangerously near the ground surface. In the former again, which are the older canals, we may suppose that equilibrium has been attained, but it is obvious that there is no possibility of the establishment of similar gradients in the latter, where the spring level still tends to rise generally. Even were the spring level to rise in the centre of the doabs to such an extent that the rivers on either side can act as drains, the additional slope obtained will bring the total slope to nothing like what is met with in the Sirhind and Western Jumna. If the spring level is still steadily rising at the tail of the doabs, as is certainly the case in the Rechna, there appears little hope that by stopping about half the total additions to the sub-soil stream a position of equilibrium will be attained.

It is sometimes maintained that waterproofing in the higher reaches of the canal would make its effect felt throughout the whole length of the doab. It is however in the head reaches that we find a convex water table with a considerable drainage back into the rivers, as well as a certain amount of relief during the monsoon from natural and artificial surface drainages. Moreover, if this view were true, one would have to suppose that the general rise in the lower reaches is due to a piling up effect, due to inflow exceeding outflow. Careful measurements of contour maps have failed to show any indications of this, and there seems no escape from the conclusion that in almost all cases any rise in the water table is due to additions arriving from the surface in the immediate neighbourhood. It would therefore appear hopeless to look to waterproofing of head reaches for a general cure, as is sometimes done.

Another point which is of considerable interest, has been raised by Mr. Elsden 14 in his paper in the 1922 proceedings of the congress, where the question of allowing the crossing of drainages by canals is discussed. So-called " dispersed " or " contracted cones " are supposed to exist beneath channels as a result of percolation, and it is assumed that when " dispersed " they will have no bad effects in heading up water, but when " contracted " they will act as barriers to the sub-soil flow. While it is impossible to accept the reasoning on which this conception is based, the two conditions of the " cone " do in effect describe limiting conditions

of the type of water distribution which may be expected. The important point is to be able to predict from knowledge of the soil, canal section, and depth to spring level, what this distribution will be. A solution for the equation in section 9 (5) may enable this to be done. It is easy to see that there will be a bigger hump in the water table beneath a leaky channel, when the depth to spring level is small, the soil coarse, and the percolation large. Moreover, since, in a case like this, it is the percolation term which is of importance the channel should be so designed as to reduce the head as much as possible. Thus the channel should be shallow and not deep.

In conclusion, it may be pointed out that, until properly conducted experiments in the agriculture of waterlogged land have been carried out, it is premature to urge the heroic remedy of lining a complete existing canal system. Much might be learnt in a tract such as that at Hafizabad by combining irrigation and under drainage. Mole draining under such conditions might have advantages over the more permanent tile drains.

Symbols used in the mathematical parts of this paper.

μ=moisture concentration (*i. e.*, grams of water per 100 grams of soil).

ϕ=hydrostatic pressure due to film tension.

P= ,, ,, ,, to gravity.

p=a vapour pressure.

g=acceleration of gravity.

η=vapour density.

w=specific volume of a liquid.

γ=surface tension ,, ,,

ρ=radius vector.

θ=an angle.

v=velocity.

T=absolute temperature.

α=average radius of particles of a soil.

λ=conductivity co-efficient.

k_1=absorption constant.

k_2=percolation ,,

C, c, M, N, a, β=constants.

σ=sigma function, or flow integral.

L=leakage.

Λ=leakage per unit wetted area.

lg=logarithm to base e.

D=depth from surface to spring level.

d = ,, of water in a channel.

h =height above spring level.

APPENDIX.

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DISCUSSION.

The Honorary Secretary read a letter from MR. WILSDON in which he expressed his regret that urgent private affairs in England had rendered it impossible for him to be present to open the discussion on the points raised in his paper. He however wished to say a few words in introduction.

The distinction between the modes of motion of water in the soil, which he had chosen as the title of his paper, was not new. As far as he was aware the first clear statement was made by Beresford, a Punjab engineer. A qualitative definition was, however, only the first step, and it was towards a quantitative formulation of the problem that he had attempted to advance. Broadly speaking, one might say that water movement would be determined by the factors governing *absorption* when the moisture content was below saturation, while *percolation* was only met with when the soil was saturated or the hydrostatic pressure positive. In support of the quantitative hypotheses developed to define these conditions it was found—

(1) that experiment showed a distribution of water beneath a channel similar to that which would be expected on theoretical grounds, and

(2) that under the conditions of absorption loss from channels, the influence of the depth of water in the channel was insignificant under all ordinary conditions.

The theory was of course far from complete ; thus it was at present quite impossible to predict what would be the distribution of water in the very complicated case when, by rise of the sub-soil water, absorption conditions began to merge into percolation. But on the small foothold which had been gained it was possible to make some attempts at a survey of the wider problems involved, and this he had ventured to do. As he anticipated that it would be in these aspects that most interest would arise in the discussion, he mentioned the following as being to his mind fundamental propositions :—

(*i*) If in a doab the depth of the sub-soil water table was such that absorptive conditions obtained, differences in the rate of addition of water, indicated by humps in the contours, must be due to the relative length of time the ground surface remained wetted. Thus there would be a hump under a canal, not because the head of water in it was say six feet, but because it might run for fifteen days, while a field might be irrigated only for two.

(*ii*) If this were so what justification was there for assuming that the *general* rise in the water table was due solely, or predominately, to the losses from channels ? Regarding the movement of water in the soil as analogous to a very

viscous fluid such as pitch, would not quite erroneous conclusions be drawn by referring all additions to the gradients, without at the same time considering the transmission constants of the soil? He contended that careful consideration of existing water table contour maps forced us to the conclusion that the existing gradients could not account for the general vertical rise in the water table. That ominous two feet a year was the result of a general fine rain from the surface of the ground, assisted only by the slow movement of water from the humps which accumulated under the more permanently wetted areas.

In his paper he had outlined other methods of reasoning which led to the same conclusion. The proposition of lining canals must therefore be viewed with the certainty, that any method adopted could only affect partially the rate of rise. With so much doubt as to the practicability, efficiency, and durability of an approximately perfect lining would it not be wiser for the present to concentrate on the treatment of the symptoms of the disease? The methods of agriculture suitable in water-logged tracts in a climate such as this had still to be examined scientifically. With an efficient system of drainage worked by the Irrigation Department from the cheap power that it should be possible to command, and the development of suitable agricultural methods for draining the fields, might not the rise of the water-table become a blessing rather than a curse? A reserve of readily available ground water would make us independent of the seasons.

In opening the discussion on Mr. Wilsdon's interesting theoretical paper, MR. C. V. G. SCOTT wished to make a few remarks on paragraph 12, in which he referred to the subject of waterproof lining as a remedy for preventing loss of water by absorption from irrigation channels, and also to drainage in water-logged areas. In this paragraph the author stated, that when dealing with true absorption, it was improbable that any lining that was practicable, would have much effect in stopping absorption, because a septum containing comparatively few holes from the point of view of the area covered, might have no appreciable resistance to diffusion. Further on he referred to the experiments carried out by the Punjab Drainage Board at Rasul on bituminous slabs, pointing out that though these slabs might not have shown any visible sign of leakage under a hydraulic head of 12 feet on the side freely exposed to the air, yet if these slabs had been resting in contact with the soil, they would have lost water by diffusion, and in support of this opinion he quoted the fact that a porous earthenware vessel, which would hold water while freely suspended in the air, would lose water by diffusion when buried in the soil.

To make such comparison between a porous earthenware vessel and a bituminous slab, appeared to the speaker to be straining scientific theory too far. Perhaps the author might not have known that the bituminous slabs were not merely "cast" as he stated in his paper,

but were subjected to high compression, up to 200 lbs. per square inch. In all asphalt mixtures with bitumen as the base, compression was necessary in order to obtain consolidation, (in the case of a road pavement this was commonly done by steam rolling) the object being to eliminate all voids, hence to compare a porous earthenware vessel with a compressed bituminous slab, did not appear to be logical. A former Chief Engineer of the Irrigation Department had described an experiment he had made with thin bituminous discs resting on dry Portland cement. The discs had been subjected to a hydraulic head for several days, and when they were removed no trace of moisture could be found in the Portland cement. A similar simple experiment would quickly demonstrate whether a bituminous lining was likely to lose water by diffusion. Such an experiment had in fact already been made at Lahore in the special Linings Division, Sutlej Valley Project, where a tank lined with bituminous sheeting 3/16" thick remained practically impervious under a head of 11·5 feet, the loss by absorption being equivalent to only ·09 cusec per million square feet of wetted area.

