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THE WATER CYCLE

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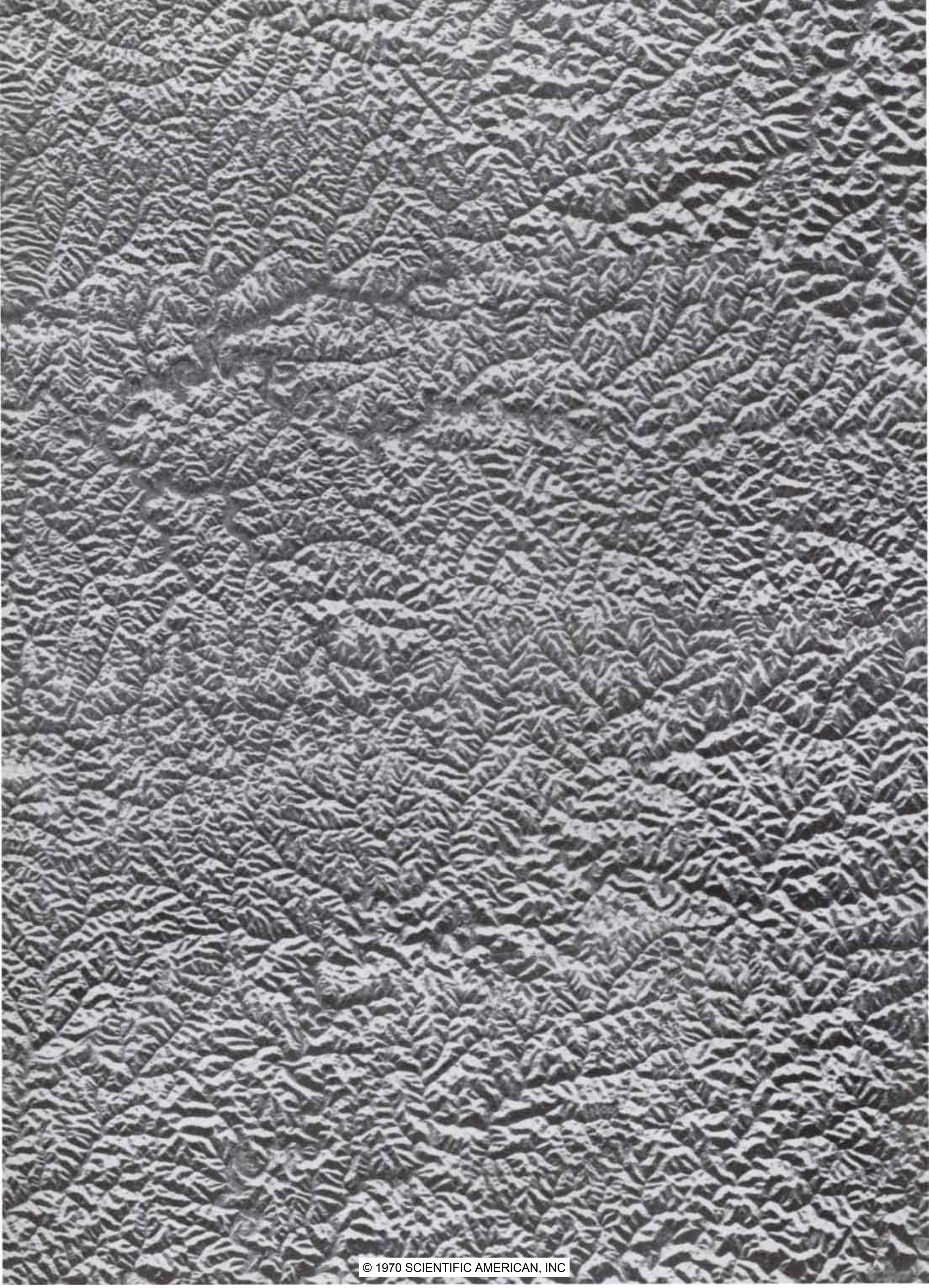
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THE WATER CYCLE

Water is the medium of life processes and the source of their hydrogen. It flows through living matter mainly in the stream of transpiration: from the roots of a plant through its leaves

by H. L. Penman

By far the most abundant single substance in the biosphere is the familiar but unusual inorganic compound called water. The earth's oceans, ice caps, glaciers, lakes, rivers, soils and atmosphere contain 1.5 billion cubic kilometers of water in one form or another. In nearly all its physical properties water is either unique or at the extreme end of the range of a property. Its extraordinary physical properties, in turn, endow it with a unique chemistry. From these physical and chemical characteristics flows the biological importance of water. It is the purpose of this article to describe some of water's principal qualities and their significance in the biosphere.

Water remains a liquid within the temperature range most suited to life processes, yet in due season there are occasions when liquid water exists in equilibrium with its solid and gaseous form, for example as ice on the top of a lake with water vapor in the air above it. Freezing starts at the surface of the water and proceeds downward; this follows from one of water's many peculiar attributes. Like everything else, ice included, liquid water contracts when it is cooled, but the shrinkage ceases before solidification, at about four degrees Celsius. From that temperature down to the freezing point the water expands, and because of its decreased density the cooler water floats on top of the warmer. Ice has a density of .92 with respect to the maximum density of water and hence an unconstrained block of ice will float in water with about an eleventh of its volume projecting above the surface. The biological significance of freezing from the surface downward, rather than from the bottom upward, is too well known to need repetition here.

