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Evaporation from the top layers of soil*

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ABSTRACT. Unless the soil is very dry volume diffusion calculated from the vapour pressure gradient does not account for all the water transfer observed. Hence it is concluded that in addition to volume transfer there is surface transfer in the top layers of soil.

1. Introduction

Study of evaporation from soil is very important for meteorologists and agriculturists. This study has been made by different people using different methods such as heat budget method, diffusion method, evaporimeter method etc (Sutton 1953). Prominent investigators in this field are F. Pasquill and O. G. Sutton in England, L. A. Ramdas in India and C. W. Thornthwaite in U.S.A.

Parker (1922) stated that there must be very great force holding water to soil and that this force is sufficient to cause the vapour pressure of soil water to be greatly reduced (lowered) at lower moisture contents, to prevent considerable quantities of water from freezing and to reduce the rate of evaporation as the soil moisture content is reduced. Ramdas and Mallik (1939) showed that as distance between water table and evaporation surface is increased, the rate of evaporation decreases rapidly. Taylor and Cavazza (1954) studied the movement of soil moisture in response to temperature gradients. In order to account for the total water transfer by molecular diffusion alone, they had to use a diffusion coefficient about four times that in free atmosphere. Hence they suggested that there may be some other mechanism of transfer since they had evidence to show that there was no liquid movement. Rollins and Spangler (1954) supported the view of Taylor and Cavazza. Dale (1957) using radiosulphur investigated the dynamics of gravitational and capillary water in sandy soil. He observed "the maximum count of radiosulphur at a distance of 20 inches above the ground water table revealed a greater capillary rise than is indicated for sandy soil on the basis of previous investigation. In fact the presence of isotope was detected at a height exceeding 30 inches above phreatic level". However he concluded that the amount transferred above 20 inches is not much. The transfer he observed could be explained by means of some mode of transfer other than volume diffusion and liquid transfer. de Vries and Philip (1957) stated that total transfer is not much affected by diffusion in the adsorbed phase.

2. Methods of measurements

In the laboratory two separate experiments were done, one using sand (0·77 mm) and the other using sandy soil (mixture of Columbia River soil, blasting sand of average diameter 0·15 mm and loam). The soil samples were kept in large plastic tubes of length 91·5 cm, area of cross section 323·2 sq. cm and wall thickness 0·64 cm. While filling the plastic tubes with soil, every care was taken to see that weight per unit height of soil column remained constant.

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TABLE 1

Typical data for the rate of water intake as read by the burette

(April 1957)

Date and Time	Reading on the burette (c.c.)	Date and Time	Reading on the burette (c.c.)
1 0900	4·3	13 0900	14·7
2 0900	6·0	14 0900	15·2
3 0900	7·1	15 0900	15·4
4 0900	8·1	16 0900	16·4
5 0900	9·1	17 0900	16·8
6 1000	9·6	18 0900	17·5
7 0730	10·5	19 0900	18·2
8 0900	11·5	20 0900	19·0
9 0900	12·5	21 0900	19·8
10 0900	13·0	22 0900	20·4
11 0900	13·0	23 0900	21·2
12 0900	14·3	24 0900	22·0

Thus the porosity of a particular soil was taken to be uniform throughout the soil column before adding water. Water was supplied to the soil columns from the bottom keeping the pressure head constant. Experiments with sand column was started on 29 May 1956 and that with sandy soil was started in the month of January 1957. Steady state was attained by sand in about a month and that for sandy soil took about seven months. During the experiments soil was never disturbed. Soil moisture determination was made in the month of February 1958 after all the experiments were finished. The criteria for the steady state are given below. Soil was supposed to have attained steady state when the daily water intake became constant and vapour pressure at all levels also became constant. When it was unsteady, it was noticed that both water intake and vapour pressure changed from day to day. The former decreased gradually and the latter increased gradually till it reached a steady state. It was also noticed that the wet front (the common boundary between moist and dry soil) remained at a constant depth below the surface at the steady state. A sketch of the apparatus is given in Fig. 1.