All experts in bitumen and its applications, both English and American whom the speaker had consulted, were unanimous that this material was absolutely waterproof, but compression was necessary when it was mixed with an aggregate.

This necessity for compression led to experiments on a slab lining, because on our running canals which could only have short closures, compression of the material on the bed of the channel was not practicable, but must be done before the material was laid.

At Rasul, work was carried on under great difficulties for want of proper equipment, so that complete mixing of the material and uniform compression could not be obtained, but with proper machinery these difficulties could easily be overcome.

The author of the paper also referred to the loss of water through the joints in the slab lining of the experimental tank at Rasul, but as related in the final report on the tank, it was found that by painting the slab lining with a layer of pure bitumen 1/8 inch thick, the tank became practically impervious, the loss by absorption being only $\frac{1}{2}$ cusec per million square feet of wetted area.

In Western Australia, under climatic conditions similar to the Punjab, tanks 20 feet deep had been made absolutely waterproof with a bituminous lining.

In applying a bituminous mixture as lining for channels in the Punjab, its waterproofness was not the principal difficulty to solve, the most formidable part of the problem was to get a grade of bitumen that would stand the large range of temperature to which it was subjected. This however was another aspect of the problem which should not be introduced in connection with the paper under discussion, but temperature tests were still being carried out.

In the concluding paragraph of his paper, Mr. Wilsdon gave the impression that drainage, particularly underground drainage, would be preferable to canal lining as a remedy for water-logging. Since the speaker had been with the Drainage Board he had found many engineers tacitly assuming that drainage was an easy and cheap remedy for water-logging.

As regards drainage being easy in a water-logged area, quite apart from local difficulties due to the contours of the country, in no case which Mr. Scott had seen, had any attempt been made to excavate drains more than 3 feet deep, the reason being that with the local labour available in the Punjab, excavation in saturated soil to a proper depth could not be carried out by manual labour alone.

As regards its being cheap, a former Agricultural Expert, Mr. Roberts estimated that for any really effective system of underground drains in the Lower Chenab tract, they should be spaced at least 20 feet apart, and that the cost would not be less than Rs. 100 per acre, the total cost for the whole tract being 25 crores of rupees.

This opinion coming from an Agricultural Expert well acquainted with the conditions that had to be dealt with the Punjab, should tend to disperse the idea that land drainage in water-logged areas would be cheap.

There also appeared to be some confusion of ideas amongst engineers regarding land drainage, the tendency being to confuse ordinary surface drains made for the removal of surplus water due to rainfall, with seepage drains meant to relieve saturated soil, and to assume that because in a certain tract subjected to water-logging due to rainfall surface drains had been successful, that they would be equally successful in water-logged areas saturated by seepage from a canal. There was obviously a great difference. In supersaturated soil, the absorptive capacity of the seepage drain must be taken into account, not merely its capacity to remove surface water. This meant as pointed out by Mr. Roberts that seepage drains must be placed at close intervals.

Other opinions in support of this could be quoted, but that of an Agricultural Expert was selected because the paper under discussion was by an Agricultural Expert.

Attention was drawn to paragraph 12 in the paper in which Mr. Wilsdon had estimated the loss by absorption in watercourses and fields at 14 per cent. which he said waterproof lining of canals would never touch.

Mr. Roberts, quoting again the same authority, however had said :

" In my opinion the amount of water that percolates to the water-table from the fields is one per cent. and therefore negligible. The rise of water-table must therefore be entirely due to percolation from the canals and especially those parts of the canal constantly running."

Again after referring to certain crop experiments carried out by Dr. Leather at Pusa, Mr. Roberts had recorded the following conclusions :—

(*a*) " Surface water does not directly affect the water-table at all."

(*b*) " Losses from percolation in the main canals are more than sufficient to account for all the rise in the water-table that has been observed."

(*c*) " It is in some form of lining the canals that the only feasible cure for water-logging lies."

In conclusion Mr. Scott remarked that if he and other engineers (and there were many) who believed in waterproof lining as the radical cure for water-logging on canal systems, were wrong in their opinion, they at least erred in very good company.

MR. A. S. HEMMY remarked that when Mr. Wilsdon asked him to introduce his paper he had at first demurred as it was not a subject with which he was personally very familiar. He would however offer a few observations on the general principles involved. There were three factors concerned in the problem of subsoil flow, first gravity, second capillarity and third chemical attraction. He did not consider it possible in our present state of knowledge to apply mathematical methods with any great degree of exactness. In clay or fine loam such as that found in the Punjab there was considerable molecular attraction. The clay attracted the moistures and swelled, with the result that all the pores got filled up and the moist clay became practically impervious. Mr. Wilsdon in his paper assumed that the chemical attraction was proportional to the capillarity. This might be challenged but was possibly correct. In dealing with the forces acting, gravity acted all the time, but capillarity varied with the moisture content. That is to say, in a saturated soil movement would be due to gravity almost entirely, while in a dry soil the main factor would be capillarity. This was shewn by table I. Looked at from the practical standpoint, Mr. Wilsdon's theories appeared to have justification as shewn by the results of the experiments described in the paper. The speaker, however, not being an engineer was not prepared to enter into the details of the different canal linings, but it appeared that Mr. Wilsdon feared cracks. Mr. Hemmy suggested that clay properly laid and protected and kept moist would be a most efficient lining.

MR. W. ROBERTS had great sympathy with the point of view of the paper though he differed from the conclusions arrived at. The paper was not pure theory as advanced by some speakers, but was the result of two years of labour and experiment, and it was a great pity that Mr. Wilsdon's work in this respect would not be continued. The results embodied a great deal of careful practical work, and as such deserved every consideration. He would

only draw attention to two points, *viz.*, the paper distinguished between percolation and absorption, and by keeping these distinct attempted to give a clear exposition of what was taking place in the soil. He, however, still felt vague as to the relative values of the two factors.

The second point was that in dealing with water losses from the soil the effect of transpiration losses was not seriously considered by the writer. Experiment had shown that transpiration alone could account for all ordinary losses from the field in Punjab irrigation practice. As a whole the paper left him unconvinced.

MR. LINDLEY wished to point out that the general problem of soil absorption from canals included three features ; the losses from channels, water-logging of tracts, and seepage returns to the rivers. This paper dealt only with the first.

At first view, the paper might seem purely theoretical but Mr. Wilsdon had also done a great deal of experimental work at Lyallpur. Many realised that such physical theory as engineers had evolved, and on which they had based formulæ was defective. Mr. Wilsdon presented a notable advance on previous knowledge and this was shown by the essential agreement between his diagram IV on page 12, representing observations, and the lower part of his diagram V on page 14, representing theoretical results. In the present state of knowledge (or lack of knowledge) of constants, more could not be expected than to account for the general form of variation.

The great body of work done by canal engineers in the problem was briefly but effectively summed up in two chapters of Buckley's " Irrigation Pocket Book." Those who studied the subject however should not confine themselves to this summary, but should see the original papers there quoted.

A most important point in Mr. Wilsdon's paper, which could not be sufficiently emphasised, was the distinction between " percolation" or flow under pressure where the soil was saturated, and " absorption " or flow under the attraction of unsaturated soil. Punjab Irrigation Branch Paper No. 10 showed that as long ago as 1875 Beresford realised and made this distinction. It had since been overlooked and forgotten, while engineers reasoned incorrectly, but it was now vindicated.

For calculating the absorption losses of channels the first known formula was given by Higham in 1896, in Punjab Irrigation Branch Paper No. 7. This made the loss in cusecs, per million square feet of wetted area, $3\frac{1}{2}$ multiplied by the depth in feet ; this formula was still quoted of the Punjab abroad, but had long ago fallen into disuse locally. Absorption was actually calculated at constant rates of eight or ten cusecs per million square feet. In a paper read before this Congress in 1917, Mr. Woods had put forward another formula, based on the argument that the loss per unit area varied as the depth but this had never found acceptance, and Mr. Wilsdon now definitely showed that the basic argument was incorrect.

