INDIAN JOURNAL
OF
METEOROLOGY AND GEOPHYSICS

VOL. 8 | APRIL 1957 | NO. 2

551.573 : 581.116

Some notes on Evapo-transpiration, Evaporation from soil and Transpiration

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(Received 22 September 1955)

1. Evapo-transpiration

Evapo-transpiration which is the reverse of the process of precipitation is the phenomenon in which water in the form of rain or condensation from land as well as from sea or large bodies of water moves back into the atmosphere. On land as opposed to that from free water there are two factors through which this transfer takes place; firstly the transpiration from the vegetation and secondly the evaporation from the land.

Meteorologists have devoted considerable attention to the understanding of the causes and to measure rainfall which is mainly a physical phenomenon. But evapo-transpiration which is rather complex since it is partly physical and partly physiological has received very little attention from meteorologists though they contributed considerably to the understanding and measurement of evaporation from free water surface. Biologists have made several attempts to measure transpiration from portions of plants, entire plants or plant communities with results that were sometimes highly unbelievable. Some information regarding the water requirements which is also called the "Consumptive use" (Blaney and Criddle 1950, Lowry and Johnson 1942 and Young and Blaney 1942) of the agricultural crops has been obtained from experiments conducted in the fields by the irrigation engineers, but no attempt has so far been made to correlate this consumptive use with the actual evaporation and transpiration that takes place under natural conditions. Information regarding this complex quantity from hydrologists who are concerned with the watershed managements is very scanty.

Physically evapo-transpiration depends upon the solar energy, wind movements, vapour pressure gradients and the movements of the water in the soil either in the liquid or in the vapour state. Solar energy which supplies the latent heat of vaporisation for converting water into vapour, varies with the time of the day, season of the year, latitude and altitude, while the movements of the water in the soil depends upon the structure, texture, temperature, state of wetness and concentration of the soil solution. Physiologically, the plant is involved from the lowermost root hair to the topmost stoma. Hence to understand this complicated phenomenon which is of vital importance in agriculture, meteorology, hydrology, irrigation and forestry it is necessary to know the relation between soil, water and plant on the one hand and the micro-meteorological factors on the other hand and finally the inter-relation between the two groups.

There are at present three methods by which this quantity can be determined under natural conditions. They are—(1) the turbulence method, (2) the heat budget method and (3) the volumetric method but the space here does not permit even to give a glimpse of these methods and it will form the subject matter of another paper.

2. Potential Evapo-transpiration

Realising the importance and difficulties involved in the determination of this complex quantity, Thornthwaite (1948) took a bold step in introducing another quantity called the "potential evapo-transpiration" in climatology. It is defined as the amount of water which would be lost from a surface completely covered with vegetation and supplied with abundant water throughout. This quantity according to Thornthwaite depends only on the amount of solar energy received by the surface and the resulting temperature than on the kind of plant. This assumption is quite contrary to the experimental results obtained by Henrici (1946a, 1946b). Besides this, it will be shown in the following pages how several factors including the plant are responsible in governing the rate of evapo-transpiration. Thirdly any formula which is based on the experimental results during which the species studied are provided with as much water as they could use, has very little application to actual field conditions where the amount of water available is the overall limiting factor for evapo-transpiration. It is for this reason that the empirical formula of Thornthwaite could not explain the natural vegetation of India, Pakistan and Burma (Bharucha and Shanbhag 1953).

In spite of its limitation, Thornthwaite's formula as modified in 1955* is the simplest one in existence at present. It could be used to compute the daily and monthly potential—evapo-transpiration of a place when its temperature and duration of sunshine are known. It may need more modification or replacement by a new one, when studied in the light of the material available in our country. Work in this direction is under progress but experiments for actual determination of the evapo-transpiration under natural conditions by using the first two methods mentioned above are not in existence as yet in any part of this vast country of ours. The third method could, however, be used but even in this case the runoff data from stream gauging stations is very meagre.

