Water for Man

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PUBLIC ATTENTION has been focused on science in recent years because of the unprecedented race to be the first country to get a man into space. Tremendous effort and resources are being concentrated to produce more powerful vehicles and other visible signs of scientific and technological achievement. Little attention and support are being given to producing new knowledge that makes possible the control of nature and the production of the material things that we so much desire.

The 1959 United States' budget contained about 7.5 billion dollars for research and development. Of this amount, 7.0 billion was for military and space development, leaving only about 0.5 billion for all other research, including federal assistance to land grant universities, the National Science Foundation, and other federal agencies that sponsor research. Only a small amount of this money was used for research that was aimed at discovering new knowledge about nature without concern as to whether it had any practical application. Only by studying nature to learn how she behaves can we get new knowledge that may some day be of tremendous importance to man.

The study of water and water problems receives considerable public attention and support. Most of this too is because of pressing problems of deficiency or purity. In only a few places can one find research into the nature of the behavior of water in relation to its environment.

My appreciation goes to the late Dr. Norman Bauer for stimulating my thinking to extend our water research from its purely utilitarian objectives into channels where an understanding of the relations of water to the colloidal-biophysical soil-plant-water system became a major consideration.

The excellent graduate students with whom I have worked at Utah State University have contributed much to the ideas presented in this lecture. My colleagues both here and in other states and countries of the world have done much to stimulate the development of the ideas and results reported. I have not given proper credit to all of their contributions, so to these people and the many others who have given help and encouragement I express my thanks.

My appreciation also goes to the faculty of the University and the committee who has extended me the honor of presenting this lecture.

Finally, I give appreciation to my wife, Frances, whose encouragement and deep understanding has made the scientific pursuit of knowledge both possible and deeply enjoyable. Her assistance in preparing the lecture is gratefully acknowledged.

Logan, Utah
January 19, 1961

STERLING A. TAYLOR
TWENTY-THIRD FACULTY HONOR LECTURE

Water for Man

by

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(Soil Physics)

THE FACULTY ASSOCIATION
UTAH STATE UNIVERSITY
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AN'S USES for water are rapidly increasing. His demands and needs for water for his personal use and for cleanliness, recreation, industry, and food production are increasing as the population and standard of living rise. At the same time, his knowledge of the behavior and nature of water is increasing.

TWO ASPECTS OF WATER SCIENCE

In the technological age in which we live, science is revered and honored for what it has done and can still do to increase man's control over nature. In the area of soil and water science, which is my speciality, much has been done to develop control over our most common and vitally needed water resource. Through research and study, man has been able to develop water systems that are tremendous. Part of the water that falls in Colorado, Wyoming, and Utah runs down the Colorado River to Lake Mead, where it is stored behind Hoover Dam until needed. Additional storage will be supplied in Lake Powell when the Glen Canyon Dam is completed. Later, the stored water will be carried in large canals and aqueducts to the cities and farms of arid southern California.

Other great projects are being planned and built. Two, which I shall mention are the Upper Colorado River, a federal project that will provide facilities to store and use all of the water that drains into the Colorado River, and the California Water Plan, a state project to supply the water needs of California. The Colorado River is the last major source of runoff water that is available for development and use in arid southwestern United States. The California Water Plan, when completed, will move water from the northern boundary of California across mountains and down the Sacramento River almost to the ocean, then up the San Joaquin Valley across the Tehachapi Mountain Range and into the southern tip of the state. Water will be supplied along the way to meet all of the foreseeable needs in the development of the state. The California Plan is unique in that it is the first large water development project undertaken by a state using private capital obtained by bonds. This project received new impetus during the last election when the bonds to provide one and three quarter billions of dollars were approved by the voters. This will permit construction of the first phases that are planned to furnish water for the needs to 2020. Vast projects, such as this, require many scientific investigations and much technical skill.
In spite of all that science has done to control and conserve water, there are still many unsolved problems; there are areas of water deficiency. There are times when even humid parts of the country suffer from water deficiency and drought.

There are those in the world who feel that the control of nature, with the political and economic advantages that go with it, is the sole justification for science. This philosophy would say that the solution of water problems is the sole justification for continued water research. This is the official attitude in Marxist countries (Thompson 1960). There are many in the United States who act and speak as if they thought the same. This view of science is too limited. Science has another aspect equally important with that of controlling nature. It is to obtain an understanding of the nature of things as they are, as they were, and as they will become; in other words, to find truth. This aim is in common with religion and philosophy although the methods are different. It inspires study into unknown relations for the joy of learning about the relations, with no thought of controlling nature or of applying the knowledge to the material benefit of mankind. Those of us who are associated with the University have a greater obligation to develop new knowledge about the nature of things than those who are associated with industry or other non-academic organizations. We must continually resist the lure of lucrative contracts from government and industry that will divert our best thinkers to solution of immediate problems at the expense of new knowledge. With the laboratories of government and industry dedicated to the solution of these immediate problems, who will develop the new knowledge if the university does not?