The speaker had had occasion to try to calculate the absorption losses of channels with more accuracy than usual in the course of precise moduling of channels in the Jhang Division, and he had taken the loss per million square feet in cusecs, as eight plus a quarter of the depth in feet. He found that admitting the supply thus calculated at the heads of channels resulted in precisely the right amount reaching the tails, while some other observations further confirmed the practical correctness of this allowance for those conditions. Mr. Wilsdon said that not more than 10 per cent. of the loss would be a variable dependent on depth in the channel, where the conditions rather favoured variability. The speaker's allowance quoted above meant 3 per cent.

The records of canal offices contained an enormous mass of reports and observations and the results of these varied enormously. Seeing that the conditions under which the observations were made were rarely recorded, it was impossible to make any use of them. For example, an observation on a water-course might be made shortly after admitting water to a dry channel, and so be obviously abnormal.

An often quoted estimate of absorption losses was that of Kennedy, *viz.*, that of every 100 cusecs entering a canal head some 20 cusecs were lost in main and branch canals, 6 more in distributaries, 21 in water-courses, 25 by wasteful application, leaving only 28 cusecs of the whole hundred usefully applied. In making this estimate Kennedy quoted the rates of loss per million square feet that he had found as 10 to $2\frac{1}{2}$ in canals, $3\frac{1}{2}$ to 6 distributaries, and $9\frac{1}{2}$ to $12\frac{1}{2}$ in water-courses. Of these he ascribed the rate of 10 cusecs on main canals to the bed being open by moving silt, but the rest of the figures would mean that absorption varied more or less inversely as the depth. Such a variation had never been asserted.

In another paper on the same subject (Vol. VI—No. 3 of the Memoirs of the Department of Agriculture in India), Mr. Wilsdon gave some figures that would have been of great interest to engineers. Taking plans showing contours of the sub-soil water-table under the Lower Chenab Canal, he measured the volume represented by the rise of the water-table from 1905 to 1916. Assuming a pore space of 40 per cent. he showed that the rise under an area between section lines approximately through Sangla and Lyallpur demanded a steady discharge of 653 cusecs to account for it. The further area down to a section line through Jhang demanded a discharge of 1,574 cusecs, a total of 2 227 cusecs steady discharge throughout the ten years. From this he deduced that the water-table under the whole canal system had absorbed 3,255 cusecs. The probable loss from canals and branches was only about half of this. From the fact that a 10″ watering (in a season) contained 0·1 ton of sodium salts per acre, and various observations of salt content, he deduced that a third of the rise of water-table was accounted for, not by loss from channels, but from fields. As Kennedy's estimate gave 47 per cent. of

head discharge as lost from all channels, and 25 per cent. wasted, this would yield Mr. Wilsdon's one-third, without contribution from the water usefully applied to crops.

The speaker asked for a clearer statement of the practical meaning of the fact that the effect of holes in a water tight lining was measured not by the sum of the areas but the sum of the diameters of the holes. *Prima facie* and very roughly this would seem to mean that if there were a million holes of 0·001" diameter in a piece of lining 1,000" square, or one such hole per square inch, they would lose as much as one hole of 1,000" diameter. It was clear that Mr. Wilsdon considered a lining that was not really water-proof comparatively useless, but the point required elaboration.

On the subject of prevention of water-logging, food for thought would be found in Punjab Irrigation Branch Paper No. 20 by Mr. Woods. He showed that years of heavy rain accounted for most of the water-logging for which many canal engineers were ready to accept the blame.

The subject of seepage returns to the rivers was only now beginning to excite interest in the Punjab. The difficulty of deducing figures of any value even from regular daily discharge observations of the rivers at a number of sites, showed how very doubtful was the value of such figures as had before been deduced from occasional single observations. Mr. Wilsdon had showed, in the figures quoted by the speaker, how the rise of water-table was still absorbing most of the loss from the Lower Chenab system twenty years or so after it had been opened. The following rough figures, deduced from the river discharge observations of 1921-22, would be of interest.

1. River Sutlej, from Gandasinghwalla to Adamwahan :—

   On 1st October, a gain of between 1,000 cusecs and nil ; falling steadily to 2,000 to 3,000 loss on 1st May.

2. Rivers Chenab and Jhelum, from Khanki and Rasul to Haveli :—

   On 1st October, 6,000 to 8,000 gain, dropping to 2,000 to 3,000 on 1st November, zero on 1st January, and about 4,000 loss on 1st May.

3. River Indus, Kalabagh to Ghazi Ghat :—

   On 1st October neither gain nor loss, rising to about 8,000 loss on 1st March.

MR. C. QUINN YOUNG said that surface drains were beneficial and could be made to unwaterlog large areas if properly located and properly maintained. He instanced the Chak Qazi-Machiana tract, opposite

Right Bank R. D. 390,000 to 410,000, Upper Jhelum Canal. The situation here was regarded as very serious in the years 1919 and 1920, so much so that the remedial measures suggested ranged from an entirely newly aligned canal to enclosing five or six miles of the existing canal with sheet piles costing lakhs of rupees. But less revolutionary councils prevailed. A system of drains was excavated, which was extended from time to time, and land which was once regarded as heavy swamp now bore good crops of wheat, the cultivation of which was brought right up to the banks of the drains. These drains were dug from four to six feet deep, and four to seven feet wide, and kept clear of weeds at all times. Beldars were employed all the year round, under a subordinate to see to their clearance. In 1919 and 1920 one could not walk or ride over the country, on account of the marshy character of the surface. Now all this had disappeared and crops, both Kharif and Rabi, were to be seen everywhere. It so happened that the land which suffered on this canal was sloping, and very favourable gradients were obtainable for the channels, anything from about 1/250 upwards. They could also be dropped into the numerous approach and outfall channels of the various drainage crossings. Under these circumstances, it was improbable that any other method than that now in vogue for dealing with the seepage on the Upper Jhelum Canal was necessary. He also issued a word of warning to those contemplating any form of light lining on canals as a means against absorption. On the Upper Jhelum Canal, owing to the numerous curves most of which were in sandy reaches, the induced velocity was often more than 50 per cent. above the designed velocity, and that which the soil could stand. The result was that dynamic forces directed against the banks washed them down. Thus, the reach below Khokra had widened by as much as sixty feet ; the curves were tending to straighten themselves out and no light lining in his opinion would stand against such dynamic action.

CORRESPONDENCE.

Mr. Calthrow noted that the Author had used the theory of surface tension in accounting for the minus pressure in soils, and had calculated that this minus pressure disappeared when an average soil in the Punjab was saturated up to 23 per cent.

It appeared to him that this theory of surface tension only held good for still water, and that directly movement occurred a further minus pressure was introduced owing to the natural attraction of one body for another, which in this case was the attraction of the particle of soil for the film of water surrounding it.

The sketch below was a diagramatic section, showing the particles of soil very much enlarged, with a film of water round each particle—

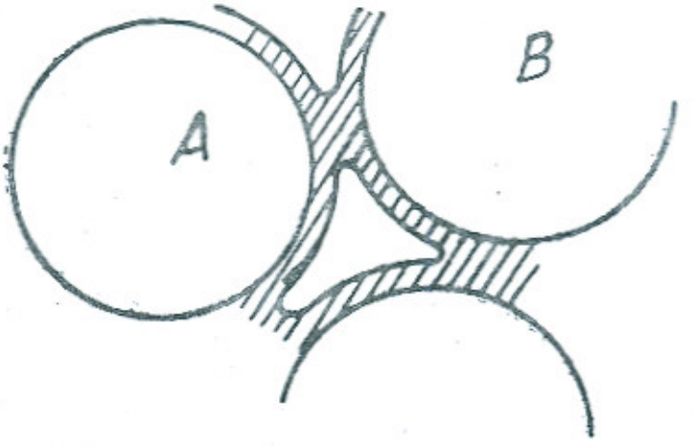


DIAGRAM VII.

To move water from particle A to particle B, a definite force would be required quite apart from that due to friction.

He considered that there was minus pressure with complete saturation and probably even with percolation, otherwise drainage problems would be very easy.

Mr. C. C. INGLIS wrote that not having had time to prepare Notes on Mr. Wilsdon's Paper the writer was unable to speak on it at the Congress; but as the following explanation made Mr. Lindley's brain "click" to the Wilsdonian conception, it was repeated here in the hope that it might help others.

In this explanation, all disturbing factors were conveniently ignored, and it was assumed that the distance of the line of saturation was proportional to the depth in the canal. This might not be quite true; but was sufficiently accurate for the purpose in hand.