It is clear from Fig. 1 that there is no water in the inner concentric tube of the burette and hence water at that level (end of the concentric tube) is at the atmospheric pressure, no matter what the level of water in the burette is above the level of the end of the inner concentric tube. Water is never allowed to go below the level of the end of the concentric tube. Before the water level in the burette falls to the end of the inner tube, it is refilled without allowing the water into the soil column or the surge bottle. Since the water level at the end of the inner tube is in direct contact with the atmosphere, any change in the atmospheric pressure caused a change in the level of water in the burette. Hence this in turn will give slight error to the quantity of water intake determined by the burette readings. Moreover it will slightly change the level of water table in the soil column. In order to avoid the small rise in the water table of the soil column and to give correct average intake of water by the soil column, a surge bottle (a large capacity bottle) was added in the supply system. By this arrangement water first went into the surge bottle and then into the soil column. Owing to the large area of the bottle in comparison with that of the burette, short period irregularities in the supply of water did not change the level of water table of the soil column. It was found that when the atmospheric pressure was more or less uniform, the daily water intake was also uniform. In any case average supply of water for a 20-day period was very uniform. A set of typical data for the daily water intake is given in Table 1. The room temperature was kept at 68°F by means of a thermostat and the room humidity was kept at 52 per cent by exposing 36 sq. ft of saturated solution of magnesium nitrate. A typical chart of the daily thermo-hygrograph record is shown in Fig. 2.

Vapour pressure in the soil was measured by means of a modified form of Regnault's dew point hygrometer. The modified form consists of a clean polished metal surface which could be cooled by means of an ice bath until dew starts to form. The temperature of dew point was taken by means of an embedded thermocouple very close to the

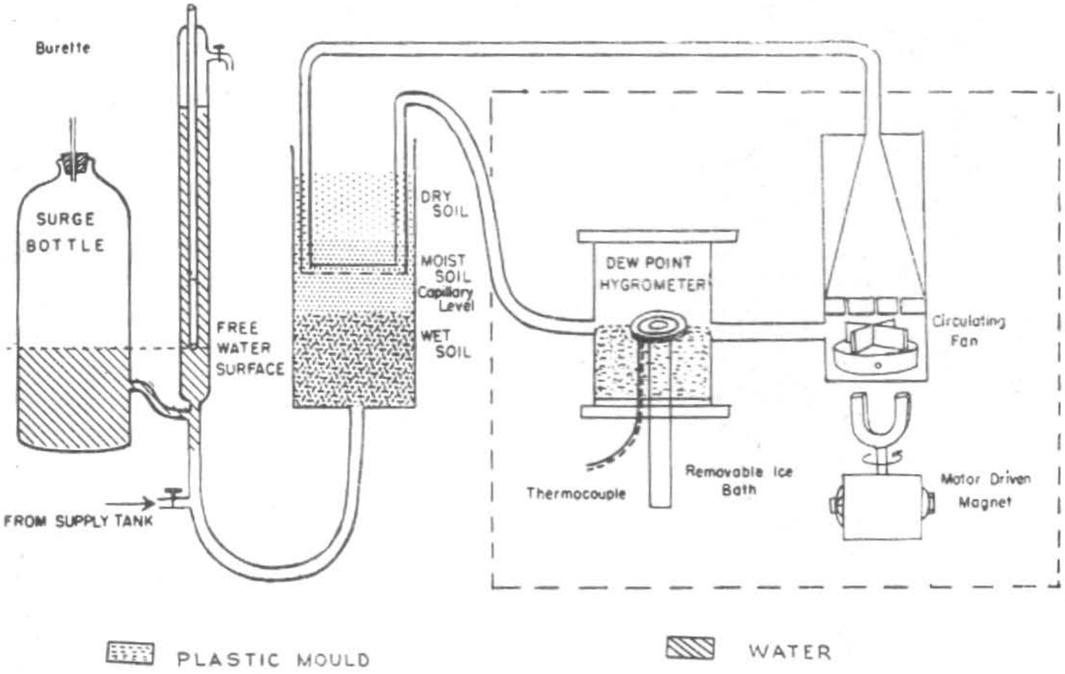

Fig. 1. Apparatus to determine vapour pressure and evaporation

Fig. 2. A typical chart of daily thermo-hygrograph of University of Washington for the peirod 7—14 April 1957

TABLE 2

Relation between Vapour (and Relative Humidity) with height above the water table

Height above water table (cm)	Vapour pressure (cm of Hg)	R.H. (%)	Remarks	Height above water table (cm)	Vapour pressure (cm of Hg)	R.H. (%)	Remarks
4·0	2·455	100·0	Sand	25·0	1·880	100·0	Sandy soil
10·5	1·854	75·5	26°C	60·0	1·316	70·0	21°C
15·5	1·796	73·3	Expt 2	70·0	1·233	65·7	Expt 1
19·5	1·742	70·9		80·0	1·153	60·2	
24·5	1·666	67·9		90·0	1·118	59·5	
31·5	1·342	52·0*		100·0	0·996	53·0*	
4·0	2·164	100·0	Sand	20·0	2·154	100·0	Sandy soil
10·5	1·641	75·8	23·5°C	32·0	1·767	80·9	23·5°C
15·5	1·539	71·1	Expt 1	42·0	1·617	74·0	Expt 8
19·5	1·494	66·8		52·0	1·539	71·4	
24·5	1·375	63·1		62·0	1·349	62·6	
31·5	1·140	52·5*		72·0	1·147	52·5*	
4·0	1·854	100·0	Sand	20·0	2·455	100·0	Sandy soil
10·5	1·316	71·0	21°C	32·0	1·966	80·0	26°C
15·5	1·267	67·7	Expt 5	42·0	1·880	76·5	Expt 5
19·5	1·153	62·7		52·0	1·767	72·0	
24·5	1·140	58·4		62·0	1·516	61·8	
29·5	0·996	53·0*		69·5	1·301	52·0*	