At Utah State University, research in soil physics has been undertaken with both of these aspects of science in mind. On one hand there have been studies to find the water requirements of crops, how to irrigate for maximum production, when to irrigate, how much water to apply, and how best to distribute the water to the soil upon which crops are growing in order to get the maximum return for each unit of water consumed in crop growth. On the other hand, there are laboratory studies dealing with the condition of the water in the soil and in plant tissue, and the nature of the forces that cause water to move. Why does water move when there is a temperature difference between two locations? How is water in soil different from pure free water? After a brief review of some of our most common uses of water and some problems associated with its supply, this paper will deal with some of the properties of soil and plant water in comparison to pure free water.
WATER—COMMONPLACE AND USEFUL

Most of us today satisfy our thirst and personal need for water from a fountain or faucet located in our homes or our place of work. Such water is convenient and pure. It has not always been so easily obtained in pure form, and it is not now in some parts of the world. The history of man's settlement and activity and the location of his towns and dwellings have been governed by the availability of usable water.

Water is one of the most abundant compounds on the surface of the earth. It covers more than one half of the earth's surface in the form of oceans, lakes, and streams. In its most common state, it is a colorless, odorless, and tasteless liquid. It also occurs as a solid in the form of ice. It is present in the atmosphere as a vapor, and occasionally the vapor condenses and falls as precipitation or rainfall. It is estimated that about 24,000 cubic miles of water fall as precipitation on land surfaces; another 71,000 cubic miles fall back into bodies of water each year (Ackerman et al. 1955). If the temperature is cool, such as it is in our climate in the winter, the water condenses and falls as snowflakes forming a mantle of white over the surface of the earth. Occasionally, the condensing water freezes into pellets of ice and falls as hail.

We associate water with beauty and recreation. Beautiful scenery is often associated with a lake or with a stream. We vacation on streams and lakes where we swim, boat, fish, and relax. Water has a peculiar property that is frequently demonstrated but which can not be measured by scientists; this property is associated with its function as a catalyst in romance.

Water has many economic uses in our lives. We use it for cleaning and sanitation. It has been used since prehistoric times for transportation and provides a cheap and efficient medium for moving boats and ships loaded with material supplies.

It is frequently used for generating electrical power for light and for operating the conveniences in our homes, classrooms, laboratories, offices, and businesses.

It provides fish, an important source of food for man. It is used extensively in industry and in manufacturing processes. Its peculiar property of requiring large amounts of energy to convert it from liquid to vapor is used for cooling. Its electrical properties make it an excellent solvent and cleaning agent.

The greatest single use of water in the United States is for irrigation and food production. The next largest water consumer is industry. Much of the water used by industry and for domestic use is contaminated, then dumped back into our streams to contaminate the whole stream and reduce its usefulness. If properly treated, much of this water could be decontaminated and reused.
WATER—ESSENTIAL TO LIFE

The life of man and other higher animals is conceived in an aqueous environment. The cell division and life processes all take place in water. A dry cell soon dies, and if enough cells become desiccated, the whole organism fails to live.

Water is essential for all of the internal reactions of the animal body. It is the solvent for nutrients and waste material, thus it provides a vehicle for their passage into and out of the body tissues. The transport of oxygen from the lungs to body tissues and cells and the return of carbon dioxide depend upon an adequate supply of blood which is about 80 percent water.

The developing embryo of mammals may contain 90 percent water. A mature lean mammal may contain 50 to 60 percent water. Animals may lose nearly all of their fat and about one-half of their protein and still survive, but a loss of about one-tenth of their water means death. This makes life in arid and semiarid climates difficult.

Water is the most abundant constituent of plant cells and tissues. It is a participant in the important process of photosynthesis which provides either directly or indirectly all of man’s food. It is intimately connected with protoplasm and other colloids in the living tissue as well as with the colloids in the soil.

THE SOIL STORES WATER FOR MAN

Most of the potable water that is used by man passes through and is retained for a time in the soil. If it were not for the retention by the soil, all of the streams and lakes would be periodically flooded then dry. The precipitation infiltrates the soil where its rate of flow toward the streams is retarded.

Once in the soil, the water may go in any one of many directions. It may percolate slowly through the soil into the deep underground reservoirs where it is stored until removed in bubbling springs, pumps, or in flowing (artesian) wells. It may enter the ground water and thus seep into streams and perpetuate the water in the drainage system. It may reappear as seepage springs at locations where the water table comes to the surface. It may appear as swamps or lakes. Man removes some water for his own uses. Some of the water is removed from the soil by growing plants; some evaporates directly from the soil; and some remains in the soil to be removed later.

The regulating function of adsorbing water, when it is abundant, followed by a gradual release, is of tremendous economic importance to man. Without the soil mantle to perform this function, man would need to store all of the water that he, his livestock, and his crops need. He would also have to supply it to the organisms at frequent intervals as it is needed; for animals, this may be once a day or even less frequently, but for plants, it must be supplied almost continuously.
Water occurs in abundance in some areas and in excess amounts in others, but in some locations water does not occur naturally, and if man is to live and have his plants and animals grow, he must provide water for them. Anciently, as well as today, man has provided aqueducts and conduits for conducting water from the place of supply to localities where it is deficient. He has constructed reservoirs and dams for storing water until he needs to consume it. He can then consume the water directly or replenish the supply in his soil for the continuous use of his plants.

**RIGHT TO USE WATER**

The construction of storage reservoirs and conveyances for water requires the investment of time and capital; consequently, we and other social groups enact laws to protect the rights of those who develop and build these systems. These laws establish water rights. Once someone has established a right to a water supply, he can sell it, trade it, or keep it. It is his personal property, or perhaps it is tied to his land, and no one can do anything to deprive him of his rights so long as he uses the water beneficially. Beneficial use and water rights have been variously interpreted in courts in such a way that some serious injuries have been perpetuated, and at other times absurd situations have developed.