Among its other thermal properties water has the greatest specific heat known among liquids (the ability to store heat energy for a given increase in temperature). The same is true of water's latent heat of vaporization: at 20 degrees C. (68 degrees Fahrenheit), 585 calories are required to evaporate one gram of water. Finally, with the exception of mercury, water has the greatest thermal conductivity of all liquids. Some consequences of water's large latent heat of evaporation, which is a major energizer of the atmosphere, will be considered below. Its great specific heat means that, for a given rate of energy input, the temperature of a given mass of water will rise more slowly than the temperature of any other material. Conversely, as energy is released its temperature will drop more slowly. This slow warming and cooling, together with other important factors, affects yearly, daily and even hourly changes in the temperature of oceans and lakes, which are quite different from the corresponding changes in the temperature of land. Among other things, this can lead to differences in the thermal regimes of soils that are of major importance in ecology. The type of soil, interacting with water, determines the earliness or lateness of plant growth at a given site; the interaction may also affect the local risk of frost.

In basic structure the water molecule has a small dipole moment and is feebly ionized. Water will dissolve almost anything to some extent (fortunately the extent is extremely small for many substances). The dissolved material tends to remain in solution because of another of water's exceptional attributes. The values given by the inverse-square law for the force that attracts separated positive and negative ions are determined by multiplying the square of the distance separating the ions by a constant that varies according to the nature of the separating medium. Known as the dielectric constant, this constant is greater for water than for any other substance. To get the same attractive force in water as in air, for example, the water separation has to be cut down to a ninth of the separation in air.

Because of its extreme dielectric constant liquid water in the biosphere is not chemically pure (unlike water vapor, which is always pure, or ice, which can be and often is pure). Instead liquid water is an ionic solution and one that always contains some hydrogen ions because the water itself can supply them. The concentration of hydrogen ions, expressed as a degree of dilution, gives the physical chemist a numerical index that describes the state of various water samples. The number is the logarithm (to the base 10) of the degree of dilution; the chemist labels it *p*H. For his tests he is armed with a *p*H meter, calibrated from zero to 14. Fourteen orders of magnitude is an enormous range for any terrestrial

WATER AT WORK for millenniums in the form of rainfall and stream runoff has produced the dissected land surface seen in the side-looking radar image on the opposite page. The annual work of terrain modeling by rainfall and runoff has been estimated to equal the work of one horse-drawn scraper busy day and night on every 10 acres of land surface. This area, in the vicinity of Sandy Hook, Ky., is drained by tributaries of the Ohio River. Each inch equals 2.3 miles on the ground. The radar mosaic, made by the Autometric division of the Raytheon Company, is reproduced by the courtesy of the Army Topographic Command.

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property, yet the water content of the soil may give a reading anywhere from pH 3 (very acid) to pH 10 (very alkaline), which is equivalent to a range of from one to 10 million. These are extremes, however, and most terrestrial plant growth—including much of the world's agriculture—proceeds in soil with a water content that ranges only a few units on each side of pH 6. The range for marine organisms is even more restrictive: coastal waters are about pH 9 and the general oceanic average is just over pH 8. Below pH 7.5 many marine animals die; eggs are particularly vulnerable. Below pH 7 the carbonate in seawater would remain in solution, rendering production of any kind of skeleton impossible.

Another method of describing the state of a given water sample is independent of hydrogen-ion content. Material in solution, whether it is ionized or not, disturbs the liquid structure of the water; in thermodynamic terms the presence of solutes decreases the free energy of the water. Many soil and plant workers find it convenient to use the symbol pF for such changes in free energy, with the steps between units also representing one order of magnitude. As with the pH range, the range of pF values is very great.

The quantity being measured in pF units is basically a potential, with the same dimensions as pressure. If all the water problems in soils, plants and animals were problems of solutions, it would be sufficient to describe the consequent variations in free energy as variations in osmotic potential, expressed in any of the conventional units of pressure. The free energy of water, however, can be decreased in other ways, notably in capillary systems. The energy to lift the water into a capillary tube (or in nature into the porous and cellular systems of soils and plants) comes out of the free energy of the water. Today this is known as "matric" potential, a term that has replaced the earlier "capillary" potential. In soils and plants the matric potential may be more than the osmotic potential. A comparison of numbers will give an idea of the pF scale and its ranges. The pressure is expressed as the height in centimeters of an equivalent column of water; thus one bar equals one atmosphere, which equals a 1,000-centimeter water column. This is equivalent to pF 3.

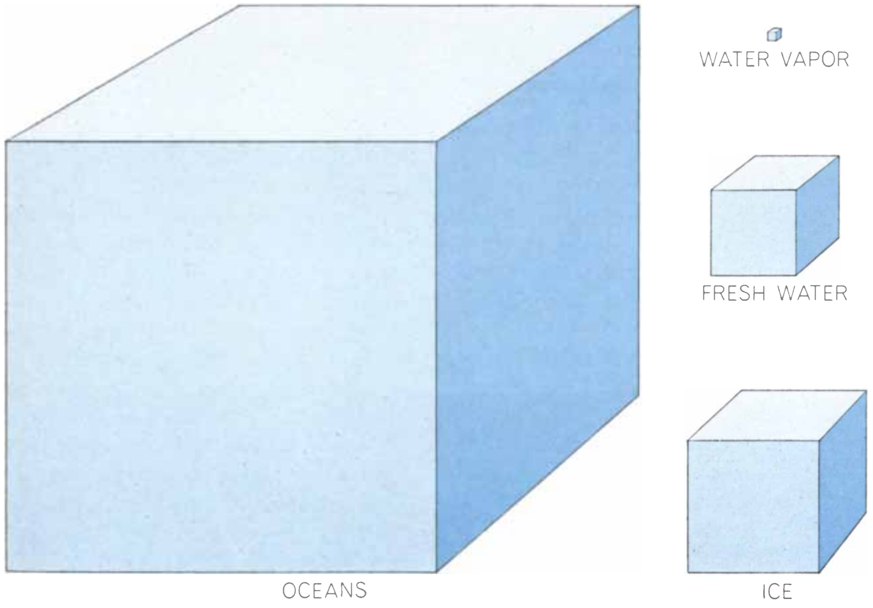
In a waterlogged soil, beginning to drain, the matric potential may be between pF 0 and pF 1; in a fully drained soil the potential may be near pF 1.7. In a soil that is as dry as plant uptake and the transpiration of water from leaves can make it, the matric potential will be about pF 4.2, which is close to 16 atmospheres of suction. The osmotic potential of seawater is near pF 4.5, which makes seawater too "dry" for plant roots; the salt content of plant cells might be anywhere in a range from less than pF 4 up to pF 4.5.