*Room humidity

Capillary head is 4 cm above water table in case of sand and 20 cm above water table in case of sandy soil
Experiment number refers to experiment number in the thesis

surface of the hygrometer. In order to measure vapour pressure in soil, a perforated tube (perforation facing downward) was placed horizontally at a prescribed depth. The ends emerged from the soil and were connected to a sealed pump and to a sealed hygrometer. By means of the pump the soil air was brought in contact with the hygrometer. The sketch of the apparatus is given in Fig. 1. The method is simple, consistant, accurate and require no calibration. Vapour pressure was measured at four different levels in each of the soils. Table 2 gives the values of vapour pressure at different temperatures and depths. Flow of air over the surface of the soil column was controlled by means of a wind tunnel. A sketch of the arrangement is shown in Fig. 3.

3. Determination of evaporation

Since the vapour pressure values at all levels are known, it was decided to calculate the vapour transfer by means of de Vries equation

$$q = -a\,v\,D_0\;m\,[P/(P\text{-}p)]\;dp/dx \qquad (1)$$

where q is the amount of water evaporated per second per square centimeter, a is a dimensionless factor and equal to 0·66, D_0 is the diffusion constant of water vapour in soil, P is the total pressure in mm of Hg and p the partial pressure of water vapour in mm of Hg, x is the distance and m is mass of the one cubic centimeter of water vapour at one

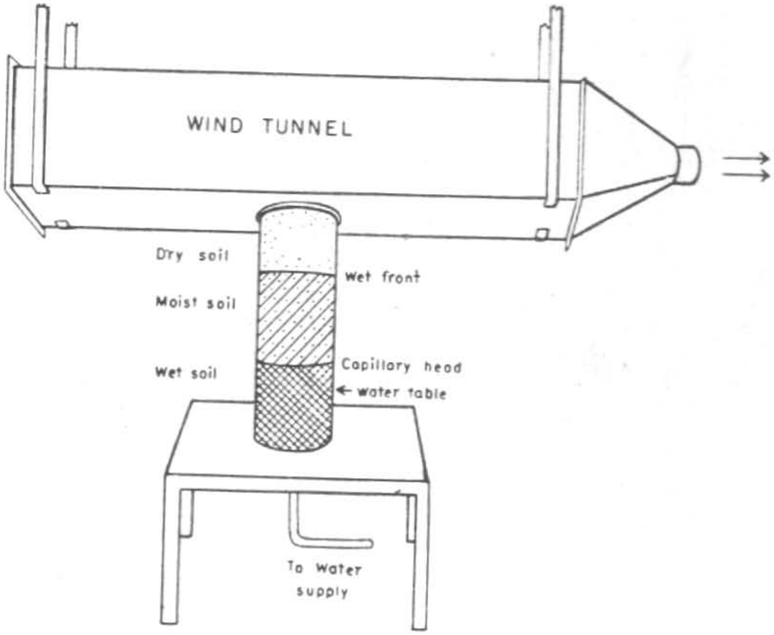

Fig. 3. Wind tunnel arrangement to give different speeds of wind over the surface of the soil column

millimeter pressure and it is equal to $(0\cdot289)\ 10^{-3}/T$ gm and v is porosity. Evaporation from sand and sandy soil was calculated using the measured vapour pressure gradient. In this calculation porosity v used was not same for all layers because of the increase in water content with depth. The porosity used was equal to the porosity of dry soil, minus the space occupied by the liquid in the layer. As stated above, care was taken to see that equal weight of dry soil occupied equal heights. Thus porosity and packing was constant throughout the soil column.