When water is placed on land and infiltrates the soil, only a limited amount of it can be retained in the soil mantle; the balance penetrates to the water table and is lost. Water penetrates soil from unlined canals and distribution ditches. Many irrigators apply much more water than their crops can consumptively use because they have the water right and want to use all of the water to which they are entitled. This excess water percolates through the soil, picking up a load of dissolved salts and nutrients as it goes. Frequently this excess water causes the water table to rise into the root zone of plants in the lower lying soil. The soil then becomes water logged, or evaporation from the soil surface causes water to move to the surface by capillarity and there leave its load of salt when it evaporates.

The productivity of the lands thus affected with salts and water is impaired and may even eventually become nil. Should one user have the right to thus damage another and impair the productivity of his lands? The present laws of our state uphold this practice.

Frequently the damaged lands can be reclaimed by drainage accompanied by chemical treatment of the soil and several years of special reclamation treatment. The question should still be asked, "Is it right for one user to apply excess water that will damage another thus causing the other to assume the expense of building drains to remove the damaging water?"
If water enters a permeable soil and becomes confined between two impermeable layers as it moves to lower areas, it will be under positive pressure as shown in figure 1. This positive pressure will cause water to rise vertically, and it may cause problems of drainage and salt accumulation. If a well is drilled into this confined aquifer,

![Diagram](image)

*Fig. 1. Excess water percolates into the deep soil; when confined between two impervious layers, there is an upward moving force. Wells drilled into the porous stratum will flow if the piezometric surface is above the top of the well. Excess unconfined water raises the water table above the impervious layer causing swampy lands and alkali unless streams or drains remove it.*

water will rise toward the surface, and if the head is great enough, water may flow from the top of the pipe, and a flowing well results. The source of water for this artesian pressure may come from water storage reservoirs, conveyance, or distribution structures, or it may come from natural infiltration.

This raises another question; if a man has a flowing well, should he have the right to deny anyone else the right to drill a well that will result in reducing his pressure until the water will not flow? In many cases, he now has that right, and the law upholds him in spite of the fact that the reduction of the artesian pressure would make much of the lower lying or nearby lands more productive. Also, the original well would still produce its original amount of water by pumping, and the new well would produce other needed water. In some states, the new well would be allowed since the right is given to use the water but not to guarantee the pressure. In Utah, it is difficult to get a right for the new well. We need to change our laws to guarantee the right to use a given amount of well water, but not the pressure, in order to be fair to all and to permit development of the additional water that we badly need.
The water right situation approaches absurdity in some cases. There is a record of one water company that brought suit against another company because the latter was planning to line its canal and prevent seepage losses. The first company claimed that it had an established right to the seepage water from the second company’s canal and that nothing could legally be done to prevent or reduce this seepage. I am told that the court ruled that the company could not line its canal unless the water saved was given to those whose rights depended on a leaky canal.¹

It is apparent that our ancient water laws should be examined in light of our present knowledge about water in soil and modernized where it is appropriate to do so. It is only after we get these social reforms that we shall be able to develop our water supplies and economy to provide for a maximum beneficial use of the existing water supplies.

WATER IN UNSATURATED SOIL

In addition to the regulating and water supply functions performed by the soil there are many interesting things to be learned about the water that remains in the soil after all of the excess has drained away. This is the water that plants use. Water is present in the most minute locations; in soil it occurs as tiny films on the surface of clays and other soil particles and in tiny capillaries. This is the water that is not recognizable as liquid water since it is so intimately connected with the soil solids. Nevertheless, it is important since it is a chief source of water for higher plants which provide food for man and animals. The properties and characteristics of water in this minute system are not well known. We are just beginning to discover the behavior of water in these situations. Some of the peculiar properties of water in this dispersed state constitute the subject of our current research.

SOME PROPERTIES OF WATER

A review of some of the basic properties of water will better help to understand the properties of the films of water that occur in soils and plants.

Water is so universally common that it has been used in many situations to establish basic relations. For example, a calorie is defined as the heat required to raise a unit mass (one gram) of water one degree (from 15 to 16) centigrade. Likewise, the weight of one cubic centimeter of water (at 4° C) has been set at one gram, thus establishing a universal density that has been widely used for a reference.

¹Willardson, Lyman. Personal communication.
One cubic centimeter of water (a cube slightly less than one half inch on each side) contains about $3.4 \times 10^{22}$ (thirty-four thousand billion billion) individual molecules. One can get a feeling of the number of individual molecules that this represents if he realizes that this is a number that might represent the grains of sand on one thousand beaches that are similar to the Atlantic Ocean beach from Maine to Florida, assuming that the beach is about 1.6 million meters (one thousand miles) long, two hundred meters (656 feet) wide, and one hundred meters (328 feet) deep. If you can imagine the number of grains of sand on this thousand miles of beach, and then imagine the number that there would be on one thousand such beaches, then you can imagine how many individual molecules there are in this one centimeter cube of water that weighs one gram. The diameter of each water molecule is considered to be about three Angstroms. Thus it would take thirty million of these molecules lined up side by side to make a line one centimeter long (slightly less than one half inch).