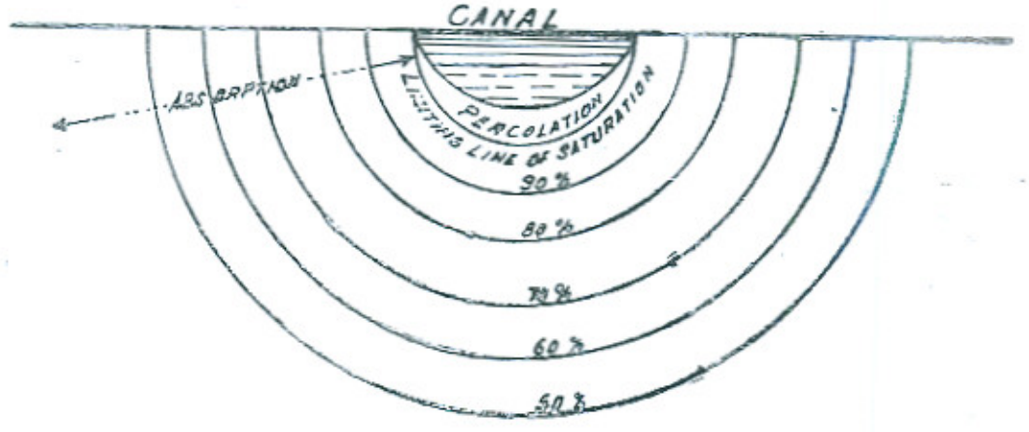
Using the term "percolation" to mean flow under positive pressure, and "absorption" to apply to flow when the soil was not saturated and the pressure in the liquid films was less than atmospheric—*i.e.*, capillary flow conditions—it would be seen that there must be a boundary along which the pressure changed from positive to negative, *i.e.*, a boundary

between percolation and absorption, *vide* Diagram VIII below :—

DIAGRAM VIII

SHOWING DISTRIBUTION OF SOIL MOISTURE

NEGLECTING ALL DISTURBING FACTORS



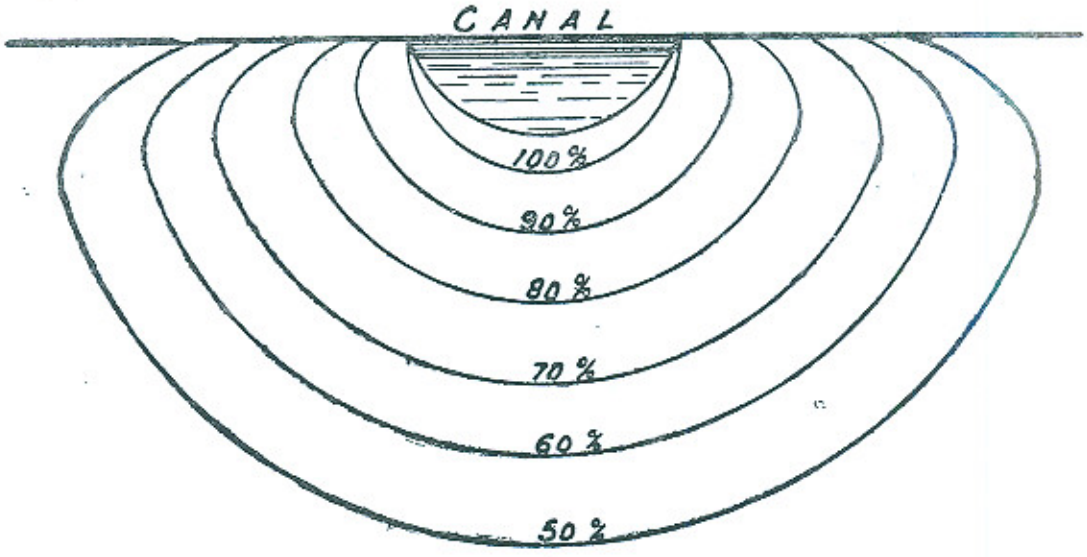
Beyond this limiting line of saturation, the moisture was sucked away as quickly as it arrived. If then a *uniform soil was assumed and disturbing factors* were ignored it could be said that the loss per sq. foot of this boundary region was constant, and hence that the loss per foot length of channel was proportional to the length of the perimeter of saturated soil bounding the percolation zone. As this in turn was roughly proportional to the wetted perimeter of the channel (under the conditions ruling in Northern India), it could be seen why losses from canals varied very approximately as the wetted perimeter. It would be seen that the whole loss from a canal started as percolation, even though the loss was mainly governed by the laws of absorption ; and the easiest way to visualise Mr. Wilsdon's statement on page 17 below table 3 ("*We must conclude therefore that the percolation correction even in a very deep channel never amounts to more than about* 10 *per cent.*") was by considering that the maximum head of water in a Punjab canal would only push the zone of saturation to that distance from the wetted perimeter which would increase the saturation perimeter by 10 per cent.

Where the soil was highly permeable the effect of head was, of course, far greater and the loss from Deccan Canals was found to be approximately equal to the wetted area of the permeable stratum multiplied by the depth of water in the canal, *i.e.*, it was almost entirely percolation. (See Bombay Congress Proceedings 1922, Vol. XI, Paper LXVIII—"Inglis on some important factors affecting the design and working of Deccan Canals".)

In the above—as already stated—numerous factors had been conveniently ignored. Thus evaporation from the ground surface will cause the water concentration curves to bend inwards as in Diagram IX,

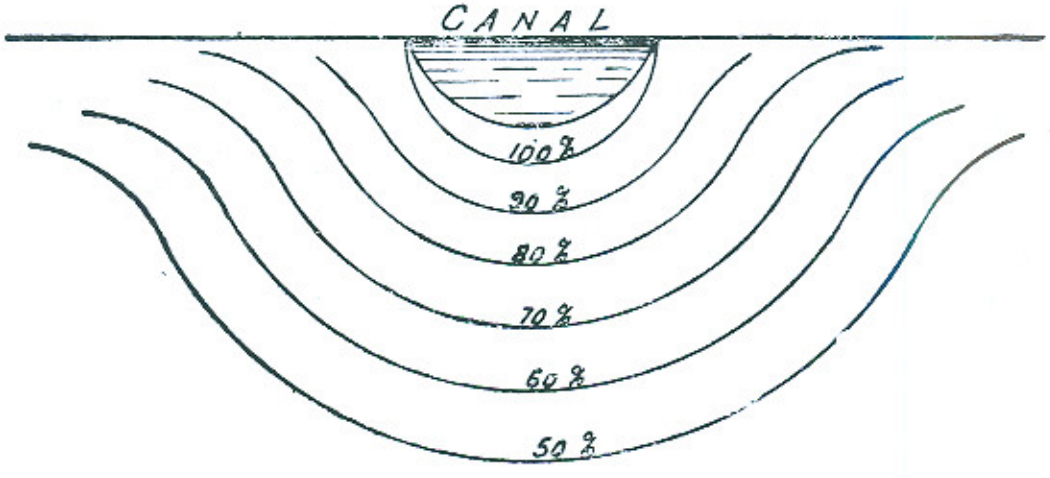
DIAGRAM IX

EFFECT OF EVAPORATION ON MOISTURE DISTRIBUTION



while irrigation would cause them to bend outwards as in Diagram X.

DIAGRAM X



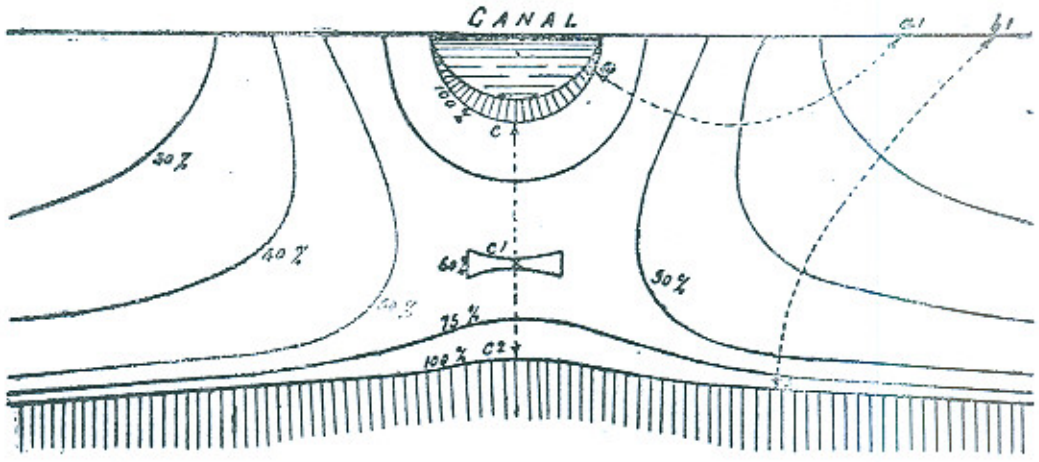
EFFECT OF SURFACE IRRIGATION

The subsoil water-table would effect them as shown in Diagram XI.