Here once again water is extreme. Associated with the matric potential in a capillary system there is a curved liquid-air interface; the value of the potential is found by doubling the known value of the liquid's surface tension and dividing the product by the radius of curvature. Water has the greatest surface tension of any liquid known, so that at any given matric potential the radius of curvature of a water meniscus will be greater than it could be for another liquid. The greater the radius of curvature, the greater the total water content. In a soil this means that more liquid can be retained as water just because it *is* water. In general, but not always, this is an advantage for plant growth.

The effects of a decrease in the free energy of water contained in porous soils or in the tissues of plants include a lowering of the fluid's freezing point and vapor pressure. If the source of the decrease is a matric potential, there is also negative pressure, or suction, that tends to pull all kinds of retaining walls together. The effect of freezing in soils and rocks is worth a brief aside. As the temperature falls the water in the larger soil pores freezes first and the free-energy gradient is such that water will be withdrawn from the smaller pores. As a result ice lenses form in the coarser pore spaces and the finer pore spaces are exposed to greater shrinkage forces. Because water expands on freezing, the ice lenses have a disruptive effect as they make room for themselves. In rock this is the beginning of one method of soil formation. There tends to be a preferred size for the rock fragments produced by ice disruption. This size is near the optimum for transport by wind and is the dominant size in many of the loess soils that have accumulated in areas near glaciers. In soil the ice disruption is the source of "frost tilth," which is sought by farmers when they leave land roughly plowed in the fall and hope for a sufficiently frosty winter.

There are still some uncertainties with respect to the world's water balance, but agreement was reached on probable values or ranges during an international symposium on the subject held in Britain this summer as one of the activities of the International Hydrological Decade. The figures that follow are taken from the proceedings of the symposium.

The world's water exists as liquid (salt and fresh), as solid (fresh) and as vapor (fresh). There is some uncertainty in the value of the total volume, but it is near 1,500 million cubic kilometers (in U.S. usage 1.5 billion). Estimates of the components are most easily expressed as



WORLD WATER SUPPLY consists mainly of the salt water contained in the oceans (*left*). The world's fresh water comprises only about 3 percent of the total supply; three-quarters of it is locked up in the world's polar ice caps and glaciers and most of the rest is found as ground water or in lakes. The very small amount of water in the atmosphere at any one time (*top right*) is nonetheless of vital importance as a major energizer of weather systems.

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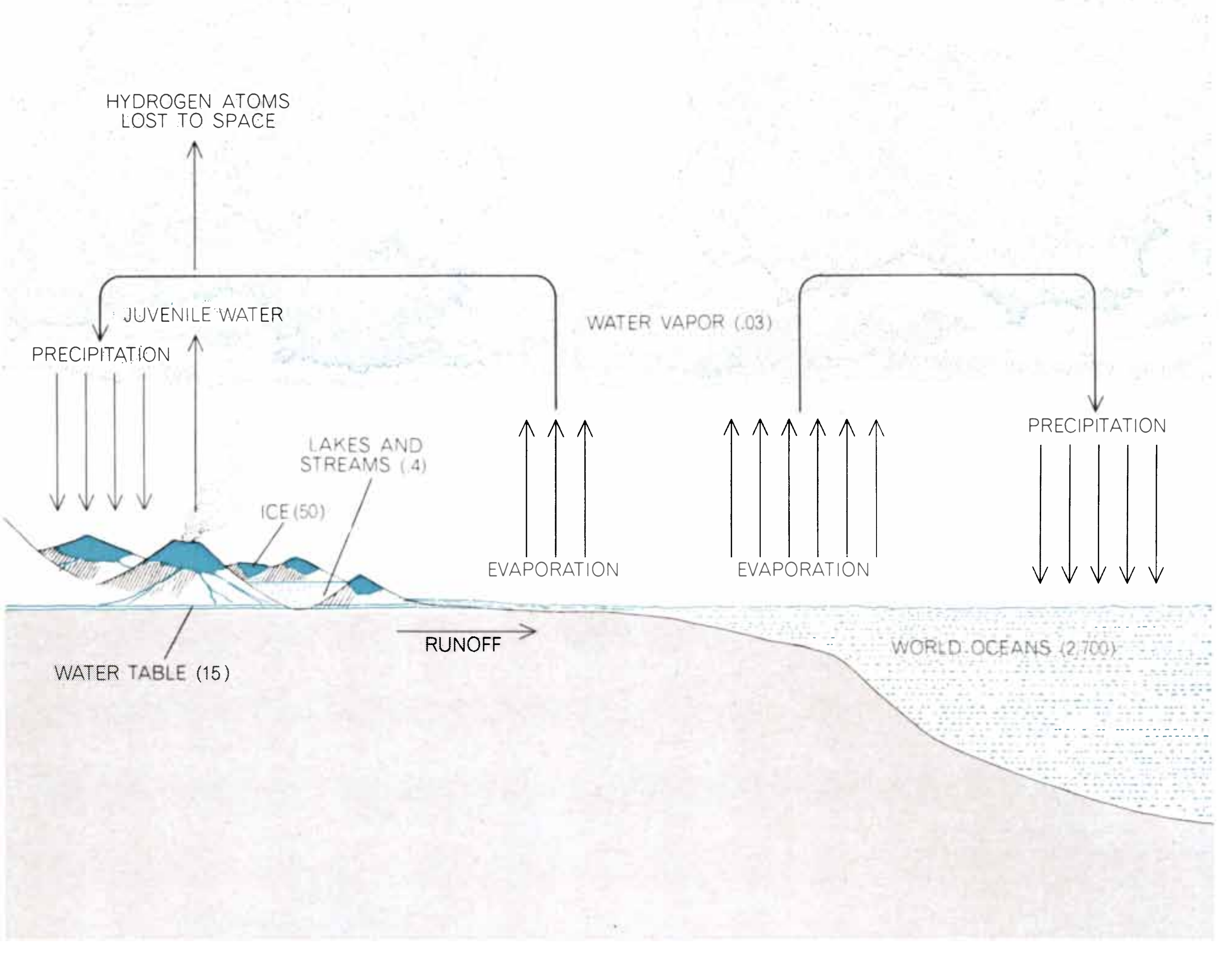
average depths per unit area of the entire surface of the earth, which has a total area of 510 million square kilometers. Oceans and seas—liquid salt water—make up about 97 percent of all water, with an equivalent depth of between 2,700 and 2,800 meters; the greater part is in the Southern Hemisphere. Of the remaining 3 percent, three-quarters is locked up as solid in the polar ice caps and in glaciers. Here measurement is quite difficult, and a spread in estimates is inevitable. The equivalent depth of ice and snow may be near 120 meters, but at the recent symposium a value of 50 meters was not challenged. The other large component of fresh liquid water is subject to similar uncertainty: the estimates for underground water may be near 45 meters, but again a value near 15 meters was not challenged. Estimates for surface water, mainly in the great lakes of the world, ranged from .4 meter to one meter. There is general agreement on the average water-vapor content of the atmosphere, at an equivalent in liquid of .03 meter. Although this is a very small fraction of the total, size is no measure of importance. Without water in the atmosphere there would be no weather; Leonardo da Vinci's dictum, "Water is the driver of nature," is justified on meteorological grounds alone. A little detail at this point will be helpful as an introduction to another aspect of the world circulation of water.