In the biophysical system with which we work, water is frequently present in films that are only a few molecular layers in thickness. At other times, they are many thousands of layers thick. We work with water in the range from pure water to apparently dry soil.

Each molecule of water is composed of one atom of oxygen attached to two atoms of hydrogen at an angle of about 105 degrees from each other as shown in figure 2. This arrangement causes an unbalance of charges with the center of positive charge at one end and the center of negative charge at the other end. Such particles are called dipoles because of their reactions in electric fields. It is this property of water that makes it such a good solvent.

When water crystallizes, it does so in such a way that each hydrogen atom in one molecule of water is close to an oxygen atom.

![Fig. 2. Model of water molecule showing two hydrogen atoms, H, attached to one oxygen atom. The approximate probably position of the two electrons, e, are shown by dotted lines. The diameter of the molecule is about 3 Angstroms.](image_url)
in another molecule and as far away from other hydrogen atoms as possible. Positions for bonding are shown by the dotted lines in figure 2. This forms a crystal lattice of a hexagonal nature in which there are empty spaces or holes in the lattice. When the ice melts, some of those empty spaces disappear so that liquid at the same temperature as ice is more dense, and thus the ice floats in the water.

In its solid state, each water molecule is arranged quite orderly with respect to all other molecules because of the hydrogen bonding. In its liquid state, there is still a tendency for the water molecules to occupy positions similar to the positions they hold in ice. The liquid water molecules are more free to move, and they have greater internal energy as indicated by the fact that about eighty calories of heat are liberated when water changes from liquid to solid. The liquid water molecules also show more disorder than when they are in the solid state. When a situation of this kind occurs, the entropy of water in the solid state is lower than in its liquid state. This is in accordance with the second law of thermodynamics which states that under natural conditions every process tends to increase the entropy of the system. Stated in other words, the natural tendency is for everything to go from a state of order to a state of disorder.

This second law of thermodynamics is an important property of matter that has universal application. It is constantly working in all nature’s process. When the entropy gets too high in my laboratory or my office, it is necessary for someone to reduce it by straightening things up and putting them back in order.

About eighty calories of heat are required to change a gram of ice to a gram of water at the same temperature; this same amount of heat is released when water changes from liquid to ice. If the temperature of water is changed from the freezing point to its boiling point, its heat content increases by a value of approximately one calorie per gram for every degree of temperature rise.

At the boiling point, another peculiar situation occurs. In its liquid state, at the boiling temperature, the water molecules are relatively close together and the molecules interact with each other. In the gaseous state at the same temperature, the molecules are far apart and are even less orderly than was the water in its liquid state; so the entropy has again increased. At the same time, the particles have more internal energy, because another 540 calories of heat are converted to internal energy for each gram of water that is converted to vapor. This we call the “latent heat of vaporization.” If water is evaporated at any temperature below its boiling temperature, more heat will be required to change it from its liquid to its vapor state; and at 25 degrees centigrade (room temperature) approximately 580 calories are required to vaporize one gram of water.

Interfacial tension. Since we are dealing with large surface areas, there is another property of water that is important in our work. This
property, interfacial tension, can be demonstrated by the surface tension between liquid water at ordinary temperatures and air (which includes water vapor). If we carefully place a needle on top of a beaker of water, the needle will float. This is because of the surface tension at the interface between water and air. The surface tension of water at ordinary pressures and temperature is about seventy-two dynes per centimeter of surface. This means that seventy-two dynes of force are required to extend the surface of water by one centimeter. If one square centimeter of additional interfacial area between water and air is formed, it will require seventy-two ergs of additional work. If this same amount of surface disappears, then this amount of energy is released in the form of heat or work. Forces and energies similar to these that we have discussed occur at all solid-liquid interfaces so that they are quite important in the biophysical system that makes up the soil-plant-atmosphere environment.

Forces that are present at the solid-liquid interface cause water to be held to or repelled from solid bodies. If the water-solid interfacial energy is more than the solid-air interfacial energy, then water will be held to the solid, and we say that it is adsorbed to the solid. This is the situation that occurs in most biophysical systems. If the water-solid interfacial energy is less than that of solid air then water will not wet the solid.

Water potential. One of the most useful properties of water films is the water potential or partial specific Gibbs free energy. It is the work that a unit mass of water can do in moving from its present thermodynamic state to some reference state. For example, water can do work in falling from a higher elevation to a lower one, and the potential is positive. On the other hand, it usually requires work (or heat) to remove water from soils or plants and we say that the potential is negative. We have defined pure free water as the reference. More work is required to remove the unit of mass (gram) of water from the system than would be needed to remove pure free water from the same location. This is indicated by a negative sign on the potential. The larger the negative number, the greater the amount of work needed to remove soil water as compared to the amount of work required to remove the same amount of water from a pure free water system at the same location. This work is called “water potential.” A positive sign would mean that less work would be required to move the water from the soil than from the reference system. We find that as temperature increases, and if all other variables are constant, the work required to remove water is less, and the water potential becomes a smaller (negative) number. We are also finding that as soil material in compacted, the potential becomes smaller (negative). Solutes dissolved in the water cause the water potential to become larger (negative). The greater the concentration
of solutes dissolved, the larger (more negative) the potential. If the films are thick, the water potential is relatively small. As the films become thinner, the potential becomes increasingly larger (more negative). A large amount of work must be done to remove water from a plant or soil system that has small thin films, many solutes, and cool temperatures.