DIAGRAM XI

EFFECT OF SUB-SOIL WATER TABLE

ON DISTRIBUTION OF MOISTURE IN SOIL



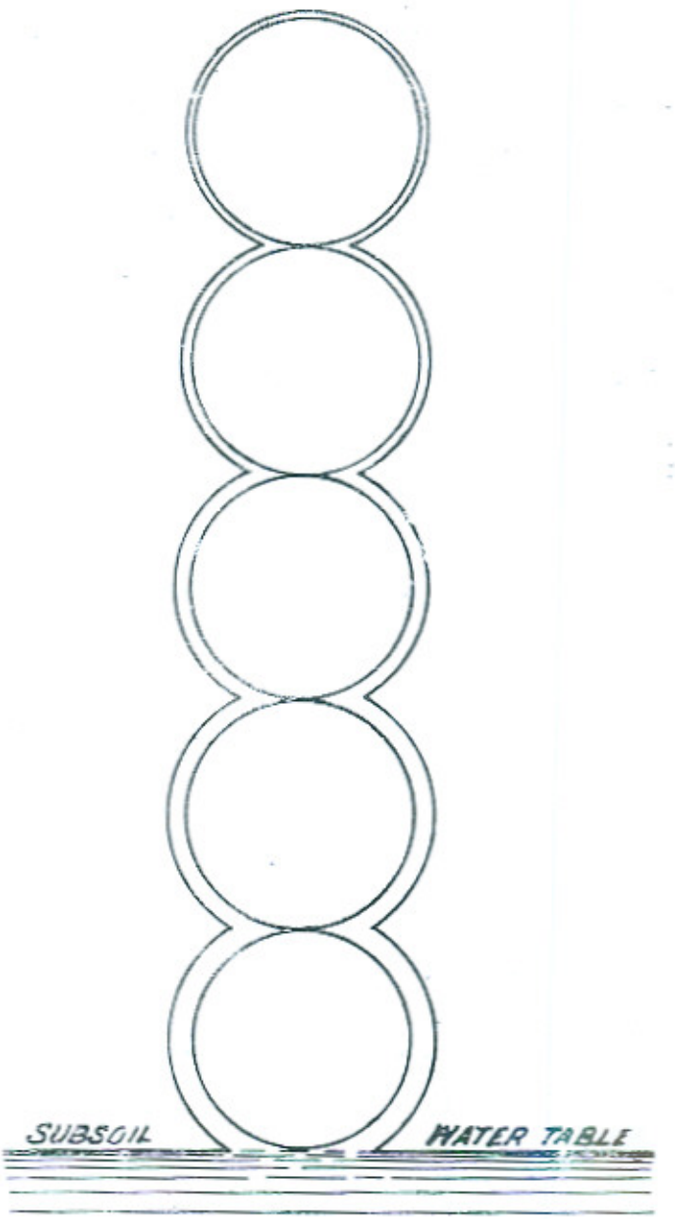
In addition to the above, variations in the salinity of soil moisture ; humus content ; layers of soil of different permeability, etc., would also have an effect, so that in practice it was well nigh impossible to get conditions which rendered it possible to collect data to establish the accuracy of the theory.

A point which was likely to puzzle people was that though Mr. Wilsdon pointed out on page 4 that the influence of gravity was negligible—a statement for the correctness of which the writer could vouch so far as Deccan soils were concerned—he did not make it clear that water eventually reached the subsoil water-table entirely through the effect of gravity.

Referring back to Diagram XI and bearing in mind that neglecting gravity, flow was due to the pressure gradient, which was determined by the moisture gradient ; the dotted line a....a_1 represented the direction of flow of moisture from the side of the canal to the ground surface, where it evaporated ; while b....b_1 showed the direction of flow from the subsoil water-table to the surface. Neither of these showed the moisture from the canal passing down to the subsoil water-table, but below the canal the soil moisture went vertically downwards, (c....c_1) passing from a higher to a lower potential, and then continued down to the subsoil water-table (c....c_2) – apparently

contrary to the pressure gradient. *This latter was entirely due to gravity.*

DIAGRAM XII



The explanation Mr. Wilsdon gave the writer of why this occurred makes the point quite clear. Imagine a series of soil grains one above the other, see Diagram XII—with a continuous film of water, which had reached static conditions, so that the amount of water was the maximum which could be held against the pull of gravity. Then imagine a drop of water put at the top ; it was obvious, even without considering the laws governing surface tension that the drop of water would pass down through the film to the subsoil water-table ; and if other drops followed a new set of conditions would be set up—as shown in Diagram XI—the subsoil table rising, as also the distribution of capillary moisture, till it would eventually change to the state shown in Diagram XI. Diagram XI, it would be noticed, was similar to Mr. Wilsdon's Diagram V (*a*).

From the discussion, it would appear that a good many people did not accept Mr. Wilsdon's theory. The writer believed this was mainly because it was not understood.

That Mr. Wilsdon's conception was in the main correct, there was little doubt ; but even if it were not entirely correct, at least it gave a working hypothesis which could be visualised, and satisfactorily explained all those points which had been perplexing soil physicists and irrigation engineers for many years.

The importance and value of the work done by Mr. Wilsdon was therefore enormous in that it revolutionised our conceptions of the movement of soil moisture, but it was a thousand pities he had not been given facilities to complete his investigations.

MR. LINDLEY wrote that on reading Mr. Wilsdon's paper, he felt the need for a physical conception to visualise, as without it he could not really understand what was happening. Knowing that other engineers would feel the same, he tried to arrive at one before the Congress meeting by discussion with Mr. Wilsdon and a few others. Unfortunately, it was not till after the meeting that a chance phrase of Mr. Inglis gave a clue to the framing of an explanation that could be understood. This explanation did not pretend to be scientifically complete and precise, and for the purpose in view practically all complications were ignored for the sake of simplicity. The effect on the simple explanation was left to the reader to consider, when he had visualised the simple case.

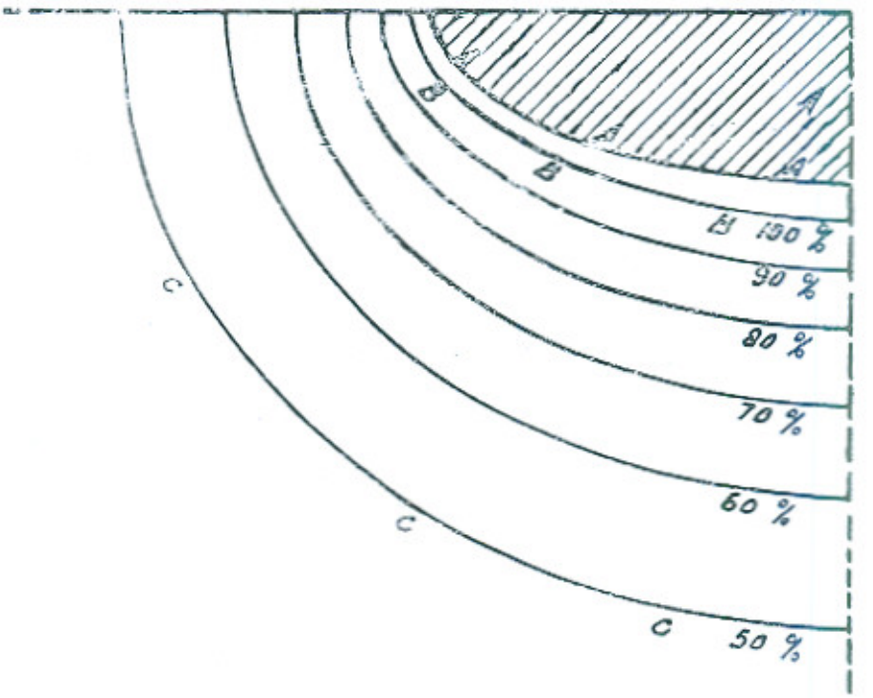
A channel or pit containing water, in dry porous soil was continuously losing water. The forces that caused this were gravity and capillary attraction. Gravity caused an intitial pressure at the perimeter of the channel, and continued to act on the water after it was in the soil. Initial pressure and capillary attraction acted equally in all directions ; gravity only acting on the water in the soil vertically.