The amount of water vapor is not the same everywhere, either geographically or seasonally. It is greatest at and near the Equator. If the air there were squeezed dry, it would yield about 44 millimeters of rainfall. In middle latitudes, say from 40 to 50 degrees, the summer yield would be near 20 millimeters and the winter yield near 10 millimeters, with large variations that depend on geography and weather patterns. In the polar regions the yield ranges from two millimeters in winter to as much as eight in summer.

Water vapor enters the atmosphere by evaporation (this term includes transpiration by vegetation), and the main oceanic sources are fairly identifiable. It leaves the atmosphere as rain or snow, and because the precipitation may take place close to the source or thousands of miles away, the residence time may vary from a few hours to a few weeks. A general average is nine or 10 days.

The general balance of evaporation and precipitation needs three sets of figures, one set for the entire earth, one for the oceans and one for the land surface.



WATER CYCLE in the biosphere requires that worldwide evaporation and precipitation be equal; hydrogen losses to space are presumably replaced by juvenile water. Ocean evaporation, however, is greater than return precipitation; the reverse is true of the land. Excess land precipitation may end up in ice caps and glaciers that contain 75 percent of all fresh water, may replenish supplies taken from the water table by transpiring plants or may enter lakes and rivers, eventually returning to the sea as runoff. Numbers show minimum estimates of the amount of water present in each reserve, expressed as a depth in meters per unit area of the earth's surface.

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Here, within a few percent, there is almost complete agreement on values. For the entire earth, average evaporation and precipitation are equal—as they must be—at very nearly 100 centimeters per year. For the oceans, expressed as equivalent depths over the area of the oceans, the average annual precipitation is between 107 and 114 centimeters, the average annual evaporation is between 116 and 124 centimeters and balance is restored by river flow, with an annual value close to 10 centimeters in all estimates. For the land surface the average annual precipitation is near 71 centimeters, the average annual evaporation is near 47 centimeters and the average annual river discharge is near 24 centimeters. (The ocean figure of 10 centimeters corresponds to the 24-centimeter land figure.)

Because half of the land surface—ice caps, deserts, mountains, tundra—contributes little or nothing to evaporation, a better evaporation average would take into consideration only the land component of the biosphere where the availability of water is combined with the opportunity for evaporation. Here the average evaporation may total 100 centimeters per year. The evaporation in high latitudes would of course be far less than the evaporation nearer the Equator.

Available measurements support this conclusion. In Finland, at 65 degrees north latitude, the average evaporation is 20 centimeters per year; in southeastern England, at 50 degrees north, it is 50; in North Carolina, at 35 degrees north, it ranges from 80 to 120. On the Equator in the Congo basin the average is 120 centimeters per year; at the same latitude in Kenya it is 150. In the papyrus swamps of the Nile in the southern Sudan, 10 degrees north of the Equator, the average is 240 centimeters per year, but this is a special case. Here the river carries its water into the desert environment of the Sudd; evaporation rates are high not only because of the clear skies and intense sunshine overhead but also because the surrounding desert is a source of hot dry air that augments evaporation. This kind of advective augmentation operates in many places other than the Sudan, particularly in semiarid regions where irrigation is practiced, and not quite enough is known about it.