Calculated values of vapour transfer (volume diffusion) are given in Table 3. In the above calculations, vapour pressure at the surface of the soil column was taken as the room vapour pressure. Actually the vapour pressure at the surface of the soil column will be slightly more than the room vapour pressure especially when there is no movement of air at the surface of the soil column. The vapour pressure at the capillary head (defined below) was taken as saturation vapour pressure. Capillary head is the level in soil column whose height above the water table is equal to the height of water column that can be supported by the capillary pull of the soil and is found by the method described by Puri (1939). It is found that just above the capillary head (defined above) moisture content was equal to field capacity. The adhesive force acts from this moisture content and starts to lower the vapour pressure as the soil moisture content is lowered.

4. Discussions

The calculated values of vapour diffusion (*vide* Table 3) in general, did not agree with the observed values of evaporation. Therefore the question arose, whether the measured vapour pressure used in the equation (1) was correct or not. The consideration given below will fully answer this question.

(*a*) According to the generally accepted idea, in the moist soil the vapour must be saturated. In many experiments the sandy soil used was visibly moist up to 2·5 cm below the surface of the soil column. The

TABLE 3

Volume and surface diffusion in relation to height above the water table

Height above water table (cm)	Diffusion in grams per day per 323·2 sq. cm			Remarks
	Total (observed)	Volume (by equation 1)	Surface (Total—Volume)	
4·0	0·88			Sand 26°C Expt 2
		0·17	0·71	
10·5	0·88			
		0·24	0·64	
15·5	0·88			
		0·26	0·62	
19·5	0·88			
		0·30	0·58	
24·5	0·88			
		0·85	0·03	
31·5	0·88			
4·0	0·76			Sand 21°C Expt 5
		0·16	0·60	
10·5	0·76			
		0·17	0·59	
15·5	0·76			
		0·18	0·58	
19·5	0·76			
		0·22	0·54	
24·5	0·76			
		0·60	0·16	
29·5	0·76			
20·0	1·72			Sandy soil 26°C Expt 5
		0·06	1·66	
32·0	1·72			
		0·11	1·61	
42·0	1·72			
		0·17	1·55	
52·0	1·72			
		0·37	1·35	
62·0	1·72			
		0·47	1·25	
69·5	1·72			

highest level at which vapour pressure was measured was at 7·5 cm below the surface of the soil column and thus definitely in the moist layer. Assuming saturated vapour pressure at the level (—7·5 cm) and ambient room vapour pressure at the exposed surface, the vapour transfer was calculated with the help of equation (1). The resulting value of vapour diffusion for the layer between —7·5 cm and 0 cm (top layer) in sandy soil was 2·7 grams per day from 323·2 sq. cm (area of the plastic tube). This value is much greater than the observed value of 1·72 grams per day per 323·2 sq. cm. Thus it must be concluded that the assumption of saturated vapour pressure at the -7·5cm level is incorrect and lends credence to the measured value.

(*b*) In dry sand the calculated values of vapour transfer using measured values of vapour pressure agreed more closely with the observed evaporation, being in the order of 90 per cent of the total evaporation, particularly in the top layer when the room temperature is raised. It means that the calculated values of vapour transfer will agree more closely with the observed evaporation as the moisture content of the soil is lowered and as the temperature of the soil is raised. This again indicated that the measured vapour pressures may be accepted as correct.

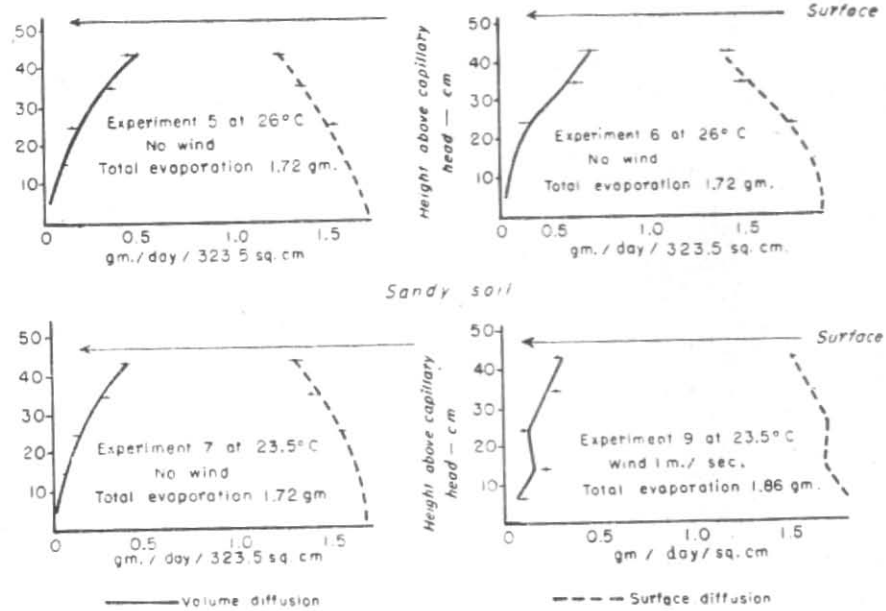

Fig. 4. Surface and volume diffusion *vs* height above capillary head

(*c*) The vapour pressure at a given level became saturated vapour pressure only when capillary head (defined) was at or above the given level.