The importance of the capillary attraction of average soils of ordinary dryness, relative to the strength of gravity and initial pressure, had hitherto been greatly under-estimated. Actually, initial pressure caused a flow which kept only quite a thin layer surrounding the channel soaked. At the boundary of this layer it was seized by capillary attraction and sucked away. Outside this boundary the flow could no longer keep the soil saturated, and the degree of saturation rapidly diminished with distance from the source.

Capillary flow in soil had hitherto wrongly been thought of as similar to what would take place in a set of fine tubes lying along the actual lines of flow, such tubes being either full or empty only. Actually, little droplets clung about points of contact and of approach between soil-particles. These droplets were not convex outside like drops falling in air, but concave and the pressure inside them was negative. The drier the soil, that is the lower the degree of saturation or the smaller the moisture content, the smaller the droplets and the greater this negative pressure.

Where the difference of pressure between adjacent droplets was not balanced by gravity, flow took place from the less to the greater (negative) pressure. If static conditions were reached in soil over a level water-table, the law of increase of pressure with depth below water-surface would be continued by the negative pressures and negative depths below (that is heights above) water-surface. Mr. Wilsdon showed that under these conditions the saturation varied as the logarithm of the height, *vide* the dotted curve of μ in the lower part of his Fig. V.

An experiment to illustrate what happened could be performed by laying a piece of blotting paper on a table, and standing the point of a fountain pen on it. A circular blot would form (if the paper were even and the feed not one-sided) and grow in increasing circles. If the paper were placed vertically instead, the circles would be slightly distorted, vertical dimensions being slightly shortened above and lengthened below, but the distortion would not be much, especially where the paper had not received much ink. If instead of feeding ink at a point it were fed at a line, the successive boundaries of the growing blot would instead of circles be confocal ellipses.



In the figure, AAA was the cross-section of a channel, made elliptical for the sake of simplicity. BBB was the boundary of saturation

surrounding it, and further ellipses were drawn as contours of decreasing degrees of saturation. For the sake of simplicity the figure ignored the distortion due to gravity mentioned above, and the difference of rate of loss from different parts of the perimeter due to pressure in the channel. Similarly it assumed that the length of the contours was inversely proportional to the saturation, ignoring the difference of velocity due to difference of pressure gradient. These assumptions led to a definite simple case and a definite picture, divergence from which would be considered later.

If it were assumed that the rate of loss were doubled, it would mean that the soil would be fully saturated where it was only 50% saturated before, that is the new boundary of saturation CCC was the former 50% contour. In both cases the initial pressure was used up in producing flow from AAA to the boundary of saturation. From AAA to BBB the velocities were doubled, so the pressure used up was doubled. At CCC the velocity was what it had been at BBB in the first case, so if BC were equal to AB, the pressure used up between BBB and CCC would be the same as the total of the first case. If BC were twice AB the total pressure in the second case would be four times the first, meaning that the loss varied as the square root of the depth in the channel. In the figure as drawn, it could be seen that BC was much more than twice AB ; and the pressure ratio would be still larger.

The finer the soil, the greater the resistance to saturated flow and the greater the capillary " suck ;" so, the finer the soil, the thinner the saturated layer surrounding the source ; in fact in ordinary loamy soils the saturated layer was probably little more than a film. A little consideration of forms would show that the closer BBB is to AAA, the greater would be the ratio AC : AB. In other words, the finer the soil was, the greater would be the increase of pressure needed to produce a given increase of loss, or the less was loss dependent on pressure.

The limiting curves of a family of confocal ellipses were inside, a straight line joining the foci, and outside, a circle of infinite radius. The narrower, therefore, the channel for a given depth, the nearer to circles were the innermost ellipses which mattered most. A little consideration of forms would show, that a pair of flat ellipses whose lengths were in a certain ratio were further apart than a pair of more circular ellipses whose lengths were in the same ratio, which meant that the wider the channel for a given depth, the less was the loss dependent on depth.

It was now possible to consider the assumptions involved in taking the curves as ellipses. Gravity was ignored. This would lengthen all vertical dimensions, but the finer and drier the soil the greater was the capillary " suck " compared with gravity, and so the less such dis-

tortion. The effect of such distortion as does occur was to decrease the distance between BBB and CCC, and so make the loss a little more dependent on pressure than assumed, that is, the effect of fineness or coarseness in making loss independent of or dependent on initial pressure was slightly more than suggested above.

Difference of loss from different parts of the perimeter of the source was also ignored, and where there was such difference it would produce a little distortion similar to that described in the preceding paragraph with the same effect. Mr. Wilsdon had, however, shown that under the conditions commonly dealt with, the relative variation of loss was not likely to be as much as a tenth of the relative variation of pressure.

It was further assumed that velocity was everywhere the same, so that everywhere the lengths of contours were inversely proportional to the saturations they represented. Mr. Wilsdon was requested to confirm or correct the surmise that, generally and practically, ellipses spaced as in the writer's figure involved an increasing pressure gradient, therefore increasing velocity and therefore the spacing opened out less than shown, and the dependence of loss on depth was greater than visualised from such a figure. The effect of all these assumptions could be gauged by comparing the writer's elliptical figure with Mr. Wilsdon's Diagram IV on page 12, observed on a water-course (relatively narrow) near Lyallpur. It should be noted that the writer showed percentage of full saturation of voids, while Mr. Wilsdon showed percentage of moisture in the soil by weight, so that 100% in the writer's diagram was about 23% in that of Mr. Wilsdon.

So far the explanation had assumed that the channel was the only source of moisture in the soil. It was also necessary to consider the static conditions over a level water-table. Capillary attraction drew up moisture from this, giving a certain moisture content at any point. If this moisture content were added to that due to the channel, and the result contoured, the result was to convert the upper part of Mr. Wilsdon's Diagram V into the lower part. There would of course be adjustments of gradients and flows and resulting moistures, but that was too complicated to enter upon here.

This meant that any rise of water-table decreased the loss from the channel. Putting this another way, the higher the water-table the damper the soil surrounding the channel, and so the less its suck. From what had been said of the logarithmic distribution of moisture content above a water-table, it could be seen that the effect of a water-table rapidly diminished with its depth below natural surface.

The effects of other points were dealt with in a written note that Mr. Inglis had submitted, and Mr. Lindley therefore did not wish to repeat them.

REPLY.

MR. WILSDN in reply wrote that the criticisms contained in the contributions to the discussion and correspondence on his paper would best be dealt with in a logical sequence. He would start therefore with the points of fundamental scientific importance, and then consider those connected with the application of the theory developed to practical conditions.

Mr. Hemmy referred the movement of water in soils to three forces—gravity, capillarity and chemical attraction. It should be noted that the treatment which had been adopted in the paper referred only to what was called the *free* water of the soil ; that held by chemical attraction was considered *bound* and was much less mobile. The general conditions of equilibrium of water held in these two states, *i.e.*, the free water and that absorbed by the colloids of the soil, had been considered in the author's memoir (*loc. cit*) and need not be detailed again. But it was important to recognise that there would be a distribution of water in the soil dependent on its colloidal content upon which that due to the free water would be superimposed. It was this fact which made the study of the distribution of water at the steady state so difficult practically. In studying the flow, it was justifiable to regard practically all movement as due to the free water, for which capillarity and gravity were predominantly responsible. It might be mentioned that in addition other factors might be an unequal distribution of dissolved material which would produce an osmotic pressure gradient, and also any temperature gradient in the soil, but it was as yet early to attempt to introduce these refinements till the main lines of the theory were substantiated. Mr. Calthrow expressed the opinion that the velocity head of water moving in the soil should be taken into account in calculating pressures. It could be shown, however, that the correction was so small compared with the hydrostatic pressure due to surface tension as to be negligible.