Once in the air, water vapor may circulate locally or become part of the general circulation of the atmosphere. The general circulation is one of the three important ways of moving water across the earth. Some indication of the worldwide volumes involved is given by the

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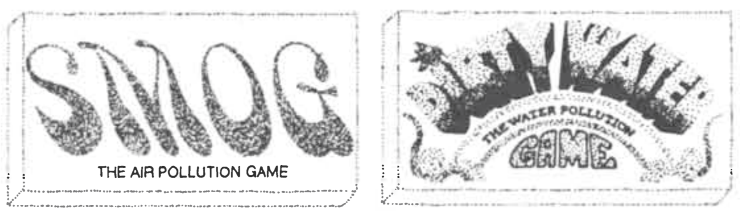

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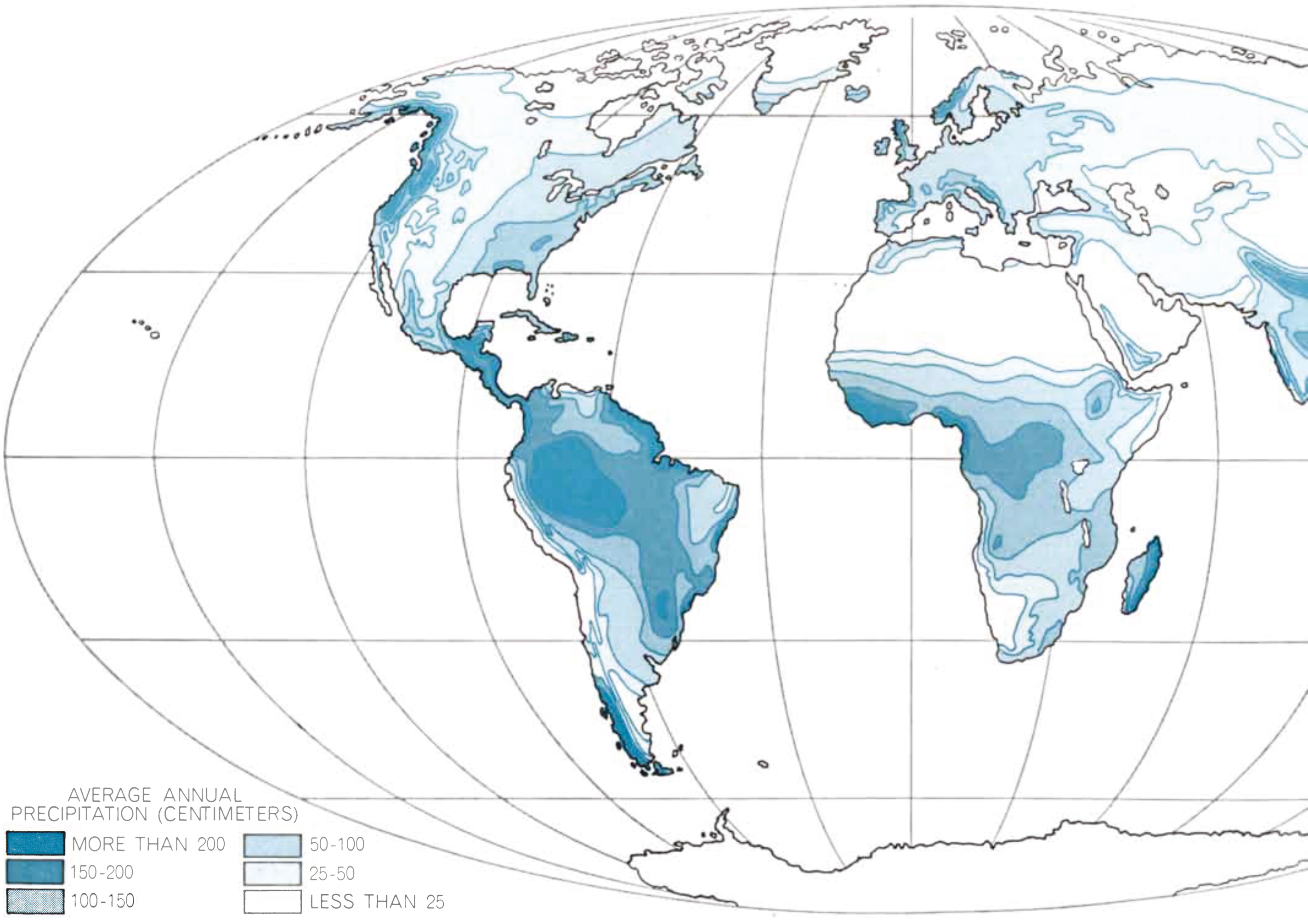
fact that the total annual precipitation over the U.S. comes to some 6,000 cubic kilometers, whereas the liquid equivalent of the water vapor that passes over the U.S. in a year owing to the general circulation of the atmosphere is 10 times that amount.

Of the two remaining important ways of moving water across the earth, the major ocean currents comprise one and the discharge of rivers comprises the other. Both have substantial effects on the biosphere. The ocean currents carry energy surpluses or deficits over great distances; one well-known instance accounts for the extreme contrast between the climates on the west and east sides of the Atlantic in the areas between 50 and 55 degrees north latitude. Without the Gulf Stream northwestern Europe would be a much less pleasant place in which to live and work; indeed, if the cold Labrador Current had replaced the Gulf Stream, the history of civilization would have been very different.

The rivers of the world not only are long-distance movers of water but also serve as conduits for dissolved and suspended material. Because of its chemical and physical properties, water is a very efficient erosive agent; erosion, transport and deposition have to be recognized as geological processes associated with water in the biosphere. They are the processes that have produced lands and soils, now densely populated and intensively cropped, where annual floods and silt deposition are regarded as the mainstay of life. Elsewhere, notably in the Americas, silt is an embarrassment in the deltas where it settles, and its production is equally unwelcome in river headwaters.