**PROPERTIES OF SOIL WATER**

We have been able to show that the entropy of water that is adsorbed on soils and in the soil system is less than that of pure free water at the same temperature and pressure (Taylor and Stewart 1960). This means that the water molecules in the soil water system are more orderly (hence less free to move) than are similar molecules in pure water. This may not always be true in biophysical systems since it is conceivable that water adsorbed on the solids composing the biophysical system could possibly be less orderly than in the pure state because of the location of the adsorption sites on the solids, thus the entropy could be greater than in free water. We are continuing these studies to measure the entropy and heat content of the water in several soil-plant systems.

Studies of the physical properties of water that is held in films and in tiny capillaries and in plant tissue are fascinating. They are beginning to be quite rewarding. There are other problems with which we are dealing that are even more challenging, some of them will now be considered.

**WATER MOVEMENT**

There are several unusual phenomena that take place in the water of the biophysical system that are beginning to be understood better than they were a few years ago. This increased understanding has come about since a few scientists have recognized that water movement is important in soil-plant processes and have begun to study the kinetic problems of water relations.

We can readily demonstrate (figure 3) that water will move rapidly into a soil that contains large pores if the water is applied directly to the porous material: it will not move into the coarse pores at all if the porous material is overlain with a soil containing fine pores. Water will not move from the fine pores into the large pores until the soil containing the fine pores is almost completely saturated. This near saturation may cause the effect of a temporary water table if the transition from fine to coarse pores is abrupt such as occurs naturally in the soil on and around the Utah State University campus.

The soil on our campus is underlain at a depth varying from a few inches to two or three feet with coarse rock. The transition from the
Fig. 3. A marked change in soil texture, such as gravel, sand, or clay, or clay underlying a loam will retard drainage.

A. Note that water penetrates the loam uniformly both laterally and vertically until the wetting front reaches the sand.

B. It will not enter the sand from the loam, but will accumulate in the loam until sufficient water is applied nearly to saturate the soil at the junction of sand and loam, then it will leak through at some point and move rapidly downward, as in

C. leaving much of the sand dry. The loam immediately above the sand is nearly saturated (Taylor 1957).

fine textured surface soil to the coarse underlying rock is quite abrupt. At this transition zone there has been precipitated a layer of lime on the rocks. This layer is almost completely cemented in some places. The lime has accumulated as a result of natural rain and snowfall percolating through the fine surface soil, dissolving lime as it percolated. When it reached the coarse pores, it did not enter them but was held up until the water got warm; then the lime precipitated (warm water holds less lime than cool water). The water then moved slowly back to the surface through plant tissue or by capillary movement to the evaporating surface and was lost from the soil. When water accumulated at the junction between coarse and fine soil until the fine soil was saturated, then the water began to enter the coarse pores between the rocks at a few points and drain away such as it might do in an open drain. The other large pores remained dry indefinitely, as illustrated in figure 3.

This phenomenon seems unusual until one understands the principles and laws governing the movement of water in porous materials with large specific surface areas. We now know that the reason water will not move into large pores that are covered with soil containing fine pores is that the movement of water in unsaturated soil is influenced by the interfacial forces that occur in soil. Thus when
soil is completely saturated, the water potential may be zero or even positive, and water moves much as though it were liquid water. It then flows more rapidly in large pores that are present in coarse materials. When held in small pores of the fine material, the water potential is negative (work is required to remove water), and the water is retained in closer contact with the fine solid particles; it is not so free to enter large pores. It does not have enough free energy to break the air-water interface at the boundary of the coarse pore until enough water has accumulated at that place essentially to saturate the system. Water will then break out into a coarse pore and drain away rapidly at the same time reducing the amount of water at other interfaces around the point of break-through so that other break-through points do not develop.

Laws governing infiltration. We find that water moves into soils according to definite laws that can be expressed mathematically. When water infiltrates an initially dry uniform soil under natural conditions, the amount of water, \( Q \), that will infiltrate a soil of unlimited extent increases in proportion, \( c \), to a power exponent, \( a \), of time, \( t \).

\[
Q = ct^a
\]

If the soil or porous material remains homogeneous, the exponent, \( a \), of time is \( \frac{1}{2} \), according to theory. Experiments with stable porous materials verify this relation. However, if the water reacts with the solid system by causing it to swell or change in size, then the exponent of time is different as can be seen in figure 4, which is a plot of \( \log Q \) vs \( \log t \) and the slope of the line is \( a \), for several different soils. If a soil is in a condition where the water will enter it rapidly initially but more slowly after a while, then the exponent, \( a \), of time is a low number. Such a situation occurs in soils that form large cracks and pores when dry, but as water is applied, the cracks and crevices swell and the movement of water into the soil becomes slow. Houston clay (121) is such soil; its initial infiltration is high, but it seals up and infiltration is finally slow. Cecil clay loam (28) has low infiltration both initially and finally. Millville silt loam (1) from the Greenville Experimental Farm at North Logan is one of the most stable soils that has been measured.

If water is applied to a soil at one spot rather than uniformly over the surface, then the flow into the soil is not in one direction but tends to be in all directions. The exponent, \( a \), may then be greater than one half. In practice, we have measured water infiltration rates in the field in which the exponent ranges between 0.1 and 0.8.