The diagram produced by Mr. Calthrow, as also Diagram XI in Mr. Inglis' discussion, raised a point which it might be as well to explain here. The changes in curvature shown in the triangular bubble in the former diagram were physically impossible. The curvature must be uniform ; this was only possible if it were assumed that the water collected in drops at the points of contact of the particles ; connexion over the wetted surface of the particle might be supposed to be by an excessively tenuous film of molecular thickness, the vapour pressure of which would then become independent of the curvature so that it might attain the same

value as that determined by the curvature of the drop (Diagram XIV).

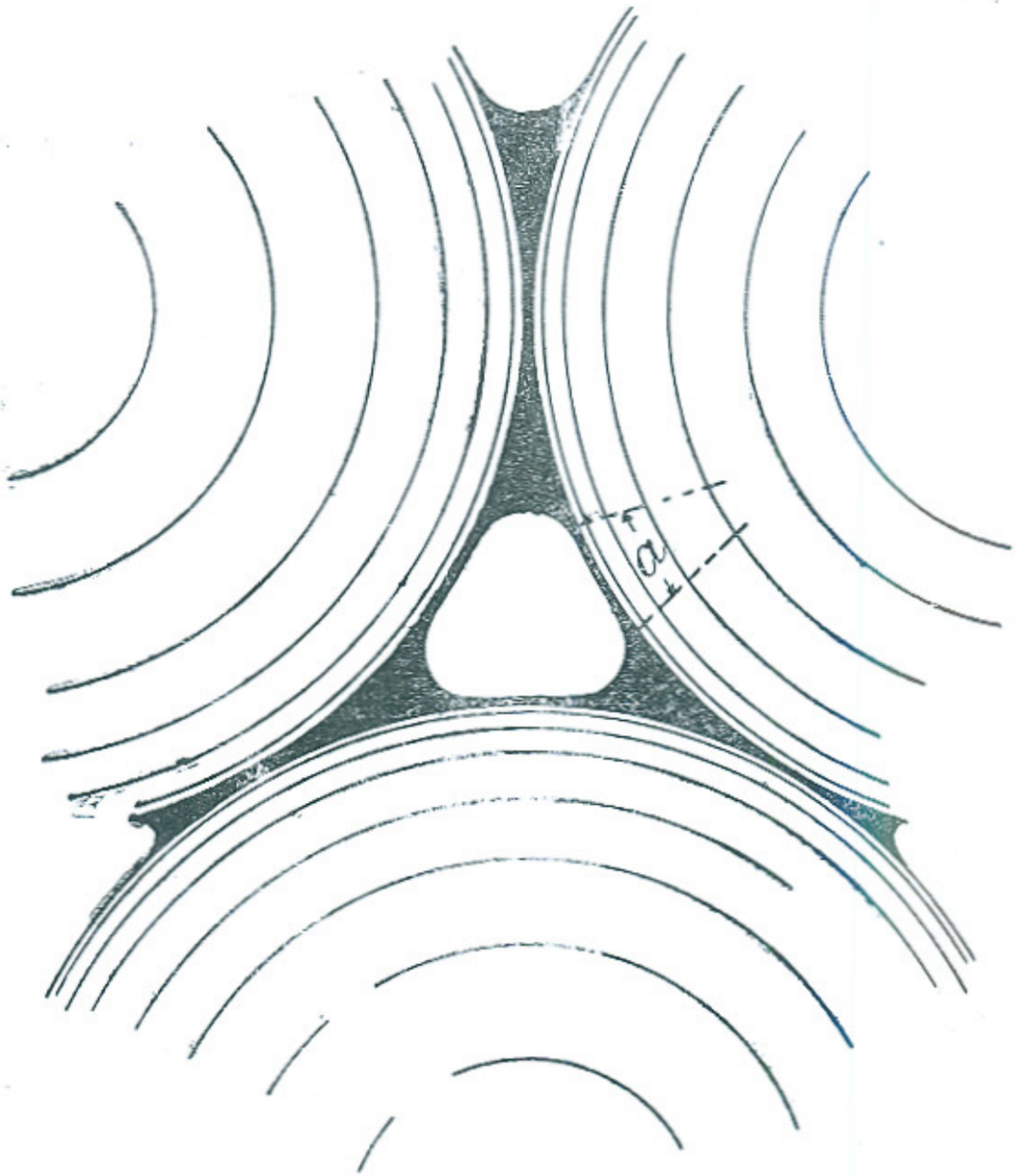


DIAGRAM XIV

Movement over the surface of such a molecular film would still be possible as was shown by experiments with soap films. On this basis, the assumption that the vapour pressure or what amounts to the same thing, the hydrostatic pressure, would be determined only by the size and shape

of the drop was justified. Another point of interest arose here which would be dealt with in a paper shortly to be published in the Journal of Agricultural Science. As the size of the drops increased, the menisci about adjacent points of contact would ultimately interfere, and this would take place at a moisture concentration considerably smaller than that of saturation. This indicated that the function developed which determined the hydrostatic pressure, would not remain strictly true as the saturation point was approached. It was not to be expected, however, that the general form of the equation connecting moisture concentration and hydrostatic pressure would be widely different. It was in any case almost too much to expect that a theoretical formula deduced on the hypothesis of the ideal soil should hold over the whole range of moisture concentration ; the hypothesis would have served its purpose if it enabled one to derive a rational formula which could be extrapolated empirically to the limiting conditions.

Both Mr. Inglis and Mr. Lindley remarked on the need of a simplified picture of the distribution of water at the steady state beneath a leaky channel. Qualitatively, the diagrams they produced give a clear idea of the phenomena to be expected ; but the quantitative spacing of the contours was a matter of importance and some complexity. In order to arrive at an approximate solution Mr. Lindley assumed that the velocities at all points were the same, and that the degree of saturation was inversely proportional to the length of the moisture contour at the point considered. The form of the contours was moreover assumed to be that of an ellipse confocal with that representing the canal bed. It must be recognised that there was no justification for either of these assumptions ; μ and ν were independent variables. For this reason it was found necessary to conduct the mathematical discussion in terms of a function σ which was such that its rate of variation in any direction was proportional to the flow in that direction, *i.e.*, $-\frac{\delta \sigma}{\delta x} = \mu v$. A solution then had to be found for the bidimensional Laplacean equation $\frac{\delta^2 \sigma}{\delta x^2} + \frac{\delta^2 \sigma}{\delta y^2} = 0$ which gave the distribution at the steady state, such that it was compatible with the particular condition defined by an equation similar to § 9 (5) and the boundaries. In the simplest case, by neglecting the second and third terms (the ground water and percolation terms), and assuming the section of the channel where $\sigma = \sigma_0$ was given by

$$\rho_0 = v - a \sin \theta$$

$$\lg \frac{\mu_0}{\mu} = \frac{c}{k_1} \quad \rho - v + a \sin \theta \Big) \text{ is obtained approximately. Thus}$$

the moisture contours were spaced logarithmically and became

approximately circular at distances where ρ—v was large compared with a sin θ (Diagram XV).

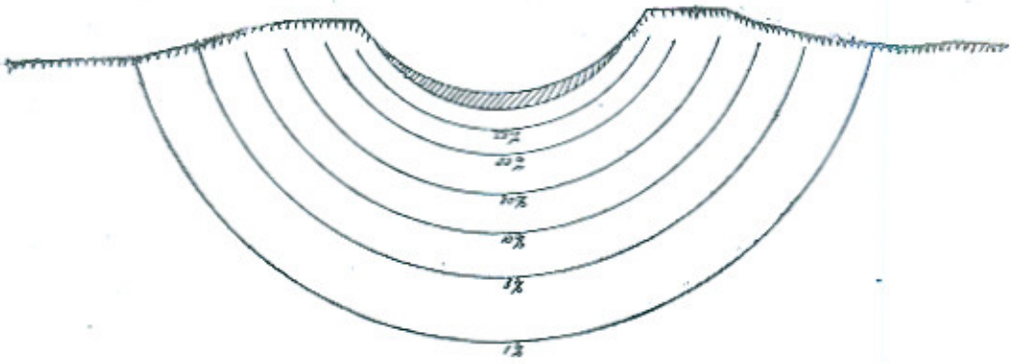


DIAGRAM XV

For less simple cases a solution might be obtained by a Fourier substitution. This method was employed in calculating the distribution in a soil with an impervious layer shown in Diagram V of the paper.