Actual determination of the daily march of evapo-transpiration in irrigated areas is very useful in predicting the soil moisture at any time, which in turn will give an idea of the time and amount of irrigation to be applied for the success and abundance of crops. Knowledge of the magnitude of this quantity for different crops under different climatic conditions will help irrigation engineers in planning new irrigation projects and using the water more economically. Seasonal march of this quantity and its variation when studied in combination with rainfall and condensation will give an idea about the surface runoff which is the cause of erosion and floods in our country. In places where the rainfall exceeds evaporation, methods to increase the infiltration rates could be practised so as to prevent the surface runoff and increase the stream flow. This additional water could be used to grow more food and power so essential to our country. Thus there are several uses of this complex quantity and in all problems of soil, water and forest conservation and utilisation it plays an important role. Hence its determination on a whole country basis at an early date is very essential for the progress of our country.

* This modification was worked out in 1954-1955 when the author was at the Laboratory of Climatology Seabrook, New Jersey, U. S. A. as a Senior Research Scholar

3. Evaporation of soil moisture

3.1. *Soil*

Soil may be defined as that portion of the weathered rock material which is subjected to the seasonal changes in moisture and is occupied or capable of being occupied by plant roots. In its structure it resembles a sponge whose frame work is built out of mineral and organic matter while the pore spaces of varying sizes are occupied by air and water which varies with respect to time and space.

Soils are not static but constantly changing in colour, depth and structure being subjected to the continuous action of living organisms such as roots, micro-flora and fauna. They swell on addition of water, sink and crack when get dried. Loose as well stable soils move downhill under the action of gravity, running water and wind.

Weathering of the rocks caused by the physical and chemical processes, which are governed to a considerable extent by the climatic and biotic factors, supplies the mineral constituents of the soils. The ceaseless operation acting on the parent material gradually increases the depth of the soil unless the environment undergoes a major change. Accompanying this process are other processes, such as geological erosion and leaching which prevent a static state in the weathered material though their effects decrease with the depth to a vanishing point.

Vegetation which is supported by the soil enriches it with the organic matter. Plant roots mixing intimately with the mineral particles below the ground get incorporated in the soil after their death and decay. Above the ground periodic fall of the dead leaves, the decaying wood of the dead branches and fallen trees together with the animal remains, add organic matter which in time becomes part of the soil. These additions are much more rapid than the weathering process which is rather slow and hence formation of pure organic layers several inches deep directly on bare rocks is not uncommon.

The structure, number, size, shape and stability of the soil aggregates are brought about by the vegetation and land use, which in turn affects the size, shape and distribution of the soil pores. These pores provide the space for the storage of water and serve as avenue for water movements as illustrated below.

3.2. *Soil water*

Soil in its relation to water may be compared to a series of sieves. A given quantity of water when poured on an ordinary sieve passes readily through it though a small portion will remain on the meshes because of the molecular adhesion. As the number of meshes in the sieve and also the number of sieves are increased and if the same quantity of water is poured on the new system, it will still flow through rapidly but somewhat less than in the previous case since more water will now adhere to the margins of the meshes.

The above example tells us two things which occur in the soil when water either in the form of rain or condensation falls on it. Part of it will adhere to the frame work formed out of mineral and organic matter while the remaining portion will move freely through the pores under the action of gravity. The water retained by the soil against gravity is termed the "capillary" water while that which flows through the pores is called the "gravitational" water. Since capillarity is a surface phenomenon the capillary water in the soil will depend on the surface area of the soil particles. If the surface area increases due to the increase in the number of particles per unit volume the capillary water also increases. Organic matter which is present in the soil plays also an important role in the water holding capacity of the soil. In the colloidal form organic matter takes up as much as 4·4 times its own weight of water (Keen and Coutts 1928). Soil particles get coated with a gel-like porous and highly adsorptive substance when the organic matter in it gets decomposed. The gel-like material sticking to the soil particles increases its surface which in turn increases the capillary water provided the soil particles per unit volume remain the same. This particular condition will be satisfied when the organic content in the soil is very low being of the order of 5 per cent or less (*U. S. For. exp. Sta. pap.* 1951). If, however, the organic content increases above 5 per cent, volume weight of the soil steadily decreases with fewer soil particles per unit volume because of the coating of organic matter and the consequent increase in volume of individual particles. Thus the amount of water held in the soil per unit volume will decrease even though the storage capacity of the individual particle and the soil column as a whole will increase. From the above consideration it is clear that the amount of capillary water per unit volume of the soil will depend upon the constituents, size and shape of the particles while the rate of movement of the gravitational water will be controlled by the size and shape of the pores. The total amount of capillary water and the time for which the gravitational water will remain in the soil column will depend on the depth of the column which varies from place to place. When a given soil holds its full quota of capillary water it is said to be at the "field capacity".