Two further points about river water deserve mention. First, the salt content of river water differs markedly in composition from that of the oceans. This suggests that the oceanic brine is not merely the accumulation of salts from aeons of land-surface leaching. Second, information about river discharge rates is scanty and not always reliable. As an example, it is only recently that a good estimate of the flow of the Amazon has been obtained. It proved to be twice the best previous estimate and indicates that almost a fifth of the world's river discharge comes from this one stream.

It is not possible to do more than guess at the average amount of water the world's plant and animal populations contain. Considered as the equivalent of rainfall, it may amount to about one millimeter over the entire surface of the earth. This is less by one order of magnitude than the amount of water vapor in the atmosphere, and its distribution is even more varied in space and time. For a fully grown good crop of corn in North America or of sugar beet in northwestern Europe the amount might come to the equivalent of five millimeters of rainfall, and its summer residence time would be two to three days. This is a measure of the rate of water supply needed to maintain optimum conditions for growth. Here, at the point of water uptake by the roots of plants, begins the problem



PRECIPITATION reaches the land areas of the world principally in the form of rainfall, which is heaviest at and near the Equator and along some western coasts at higher latitudes (*darker colors*). Variations in precipitation are the result of atmospheric circula-

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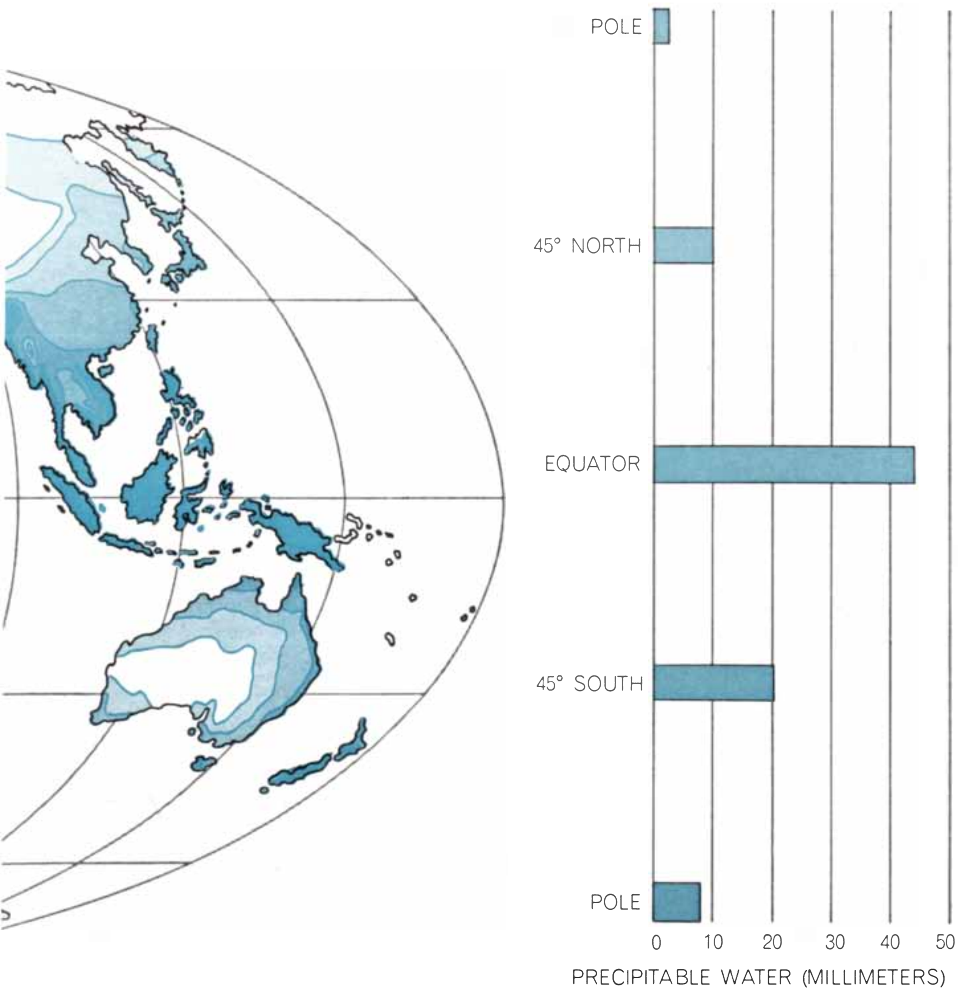
with respect to water in the biosphere that makes all other water problems seem trifling.

With unimportant exceptions, the basis of all life on the earth is photosynthesis by green plants, a process that involves physics (in the fixation of solar energy) and chemistry (in the union of carbon dioxide and water to form carbohydrates and more complex biochemical compounds). Water comes into the story in two ways: in transit (as part of the transpiration stream) and in residence (as its hydrogen is chemically bound into the plant structure). The amount that is bound, however, may be less than a fifth of the amount in transit. To give scale to the argument that follows, here are some values based on a real crop in a real climate. In producing 20 fresh-weight tons of crop, 2,000 tons of water will pass into the plants at their roots. At harvest perhaps 15 tons of the water supply will be in transit, leaving the crop with a dry weight of five tons. To produce the five tons of dry matter three tons of water will have been fixed and transformed. The energy fixed in the dry matter will be 1 percent or less of the total solar energy received by the crop; nearly 40 percent of the energy will have been used to evaporate the transpired water. Here is a clear interaction of the kind envisioned in the article that introduces this issue of *Scientific American,* where G. Evelyn Hutchinson describes the biosphere as "a region in which liquid water can exist [and that] receives an ample supply of energy from an external source."