If Mr. Lindley's simplifying assumptions were adopted quantitatively, the spacings in the two cases could be compared.

From § 7 (2)

$$\frac{d\mu}{dx} = v = -\frac{k_1}{\mu^2}\frac{d\mu}{dx}$$ was obtained.

Therefore $$\frac{d\mu}{dx} = -\frac{\mu^2 v}{k_1}$$

But μv multiplied by P, the perimeter of the contour was equal to L the leakage, which was constant; if it were also supposed that $\mu \propto \frac{1}{P}$

then $$\frac{d\mu}{dx} = -\frac{Q}{P^2}$$ where Q was a constant.

In order to avoid elliptic integrals, if it were supposed that P was given by

$$\rho - a \sin\theta \text{ then } \mu = \frac{Q}{\rho - a \sin\theta}$$

This represented a variation of a very different character from that derived strictly, and the latter appeared to be more in accord with the admittedly scanty experimental evidence at present available.

An approximate idea of the distortion of the moisture contours and the advance of the zone of saturation beyond the bed of the channel could also be obtained directly from the equations developed in the

paper. Integrating the first and last terms of § 9 (5) between the limits ρ and ρ_p, where ρ_p represented the radius to which the zone of saturation extended

$$\rho - \rho_p = \frac{k_1}{c} \lg \frac{\mu_o}{\mu} + \frac{k_2}{c} \rho_o \sin^2 \theta \left(\mu_o - \mu\right)$$

The vertical dimensions were thus lengthened by an amount $\frac{k_2}{c} \rho_o \sin^2 \theta \left(\mu_o - \mu\right)$ more than when gravity was ignored.

The correction would be very small in a fine soil since k_2 was proportional to a^2.

In order to obtain an approximate idea of the value of $\rho - \rho_p$, the distance to which the zone of saturation moved, it might be assumed that the leakage, calculated from the contour limiting the zone of saturation, would be the same as if the water were being absorbed from a channel of this section, in which the head was zero. It would then be possible to equate this to the value obtained by taking into consideration the percolation term. From § 10 (5) was thus obtained

$$L = k_1 \lg \mu_o \left(\pi \rho_p - 2\ a\right) = k_1 \lg \mu_o \left(\pi\ r_o - 2\,a\right) + k_2 \mu\ v_o^2 f\ (\beta)$$

where $f\ (\beta)$ was a function of the canal section

$$\rho_p - v_o = \frac{k_2\ \mu_o\ f\ (p)}{\pi\ k_1 \lg \mu_o}\ v_o^2$$

and since

$$\frac{k_2}{k_1} = \frac{a}{A \times 36}$$

$$\rho_p - v_o = Q\ a\ v_o^2$$

The zone of saturation would thus move out a distance proportional to the square of the depth of the channel and the radius of the soil particle ; as would be expected the zone of saturation would be larger in a coarse than in a fine soil. Strictly of course $\rho_p - v_o$ would depend on θ.

A point of importance was raised by Mr. Inglis which might be worth further explanation. It related to the fact that although the ground water-table imposed a positive mositure gradient, water still reached the subsoil. This was easily seen by inspection of § 9 (2) ; the pressure gradient was made up of the departure of the moisture gradient from the equilibrium and the gravity term. The latter was always positive and was unaffected by the ground water gradient as could be seen in the calculation of the leakage in § 10 (5). All that the presence of the ground water gradient did, was to reduce and ultimately eliminate the absorption term. The leakage from a canal should therefore decrease with rise of

water-table until purely percolation conditions obtained. The leakage *per unit area* would then be proportional to $\frac{a}{A \times 36} \mu$. d $f(\beta)$ as shown in § 11 (2) where the function $f(\beta)$ depended only on the shape, and not on the depth, of the channel. As Mr. Inglis had pointed out, these were the conditions met with in Deccan canals. It would be of great value if the conditions, when rise of sub-soil water by reducing the absorption would bring the total losses from the canal into equilibrium with the sub-soil gradient, could be calculated. A preliminary examination would indicate that the problem was not insoluble. Definite knowledge on this point would do much to lay the ghost of complete water-logging which haunted irrigation prospects in the Punjab. There could be little doubt as to the real distinction in kind between percolation and absorption in view to the applicability of the theory to both sets of conditions.

The observations made in § 12 on the subject of losses through faulty linings appeared to have given the impression that the author thought it *impossible* to construct any sort of water-tight lining to a canal. His intention was to demonstrate that cracks in the material or faults in the joints might render any economically feasible lining practically ineffective in stopping leakage. He had in mind, principally, proposals, such as were at one time entertained, to line canals with unjointed blocks of cement, or very thin linings such as "jutelukh." The relation of Brown and Escombe for the rate of diffusion of a gas through a perforated septum would only be applicable to a lining in which cracks were related to the order of magnitude of the thickness in the same way. Mr. Lindley's example could be confirmed experimentally with a gas and a thin plate. The author's contention was only that within certain limits defined by the thickness of the lining, and the size of the faults, comparatively few cracks from the point of view of area might render the lining useless.

Mr. Scott quoted the opinions of Mr. Roberts on the subject of losses from fields, and Mr. Roberts repeated his conviction that transpiration by crops alone accounted for all the water applied in irrigation. An appeal to authority without a consideration of all quantitative measurements which bore on the problem could scarcely be expected to advance knowledge. What scanty figures were available for transpiration rates for crops in India demonstrated more than anything else, the remarkably large variations to which they were subject. While the maximum rate found amounted to about 17 inches, crops could be matured with one-third of this amount. One had to ask oneself not whether the crop was *capable* of evaporating all water applied in irrigation but rather if it actually did so. Water applied was competed for, evaporation from the soil and the osmotic pull of plant root systems acting in one direction opposed by the capillary pull of dryer soil and gravity on the other. It was thus obvious that *some* water must be lost. The writer had already

advanced what appeared to be a conclusive argument, referred to by Mr. Lindley, in support of this contention. If *all* the water were evaporated or transpired by crops, the sodium salts which were applied with the water and which were not removed by the plant, should have rendered by now all soils saline. Not only did this consideration prove that some water was lost to the sub-soil from each irrigated field, but a rough approximation to the ratios of the amounts evaporated and transmitted could be formed. Calculation showed that about one-third of the water lost to the sub-soil after the entry of water into the distributaries must be derived from fields. Thus on the Lower Chenab Canal 38 per cent. of the canal head discharge reached the sub-soil ; 18 per cent. was lost in mains and branches, 13·3 per cent. in distributaries and watercourses, and 6·7 per cent. from fields. The losses to the sub-soil from fields were then only about 10 per cent. of the water usefully evaporated by plants. The average application of irrigation water worked out to about 21·5 inches to which must be added rainfall. The 2·12 inches of water from this amount, which was lost to the sub-soil was not such a serious amount as to preclude acceptance of the deduction. An ample margin was left for the maturation of crops ; there must be *some* loss from the fields and the figure arrived at was not unreasonable.

The application of the above considerations to the proposed cure of water-logging by lining was obvious. If a perfect lining could be made in all the mains and branches, the losses to the sub-soil would only be reduced by about $\frac{18\%}{38\%}=\frac{1}{2}$. Any lining which it was feasible to put down in existing channels would certainly not be perfectly water-tight. Moreover, absorption losses would automatically diminish as the water-table rose. There thus appeared a clear case for delay in adopting the heroic remedy of lining an existing canal system for the purpose of preventing water-logging. There were yet no certain indications of the extent to which the evil would spread, and no steps had yet been taken to determine possible methods of reclamation by drainage. Mr. Scott referred to the difficulty and expense of drainage under Punjab conditions. He gave the probable cost of laying tile drains throughout the whole irrigated tract of the Lower Chenab Canal as 25 crores of rupees. It was inconceivable that it would ever be necessary to drain the whole tract ; probably only a small fraction of the whole would require permanent drainage. By the use of power machinery and mole drainage implements, worked under Government agency or by co-operative societies, reclamation could be effected at an infinitely smaller cost. The construction and maintenance of properly aligned main drains, even if they required pumping in the absence of sufficient fall, would represent a small fraction of the cost of construction and up-keep of a lined canal system. In any case it would be indefensible to adopt lining as a remedy until a trial of reclamation by proper drainage systems in water-logged areas had been made.