Temperature dependence. The rate of water entry into soil is also a function of the temperature of the system. As the temperature increases, the water entry rate increases. This phenomenon is an example of the kind of behavior that occurs when there is an energy
Fig. 4. The infiltration of water into various kinds of soil in the field. Those with steep slopes and large values of, \( a \), (shown on each curve) have stable soil structure, those with small values of, \( a \), deteriorate and swell when water wets them. (1) Millville silt loam (Logan), (24) Honeyoye gravelly silt loam, (119) Austin clay, (121) Houston clay, (28) Cecil clay loam, (140) Aiken clay loam, (137) Crown sandy loam, (139) Badger loam. (Data for 24, 140, 137, 139, 119, 121, 28 from Free et al. 1940.)
Fig. 5. The logarithm of the water intake coefficient as a function of the reciprocal temperature for Millville silt loam. The slope of the line is $-E^*/2.303 R$ (R is the universal gas constant).

barrier to flow in the system. If one plots the logarithm of the rate of infiltration as a function of the reciprocal of the absolute temperature at which the infiltration was measured, the result is a straight line as shown in figure 5. The slope of this line gives the activation energy or the amount of additional energy that water must have in order to move from moist to dry soil (Biggar and Taylor 1960). The energy barrier to the movement of water into soil that we have been able to demonstrate gives us an explanation as to why there is a sharp wetting front at the infiltration boundary. This wetting front is manifested by a high water content at one point, and just a short distance away there is low water content per unit volume of soil.

The cause of this energy barrier has not yet been fully established; however, we are now studying this problem and have found
that as water moves into dry soil, heat is evolved. This heat might be caused by free water with high internal energy losing part of its energy when it is adsorbed. This is somewhat similar to the liberation of heat that occurs when water is changed from liquid to ice; that is, the internal energy of the water is reduced as it comes under the in-

Fig. 6. The rise in temperature as the wetting front from infiltrating water approaches and moves past a small thermistor type thermometer.

fluence of the soil colloids, and heat is liberated. We are not sure that this is the answer since the heat might be a manifestation of the interfacial energy that is released when the air-water interface is destroyed. We are now in pursuit of the answer to this problem by collecting new experimental data to give a further indication of what actually happens. If a column of dry soil is instrumented with a sensitive thermometer and water is allowed to enter at one end, both the temperature at the thermometer location and the location of the wetting front can be observed. The temperature can then be plotted
as a function of the distance from the thermometer to the wetting front. The sharp rise is a result of either the destruction of the interface or the loss of internal energy of water. The data suggest that both may be the case. The temperature of the water then drops back to the temperature of the water that was initially introduced.

The rise in temperature produces a tendency for water to move back on itself into the cooler water, thus causing an energy barrier at the wetting front. There may also be other factors that resist the flow of water into dry soil that we have not yet been able to identify.

**Evaporation.** Recently we have shown that there is an energy barrier to the evaporation of water from a soil system (Wiegand and Taylor 1960). This energy barrier is even greater than that of water moving into the system. The activation energy for water infiltrating Millville silt loam varied from 5.4 to 12.0 kilojoules per mole of water, and for evaporation from the same soil, it varies from 29 to 40 kilojoules per mole when the soil is quite moist. We still need to establish the cause or explanation for the energy barrier to evaporation of water from the soil system, but we have several good indications. In quite moist soil, the barrier is of the same order of magnitude as the latent heat of vaporization, hence the formation of water vapor might limit the process. In drier soil, it appears to be about the same as for self diffusion; hence, the flow of water through the dry soil to the evaporating surface might limit evaporation.

**WATER MOVEMENT INDUCED BY THERMAL GRADIENTS**

One of our most fascinating studies involves the movement of water in response to a thermal gradient. As heat energy flows through the soil-water system, it carries with it water. Experimentally, we are able to measure the flux or the amount of water flowing in one direction and the amount of heat flowing in the same direction. This indicates that a temperature gradient across a soil-water system will carry water along with the heat from the hot to the cold region.

When a substance flows along its own potential or free energy gradient, the flux is proportional to the magnitude of the gradient and a transfer coefficient that depends upon the conductivity of the medium for the substance flowing. When a substance flows in response to a potential gradient of something else, it depends upon the flow of the other substance (or energy) and a linked transfer coefficient. When water flows from warm to cool as a result of linked water-heat transfer, a pressure difference might build up, and as the pressure difference increases, water will be forced along this pressure gradient in opposition to the thermally induced flow. We find that when a steady state is reached with respect to the water flux, the ratio of the difference in pressure, $\Delta P$, to the difference in temperature, $\Delta T$, 

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is a function of the partial heat content of the water $H_w$, and the ratio of the linked transfer coefficient, $L_{WT}$, to the coefficient of conductivity, $L_{ww}$, of the water through the system as follows:

$$\frac{\Delta P}{\Delta T} = \frac{1}{TV_w} \left( H_w - \frac{L_{WT}}{L_{ww}} \right)$$

where $T$ is the Kelvin temperature and $V_w$ is the partial volume of water. Similar explanations are found for the movement of water in response to electrical potential gradients. The explanation for salt concentration induced flow is somewhat more complicated, but the same principles are operating. The explanation of these phenomena depends upon a knowledge of the flow rate and movement of water and other things through the system.