3·3. *Evaporation from Soil*

The force needed to remove unit quantity of moisture from the soil when it is at its field capacity is the least and as the soil gets drier this force increases. It is expressed either in terms of the height of the water column of unit cross-section or as the logarithm of this column height (*pF*). As the *pF* value of the soil increases the soil moisture is retained more firmly against adsorption by the plant roots, until a point is reached when the roots cannot obtain water at a rate sufficient to meet their water requirements. The plant then loses its turgor or in ordinary parlance wilts. This moisture content of the soil is termed the "wilting coefficient". Naturally this would differ somewhat for different plants, but for most ordinary plants the wilting coefficient is approximately one and half times the "hygroscopic coefficient" which represents the limit of drying of the soil at ordinary air temperature. Thus the amount of water available for transpiration lies between field capacity and wilting coefficient while that which could be evaporated lies between field capacity and hygroscopic point. Expressed in terms of energy (*pF*), the following are the moisture contents of the soil (Hall 1947)—

Moisture contents of the soil	*pF* values
Hygroscopic moisture (50% humidity)	6·0
Moisture at wilting point	4·2
Moisture at field capacity	2·5

It must be emphasised at this stage that the value of field capacity, wilting point, hygroscopic point, when expressed in terms of *pF* values, are the same for all soils.

Even though the energy values are constants the moisture contents and the available water are not the same for all soils. The moisture content of clay is relatively high since its large number of small particles give it a large surface area for adhesion. By contrast, sand with its small number of large particles can hold less water at the same energy level. This is made clear from the moisture content of clay and sand. Clay holds 38 and 20 per cent of moisture by volume at field capacity and wilting point respectively, while for sand these figures are only 2 and 5. These figures besides showing that the moisture contents of different soils at the same energy level are different, also give an idea of the available water for plant use, this water being greater from clay than that from sand.

3·4. *Factors controlling soil moisture evaporation*

Factors which control evaporation of the different amounts of available soil moisture may be divided into two classes—(*a*) the meteorological factors which aid or retard the process and (*b*) the physical nature of the container which has a profound influence on the rate with which water vapour is released.

(*a*) *Meteorological factors*—To understand the part played by the meteorological factors in the rate of evaporation, it is necessary to understand the fundamental physical process of evaporation. The water molecules as of all other substances, are in a state of continuous motion. Some of the molecules occasionally break through the surface of water and enter the atmosphere above it. The number of such molecules is entirely governed by the kinetic energy of the molecules, which is a function of surface temperature of water. On the other hand, molecules of water vapour in the atmosphere above the water surface, impinging on the water surface, re-enter it. The excess of the molecules leaving the water surface over those entering it, determine the rate of evaporation. When the rate at which molecules leave the water surface equals the rate at which they enter, the net gain or loss is zero. At this stage the atmosphere above the water surface is said to be fully saturated.

As long as the atmosphere above the water surface is unsaturated there will be a net loss of molecules from the water surface. This loss is accompanied by a transfer of certain amount of energy from the water to the atmosphere above. Physically this loss of energy amounts to a decrease of temperature of water. As evaporation continues an equilibrium condition will be eventually reached, if the vapour molecules from the atmosphere above are not removed, when saturation will set in with vapour at a pressure determined by the temperature of water. In order that evaporation may continue it is necessary either to increase the temperature of water by adding heat to it or to reduce the vapour pressure above the atmosphere by removing the vapour.