The average value of 40 percent for the net solar radiation income retained by a green crop cover varies, of course, with season and climate. The first loss is to reflectivity: of the solar radiation reaching the crop about 30 percent is reflected. There is also an income of long-wave radiation from the sky, but this is outweighed by the outgo of long-wave radiation from the earth to the atmosphere. When the deficit is met by deducting it from the remaining balance of short-wave solar income, the net retained income is decreased to 40 percent of the initial input. As already noted, when the water is available, very nearly all this energy is used in evaporating water.



tion patterns and also reflect the amount of precipitable water vapor present. This is greatest at the Equator, least at the poles and more in summer than in winter (*graph at right*).

Here once again water stands at the extreme of a range of physical properties. The volume of water evaporated per unit of energy input is less than it would be for any other liquid. The relevant physical constant, the latent heat of vaporization, is somewhat less than 600 calories per gram at ordinary temperatures, but the rounded figure is adequate for the present purpose. If we let R_I represent the total radiant income in calories per square centimeter over a period of time, then the net radiation is about $.4R_I$ and the evaporation equivalent is near $R_I/$-1,500 grams per square centimeter (or centimeters of water depth as the equivalent of rainfall). Consider some real midsummer values to show what this means. In a humid temperate climate the value of R_I is close to 450 calories per square centimeter per day. This works out to an evaporation equivalent of three millimeters per day, which is a good estimate for June in southeastern England. For many of the farming areas of the U.S. the R_I value is close to 650 calories per square centimeter, bringing the evaporation rate up to about 4.5 millimeters per day. The maximum rates known, which are found in irrigated areas, range from 4.5 to 7.5 millimeters per day. It is possible that the higher rates are influenced by advection from surrounding nonirrigated areas, as is the case in the papyrus swamps of the Nile.

The most important fact to be considered in connection with this wide range of evaporation rates is that there are only very small variations among the evaporation rates of different kinds of plants. Thus the governing factor in variation is almost exclusively a climatic one. This fact and much other evidence suggest that the supposed water "need" of a crop is dictated not by the plants but by the weather. In this connection the concept of "potential transpiration," which came into use simultaneously and independently in at least two parts of the world, is of great value both in research and in the practical aspects of soil water management. It is worthwhile seeing how potential transpiration is linked with elementary plant physiology and with some of the physics of soil water already considered.

A growing plant takes in water at the roots and, in the absence of immediate replenishment, the process dries

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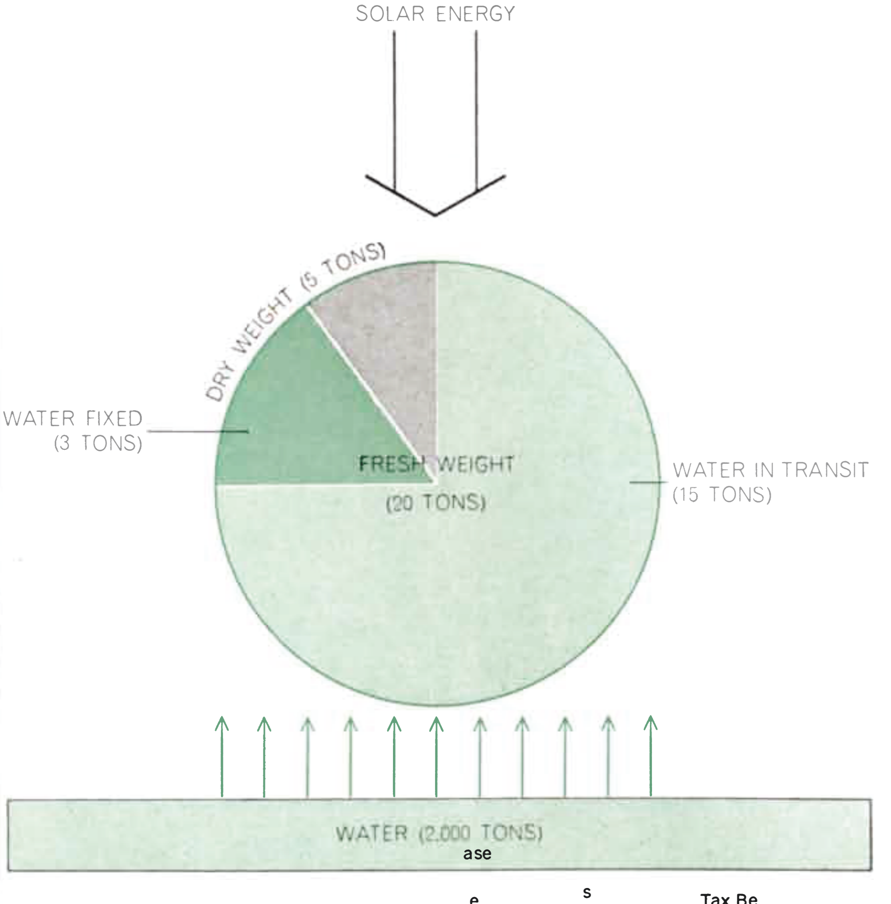
the soil so that more and more energy is required for further extraction. The energy requirement is very small, however, compared with the amount of energy needed to evaporate the same quantity of water from the plant's leaves. There can be no serious error in assuming, as Frank J. Veihmeyer of the University of California at Davis does, that all soil water is equally available for transpiration up to the stage marked by the onset of wilting. The purpose of well-managed irrigation, of course, is to make sure that plants never get to the wilting stage. For maximum growth irrigation may have to consist of frequent small applications of water rather than occasional large ones.