These experiments based on application of thermodynamics of irreversible processes have established the principle of "linked transfer" in soil systems (Taylor and Cary 1960). This principle is that whenever there is a flow of one form of energy or matter in a porous colloidal system such as soil, it induces a flow of other forms of energy or matter. The net flux, $J$, of any component, $i$, is the sum of the product of a force, $X_k$, by an appropriate transmission coefficient, $L_{ik}$, as follows:

$$J_i = \sum_k L_{ik} X_k$$

The forces must be chosen such that the product of the forces by the fluxes gives the time rate of increase of internal entropy. The net flux in a system depends upon the relative magnitudes of the transmission coefficients and the contribution of the various processes to the creation of internal entropy. Hence, the flux depends upon the nature of the porous or colloidal matrix.

FORCES CAUSING WATER TO FLOW THROUGH POROUS MATERIALS

We have found answers to two rather perplexing problems that have not been previously understood. One is connected with water movement in plant tissue; the other, with movement of water in response to temperature differences.

The common explanation for water moving into and through plant tissue is based on diffusion through a semipermeable membrane. It is generally considered that plant membranes are permeable to water, but are impermeable to solutes. It is reasoned that the osmotic pressure difference thus created will cause water to move across the membrane and into the plant. This explanation requires that only water move through the membranes, yet we know that solutes move through these same membranes in the form of plant nutrients and also
as sugars. There is evidence that water moves through some of these membranes at the same time that nutrients and sugars are moving through them. The membranes appear to be quite readily permeable to the solutes as well as to water. Since this is true, how can we say that these membranes are differentially permeable and that water moves through them in response to an osmotic drag? A possible an-

![Diagram of apparatus used in determining the thermo-mechanical pressure in soil. Apparatus for electro-mechanical and solute-mechanical pressure are similar.](image)

swer to this problem has been found in a seemingly unrelated experiment that I will now describe. The problem will then be considered in light of the findings of the experiment.

A soil sample or other membrane (such as sausage casing, cellophane, or dialysis membrane) is placed between two sealed containers of water as shown in figure 7. A pressure measuring device (a simple manometer) is connected to each container. The water in one container is heated and that in the container on the other side of the membrane or soil is kept cool. Water will at first rise in the manometer tube on the warm side as a result of expansion as it warms. Water then moves through the membrane from warm to cool until it rises higher on the cool side than the warm side. This is an unusual phenomenon since water usually flows from a high elevation to a low one, not from low to high as we have in this experiment. A few years ago, it would have been difficult for me to believe that water could be made to flow uphill. Yet, I have performed an experiment in my own laboratory that demonstrates that it can be done. Not only can this be done with the use of a temperature difference, but it is also
possible with a small electrical potential difference, or a salt concentration difference (Taylor and Cary 1960).

The results of these experiments are contained in Table 1. The explanation for the maximum pressure difference is simple. As water moves from hot to cold, the pressure gradually builds up on the cool side.

Table 1. The pressure difference that develops for a given temperature difference $\Delta P/\Delta T$, the pressure difference per volt of electrical potential difference $\Delta P/\Delta E$, and the pressure difference per unit of salt concentration difference $\Delta P/\Delta C$, (concentration of solution measured by the electrical conductivity of the solution in mho's, Taylor and Cary 1960)

<table>
<thead>
<tr>
<th>$\Delta T$ C°</th>
<th>$\Delta P/\Delta T$ mb/C°</th>
<th>$\Delta E$ Volts</th>
<th>$\Delta P/\Delta E$ mb/volt</th>
<th>Solution</th>
<th>$\Delta P/\Delta C$ mb/mho</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.1</td>
<td>0.111</td>
<td>1.50</td>
<td>3.6</td>
<td>NaCl</td>
<td>70</td>
</tr>
<tr>
<td>28.1</td>
<td>0.067</td>
<td>1.18</td>
<td>3.6</td>
<td>CaCl₂</td>
<td>60</td>
</tr>
<tr>
<td>29.2</td>
<td>0.096</td>
<td>1.14</td>
<td>3.5</td>
<td>CaSO₄</td>
<td>80</td>
</tr>
</tbody>
</table>

As the pressure builds up, there is an increasing amount of return flow of water through the membrane to equalize the pressure difference. The net flux continues to be from warm to cool until the return flow in response to the pressure difference is equal to the thermal, electrical, or salt induced flow when a steady state is reached in which heat, electricity, or salt is flowing, but there is no net flux of water. The rate of flow and the amount of pressure difference that can be made to occur at the maximum or steady state depend upon the physical properties of the membrane, the temperature (or voltage) difference, and two transmission coefficients.

The usual explanation for water movement in response to thermal gradients is that water moves from hot to cold as vapor; then it might return from cold to hot in the liquid phase. We have been able to demonstrate that this really does occur, and at the same time, we can show that water will move from hot to cold in a liquid state and in the absence of a vapor phase. This phenomenon is not easy to explain by the classical theory of water flow, which is, that water always flows from a region of highest pressure (or Gibbs free energy) to a region of lower. The flows that we were observing were in the opposite direction. It is well known that equilibrium thermodynamics is invalid where temperature is not constant. It was apparent, however, that whenever these peculiar results occurred, we did not have an equilibrium system; something was always flowing—either heat, electricity, or salts. Further, the processes taking place appeared to be irreversible.