To summarise, the process of evaporation requires—

(1) A source of heat to maintain the water temperature which in turn will maintain the molecular motion.

(2) An excess in the number of molecules leaving the water over those re-entering it or in other words, the saturation vapour pressure at the surface temperature of water must exceed the actual vapour pressure in the space immediately above the water surface.

In nature these fundamental requirements are provided by the following meteorological factors—

(1) Sun and sky radiation provides most of the energy needed to maintain the temperature of the water and the molecular motion (Crabb 1952, Penman 1948, 1949a, 1949b)

(2) The atmosphere immediately above the water in which the actual vapour pressure is less than the saturation vapour pressure at the temperature of the water surface (Miller 1937).

(3) Wind movements which remove the excess of water vapour above the water surface and thus prevent the saturation point being reached (Miller 1937).

(4) The air temperature also plays an important role in at least two ways—(*a*) It controls the temperature of the water through thermal conduction and thus acts as a source or sink for heat energy depending upon whether the air is warmer or colder than water and (*b*) Since it controls the temperature of water it partially determines the vapour pressure deficit.

(*b*) *Physical nature of the "container"*—Evaporation is controlled by the nature of the container through its response or relation to meteorological factors. A body of clear water absorbs a large percentage of solar and sky radiation while muddy water will reflect much of it. In case of deep water the energy will be distributed throughout a large mass of water to a depth of several feet with the result that the diurnal variation of the surface temperature will be small. Black soil will absorb a large percentage of incident radiation as compared with any other soil in the same condition. Most of the sun and sky radiation falling on the soil is retained in a thin layer near the surface since soil is opaque to light. This causes a large rise in the soil surface temperature. With a saturated soil surface the solar energy is available for evaporation instead of warming the soil. Therefore this evaporation will be greater than that from a large mass of water under similar meteorological conditions. This is true for a wet soil surface, but as soon as the surface becomes dry other factors come into operation. At this stage evaporation does not take place from the inter-face of soil and air, but a few millimetres below. Hence the water molecules have to diffuse through the dry soil which acts as a "potential barrier" before being caught and blown away by the prevailing wind. This potential barrier which increases the path of the molecular diffusion reduces the rate of evaporation (*Dep. Agric. Soil Res. Lab. Tech. Bull.* 1949; Staple and Lehane 1944).

Secondly heat conduction from the surface into the deeper layer of the soil becomes smaller as the pores are filled with air whose thermal conductivity is smaller than that of water.

The rate of movement of water vapour molecule from the layers of soil to the surface is determined by the size and shape of the pores. The greater the number of large pores the more direct the routes by which vapour can escape. Sand and other soils with large pores or cracks are, therefore, subjected to higher rate of evaporation than are fine textured soils.

The depth to which evaporation from bare soils extends depends on the soil porocity and the depth of the water table. On fine textured upland soils where the water table does not influence evaporation, water losses will be limited generally to the first foot of the soil. Coarse textured soils and cracked soils possess more and large avenues for escape of the vapour particles, and here evaporation may remove water from depths as great as 5 tc 6 feet (Lassen, Lull and Frank 1952).

Where water table lies close to the surface so that capillary flow supplies water to the surface for evaporation, soil porocity again is the limiting factor, but this time movement of water will be in the liquid state rather than in the vapour state. Since capillary conductivity depends inversely on the radius of the pores, fine textured soils will affect the water table to a greater depth than coarse textured ones. For a coarse sand the limiting depth is about 14 inches while that for clay or heavy loam it is 5 to 4 feet (Kittredge 1948, Penman 1946). Thus in areas where evaporation opportunity is great because of high water tables, the depth to which evaporation is effectively greater in clay than in sand; whereas in upland soils, where the water tables are not a factor, the reverse is true.