If the measured vapour pressure values are accepted as correct then there must be some other mechanism of transferring of water substance other than by vapour diffusion through the soil. Capillary transfer in the usual sense cannot account for the extra transfer (other than that accounted by volume diffusion) observed in fairly dry soil whose interspaces are visibly free of liquid matter. This goes to prove that the only other mechanism, which is surface diffusion, does exist even in dry soil. The idea that water transfer takes place both as surface diffusion and as volume diffusion is supported by the following facts.

(1) It was observed that fine suspended organic and dissolved inorganic impurities collect at the capillary head. These do not move further upwards because the liquid movement above the capillary head is not precisely in the liquid form though there is moist soil above the capillary head.

(2) While the experiments were under way (in the unsteady state), it was observed that vapour pressure gradually increased at every measured level. During that time the wet front (the common boundary between dry and moist soil and it is above the capillary head) gradually moved up passing one or two levels where vapour pressure was being measured. If the wet front contained free water, the vapour pressure at the wet front should have been saturated vapour pressure, but the measured vapour at the wet front was much below the saturated vapour pressure.

(3) Dale's experiment shows that water moved much above the measured capillary height in some other form than vapour in the fairly dry sandy soil. This he concluded by means of the counts produced by the radiosulphur which cannot be carried by vapour movement. He does not explain how he got the counts much above the known capillary rise, but transfer by surface diffusion seems to offer the most logical explanation.

(4) Rollins and Spangler (1954) and Taylor and Cavazza (1954) suggested that there must be some other mechanism of transfer other than volume diffusion in order to explain the large vapour transfer they observed in unsaturated soils.

From all the evidences given above one has to conclude that the increased velocity of vapour flow might be due to surface migration or molecular hopping, as suggested by Taylor and Cavazza (1954). They suggested that it might be profitable to challenge the commonly accepted theory that velocity of moisture flow in soil is governed by the magnitude of static or thermodynamic moisture potential. Finally they suggested that an investigation should be made particularly as they apply to flow of water vapour or adsorbed moisture. Their challenge of the commonly accepted theory has been amply justified by many evidences given in this paper.

Since the vapour diffusion is known the surface diffusion was calculated by subtracting volume diffusion from the total evaporation. The surface diffusion values are given in Table 3. A graph showing the relation between both surface and volume diffusion with depth below surface is given in Fig. 4.

5. Conclusions

1. Above the capillary head both surface and volume diffusion occur.

2. Surface diffusion increases with depth, but volume diffusion decreases with depth.

3. Surface diffusion decreases with temperature, but volume diffusion increases.

4. Smaller the particle size, greater the surface transfer.

6. Acknowledgement

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REFERENCES

Dale, W. C. 1957 Dynamics of gravitational and capillary water in the sandy soil of glacial outwash, Master's thesis, University of Wisconsin.

de Vries, D. A. 1950 Some remarks on heat transfer by vapour movement in soils, Trans. IVth int. Cong. Soil. Sci., 2:41-43.

de Vries, D. A. and Philip, J. R. 1957 Moisture movement in the porous material under temperature gradients, *Trans. Amer. geophys. Un.*, 38:222-232.

John, P. T. 1957 Movement of water in soils, Proc. N.W. branch, *Amer. geophys. Un.*, Pullman, Washington.

1958 Vapour pressure gradient and water moement in the top layers of soil, Ph.D. thesis, University of Washington, Seattle, U.S.A.

Parker, F. W. 1922 The classification of soil moisture, *Soil Sci.*, 13: 43-54.

Puri, A. N. 1939 *Soils: their physics and chemistry*, Reinhold Publishing Corporation, New York, p. 347.

Ramdas, L. A. and Mallik, A. K. 1939 *Curr. Sci.*, 8, 6.

Rollins, R. L. and Spangler, M. G. 1954 Movement of soil moisture under a thermal gradient; Highway Research Board Proc., pp. 492-508.

Sutton, O. G. 1953 *Micrometeorology*, McGraw-Hill Book Company, New York, pp. 303, 308.

Taylor, S. A. and Cavazza, L. 1954 The movement of soil moisture in response to temperature gradients, *Soil Sci.*, Soc. Amer. Proc., 18: 351-358.