The explanation was found in the theory of the thermodynamics of irreversible processes (Prigogine 1955). The flow takes place in the direction of the maximum production of entropy in the system. The magnitude of the net flux depends upon the combined contribu-
tion of all forces that cause the water to move and upon the rate that
the material moves through the soil. A further requirement is that
the product of the force by the flux is such that the time rate of in­
crease of entropy in the system must be a maximum.

This theory is not easy to test because there is no known method
for measuring directly, entropy or its production in a system. It must
be measured indirectly from the temperature dependence of measur­
able properties. We have used the temperature dependence of the
water potential which is measurable in all soil-water systems that we
have studied.

When a phenomenon occurs such that the movement of one
material carries with it another material, such as the movement of
heat carrying with it water, we say that there is a linked coefficient
of transfer for that material.

In view of our recent experimental findings, we now believe that
the principle of linked transfer can be validly applied to the dynamic
biophysical soil-plant-water system. In the plant there is a constant
flow of both materials and energy. It is well known that plant
nutrients and sugars are moved through plants by translocation. It is
also known that energy and electricity move in plants. Bioelectric
potentials and currents have been observed and can be readily meas­
ured in many plant tissues. These phenomena provide forces that
might cause water and solutes to move simultaneously through cells
and tissues. It is now apparent that natural differential permeability
could result from differential rate processes going on simultaneously
in the plant tissue. Differential permeability might be simply water
moving more rapidly through the plant tissue than the solutes are
moving.

The application of irreversible thermodynamics to the biophysical
plant-soil-water system is only just beginning, but our results are
already encouraging. The processes that take place in living plants
are always dynamic. Things are always moving; energy is continuous­
ly flowing and being consumed. This indicates that the living world
is a dynamic system; if man is to be successful in understanding what is
happening, he must understand the dynamics of the system. We are
now ready to consider some of the perplexing problems of this dynamic
system.
PLANTS AND SOILS are known to have a natural affinity for water. This affinity can be related to differential rate processes. For example, if evaporation from plant tissue exceeds water uptake, the plant will wilt. As the plant wilts, the affinity for water by the plant tissue becomes greater, and the evaporation rate is retarded. At the same time, the uptake rate might be somewhat increased. The affinity of plant tissue for water is a function of the amount of water in the tissue. We are now developing vapor pressure methods for measuring this attraction quickly and effectively. The curves in figure 8 were obtained by laborious vapor equilibrium methods. It is apparent that the same amount of work will remove more water from tomato than from privet. Tomato should then lose water more easily and it might possibly be less drought tolerant and less able to survive.

![Graph showing water potential vs. water content for tomato and privet leaf tissues.](image)

Fig. 8. Water potential–water content relation for tomato and privet leaf tissues (from Slatyer 1958).
dry conditions. We hope to find if there is any relation between the shape of these curves and drought tolerance.

We have long been able to measure the affinity of soil for water. An example of some curves relating the water potential to the moisture content are shown in figure 9. The Oxford clay subsoil and the Benjamin silty clay loam will supply moderate amounts of water between any two potentials in the plant growth range; Millville loam will supply even more as shown by the slope of the curves. Wasatch coarse sandy loam, on the other hand, can supply little water, it would be a droughty soil.

By studying plant and water retention curves for plants and soils, we hope to be able to predict what kind of behavior might be expected as the water is removed from the soil by plants growing on it. We may be able to determine some of the characteristics of water retention

Fig. 9. Water potential—water content relations for four Utah soils.
in drought resistant plant material and perhaps get an idea of why desert shrubs and plants survive severe dessicating conditions that would cause death to more succulent materials.

There are many unusual phenomena that occur in both plants and soils that we are eager to study in the light of these new ideas and theories.

As we learn more about the intricate relations of water with plants and soils, our curiosity becomes greater. We are able to imagine many exciting relations, all of which must be tested and examined by experimentation. These experiments must be designed to extract the true facts from a reluctant nature. Many times new equipment must be built and tested; then many hours must be spent in collecting and analyzing the data. More often than not the data prove that our imaginings were incorrect, but occasionally they confirm our idea. Then there is the eager excitement of a new discovery. Each new discovery adds to our basic knowledge of nature and ties back to our existing store of knowledge. In this way, we are bringing light into the darkness of the unknown as we slowly push back the frontiers of knowledge.

LITERATURE CITED


TWENTY-THIRD FACULTY HONOR LECTURE
DELIVERED AT THE UNIVERSITY

January 19, 1960

A basic objective of the Faculty Association of the Utah State University, in the words of its constitution, is

to encourage intellectual growth and development of its members by sponsoring and arranging for the publication of two annual faculty lectures in the fields of (a) the biological and exact sciences, including engineering, called the Annual Faculty Honor Lecture in the Natural Sciences, and (b) the humanities and social sciences, including education and business administration, called the Annual Faculty Honor Lecture in the Humanities.

The administration of the University is sympathetic with these aims and shares the cost of publishing and distributing these lectures.

Lecturers are chosen by a standing committee of the Faculty Association. Among the factors considered by the committee in choosing lecturers are, in the words of the constitution:

(1) creative activity in the field of the proposed lecture; (2) publication of research through recognized channels in the fields of the proposed lecture; (3) outstanding teaching over an extended period of years; (4) personal influence in developing the character of students.

Dr. Taylor was selected by the committee to the Faculty Honor Lecture in the Natural Sciences. On behalf of the members of the Association we are happy to present this paper: WATER FOR MAN.

Committee on Faculty Honor Lecture
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