Evaporation is also affected by the vegetation covering the soil. Thus trees which act as wind breaks increase the rate of evaporation due to higher temperature near the ground caused by poor wind circulation behind the wind breaks (Hide 1954, Kolasew 1941 and Zingg *et al.* 1952). The plant residue which is added to the soil from time to time conserves heat which brings about a higher rate of evaporation (Lemon 1954). It is also well established that evaporation rates vary considerably, according to the degree of protection afforded to the surface by the plant (Kittredge 1948).

In case of agricultural lands the evaporation rates during part of the year will be similar to that from bare lands carrying stubbles, while during the growing season the rates will change from time to time due to varying height, colour of the crops and the degree of protection offered to the soil.

4. Transpiration

Transpiration from the plants is governed by three factors. They are—(1) meteorological, (2) physical and (3) biological.

4·1. *Meteorological factors*

Same factors namely the absorbed sun and sky radiation, air temperature, air humidity and air movements which are responsible in bringing about and fixing the rate of evaporation, are the only external agents that determine the rate of transpiration. But these meteorological factors are altered considerably by the location, colour and orientation of trees and their leaves. Thus the shaded leaves will transpire less than the unshaded ones because of the difference in the available sun and sky radiation. It is a known fact that wind increases with height (Anderson, Anderson and Marciano 1950) in the layers nearest the ground with the result that transpiration from short grasses will be less than that from isolated trees, other things being equal. The colour decides the amount of energy absorbed by the leaf, which in turn governs the rate of transpiration. Dark green leaves will absorb more energy than light green ones, and hence will transpire more when other conditions are kept constant. Orientation of the leaves with respect to the incident beam of light determines the amount of energy absorbed which in turn affects the rate of transpiration. A leaf turned with its surface normal to the beam of incident radiation absorbs more energy than the one turned edgewise to the beam resulting in a corresponding difference in the rate of transpiration (Clum 1926, Curtis and Clarke 1950). The mechanical influence exerted by the wind such as bending and waving of the leaves to and fro and thus altering their exposure from time to time will, have a profound influence on the rate of transpiration. Numerous other examples can be cited wherein the rate of transpiration will be affected by the modification of the meteorological factors through the transpiring agent, the plant.

4·2. *Physical factors*

Physically, transpiration from a plant is impossible soon after the soil moisture reaches the wilting point. The available moisture for transpiration is thus limited between field capacity (pF 2·5) and wilting point (pF 4·2) because at this higher energy level the suction exerted by the roots cannot exceed this limit or that the movement of moisture is so slow that it is impossible to cope up with the transpiration rate. Since the amount of moisture within these two energy levels are different for different soils as has been pointed out (in Section 3·3), the total transpiration from different plants growing on different soils will be different. Secondly the rate of transpiration also changes as the force needed to withdraw water from the soils within these two energy levels are not the same but continuously increases as the moisture in the soil falls below the field capacity (Kozlowski 1943, Schneider and Childers 1941, Spalding 1905). The depth of the soil mantle, the formation of the claypans and fragipans which restrict the depth of the rootzone will in turn alter the amount and rate of transpiration.

4·3. *Biological factors*

Biologists (Livingston 1938) have so far recognized two types of transpiration—(1) Cuticular; (2) Stomatal. In the cuticular transpiration vapourisation of water and its escape into the air as it is formed takes place just at the periphery of the leaf while in the stomatal transpiration, this conversion occurs at the periphery of the substomatal chambers within the internal atmosphere of the leaf. The vapour then has to pass through the open stomata before escaping into the atmosphere. The stomatal transpiration is thus governed by the opening and closing of the stomata and also by the internal atmosphere of the leaf. Out of the two, the cuticular transpiration is usually smaller than the stomatal, when open stomata are frequent, but it is more important when stomata are sparse or predominantly closed.

Physiologists (Livingston 1938, Weaver and Mogensen 1919) working in this field have found that the rate of transpiration is governed by the following four internal factors of the leaf—(*a*) the water vapour pressure of the cuticles, (*b*) the frequency of the stomata and the average size of their opening, (*c*) the vapour tension in the substomatal chambers and (*d*) the area of the leaf surface. These factors are altered considerably by the influence of the external factors such as the radiant energy, humidity, temperature and movements of the air, the texture, the moisture content and fertility of the soil; while the last one depends to a considerable extent on the plant species.

Little is known about the vapour pressure of the cuticule and that of the cell walls about the stomatal chambers. It depends on the nature of the surfaces, their temperature, as well as on their relative degree of wetness, and also upon the current rate at which heat from the absorbed radiant energy is being received at the vapourising surface without corresponding rise in temperature.

Opinions of the scientists regarding the closing and opening of the stomata and thus controlling the rate of transpiration are very diverse. In a study (Henrici 1946a) carried out in South Africa it was found that the stomata of all tree foliage closed as soon as there was a strong wind and thus restricted the transpiration almost immediately, while on grass the effect was quite different. An increase in the transpiration rate was noted at first but soon afterwards this had also decreased. These findings are in opposition to the view that the sweeping wind always accelerates transpiration (Firbas 1931, Henrici 1946b). Controversies also exist regarding the effect of sunshine on the rate of transpiration. Some are of the opinion that after 9 to 10 A.M. no further increase in transpiration is possible due to stronger light (Henrici 1946a) while others (Spalding 1905, Thornthwaite 1948) hold that when water supply is available the transpiration will be greater the greater the intensity of sunshine. This latter view is quite contrary to the findings that (1) plants which had all along received a meagre supply of water are nevertheless in a position to transpire rapidly when full supply of water is given to them (Spalding 1905) and (2) the rate of transpiration from trees with fully open stomata is very small at about 5 P.M. even on very bright days (Henrici 1946b). Thus even though the external factors and the opening of the stomata are made responsible for the rate of transpiration there must be still some internal factors of the plant which regulate it because of the facts stated above and also the closing of the stomata even in good sunshine when the water reserves in the soil are sinking.

Most of the water required by the plant is extracted by the roots from the soil particles in contact with them, even though there is some movement of water from the adjoining soil column, moisture held by the soil particles several inches from the roots does not become readily available for the plants (Veihmeyer and Hendrickson 1951). Hence the rate of water extraction which in turn determines the rate of transpiration is governed by the biological factors "the root system of the plant". Obviously the greater the volume of the soil occupied by the roots, the greater will be the water removed. There are considerable differences among the species in respect to the depth of the root system, Dogwood being a notably shallow rooted species, while Pine often sends roots to a depth of many feet (Lassen, Lull and Frank 1952). These genetic character of the plant with respect to its root growth is altered considerably by the physical factors as pointed above.

The rate at which elongation of the roots takes place in search of moisture is different for different species, and also different in different seasons. Stephenson (1935) states that young actively growing roots in a permeable soil may grow at rates of half an inch to two inches in a day, while in an experiment (Lassen, Lull and Frank 1952) with the tomato plant it was found that the root zone which was at 4 ft on 15 June, reached 6 ft on 20 July, 8 ft by about 15 August, and 12 ft on 3 September, using all the available water throughout the depths. This shows that in the case of annual plants the rate of extension of the root system during the growing season is not constant which results in different rate of extraction and of transpiration. In case of perennial vegetation also the same result must hold good but data on the root size and its growth is still lacking. The rate of root growth and its extent is controlled considerably by the pore space, aeration, fertility, moisture content and temperature of the soil. All these factors change in the soil profile at the same place and from place to place.

5. Conclusion

A short description of the processes of evaporation and transpiration given above shows that even though both the phenomena are very difficult to study in nature because of the several variables involved, the second, *viz.*, the transpiration, is more complex than the first, the evaporation. Hence it has received very little attention in spite of the fact that transpiration and not evaporation removes greater amount of water in unit time by acting simultaneously on the whole depth of the soil column occupied by the roots and also removes more water since it can reach greater depth (Hall 1947, Russsel 1950). Whatever may be the complexities of transpiration, one thing is certain that it must be recognised along with evaporation in any study of hydrological balance.

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