Given an adequate supply of water, the chain of consequences is simple. There are maximum values for each of several factors: water content in the plant, hydrostatic pressure in the plant and leaf turgidity. When neither the intensity of the light nor the concentration of carbon dioxide constitutes a limiting factor, maximum leaf turgidity permits maximum opening of the stomatal apertures in the leaf surface, thus affording the best possible opportunity for movement of carbon dioxide into the leaf. The state of the stomatal opening that allows easy inflow of carbon dioxide, however, also allows equally easy outflow of water vapor. By far the greater part of the water need of plants is actually a "leakage" process that has to be kept going to ensure continued growth. Given a sufficiently wet soil around the plants' roots, the rate of leakage is dictated not by plant physiology but by the physical factors of temperature, humidity and ventilation. The sole constraint is imposed by the law of energy conservation. In its last stages the transpiration stream undergoes a change of state from liquid to vapor, and the rate of change depends on the rate at which energy can reach the system to supply the necessary latent heat of vaporization.

So much for the physics of the process. When the supply of water in the soil approaches exhaustion, plant physiology rather than physics begins to predominate. Plant type, root structure, phase of



ROLE OF WATER in photosynthesis is quantitatively minor compared with its role in transpiration, as this crop-water graph indicates. To produce 20 fresh-weight tons of crop in a season, some 2,000 tons of water will be drawn from the soil. At the harvest, water in transit will account for some 15 tons of the crop's fresh weight. Drying reduces the crop's weight to five tons. Of these, three tons, or .15 percent of the water used in the season, comprise hydrogen atoms from water molecules, photosynthetically bound to carbon atoms.

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plant development, soil type, soil depth—these become the important factors. What is available for utilization has more significance than the weather has, particularly in semiarid zones.

Because agriculture is most active in the more humid zones of the biosphere, it is useful to estimate how much reserve soil water is available on the average in these zones. Factors already described prevent any exact answer to this question. Nonetheless, a cautious estimate, advanced with considerable reservation, would be about 10 centimeters of rainfall equivalent. Three examples will suffice to show the need for caution. There are large agricultural areas of North Carolina and neighboring states where an inert subsoil is covered by no more than 20 centimeters of useful topsoil. Here the entire water reserve available to the agricultural cycle cannot exceed a rainfall equivalent of five centimeters. This is one extreme; the deep volcanic soils of East Africa are at the other. In those soils the roots of many plants go down as much as six meters below the surface. The available water in a profile that deep is equivalent to nearly 50 centimeters of rain, and the plant can extract water throughout a long dry season at something very close to the potential transpiration rate. An example from France falls somewhere in between. There the drying of the soil was observed while a crop of sugar beet transpired at the full potential rate throughout a dry summer. At the driest stage the crop had withdrawn from the soil available water equivalent to 27 centimeters of rainfall.

Soil water and ground water are closely related, but whereas soil water is always biologically important, the importance of ground water may range from being trivial to being all that matters. The soil is a kind of buffer between rainfall and ground water. In general any deficit in soil moisture that has built up in a dry period must be completely restored by rain before there is any water surplus available to move down to ground water. This is an important consideration for the water engineer, who may be drawing a water supply from a stream (permanent streams are sustained by ground water) or may be tapping an aquifer directly by means of a well. In the first instance the engineer will presumably have to work within legal constraints on how much river water he can divert. In the second, if he is to choose a safe aquifer pumping rate, the engineer must (or should!) have some awareness of the current soil-moisture deficit

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and of the likely rates of rainfall in the months ahead. The river engineer can use the same information for another purpose: the soil-moisture deficit will enable him to estimate the risk of flooding in the event of a heavy storm.

In some countries the control of ground water is a major outlet for engineering skill, and its exploitation is the basis of farming technique. One need only think on the one hand of the Netherlands and on the other of such semiarid regions as Iran, where deep tunnels tap the buried aquifers and carry ground water to valley bottoms. In many semiarid regions the vegetation along transient streams maintains its luxuriance because the ground-water level there is close to the surface and within reach of plant roots. The plants' effective reach depends both on the soil and on the kind of plant, but in general it is seldom more than a few meters. The movement of any water table deeper than that is unaffected by the plant growth or the evaporation processes taking place above it, and its ground water contributes nothing to the biological activity at the surface.

What has been said about water so far has involved terms that are generally accepted, and the concepts themselves are supported by good reasoning, good evidence or both. The remarks that follow, although also based on reasoning and evidence, are more speculative and personal. If the biosphere is taken to be the place where water and energy interact, can the interaction be expressed quantitatively in terms of biological productivity? The answer has to be no. There are too many variables. All the same, by rearranging some of the water quantities and energy quantities that are known, a suggestive relation can be obtained.

Start with the fact that, for a good crop, 1 percent or less of the incoming solar radiation is fixed as dry matter (here and in what follows the 1 percent refers to the total botanical yield, irrespective of economic value). We shall give this percentage the symbol ε, and express it numerically as 100 per 10,000. This degree of efficiency is achieved only by an experiment station or by an extremely competent commercial farmer. Based on the statistics of world cereal production, including straw as well as grain, the average achievement in highly mechanized industrial farming shows an efficiency of only about 35 per 10,000. This decreases to roughly 17 per 10,000 in North America, and in tropical Africa and Asia subsistence farming rarely shows an efficiency better than 8, even when the possibility of two crops per year is allowed for. There is obviously room for improvement everywhere and the question in the present context is: Where does water come in, and how?

Some evidence is now being accumulated suggesting that, when there are no limitations on water supply, the total crop growth is proportional to the total of potential transpiration over the period of growth. The factor of proportionality depends on many things: plant variety, management, kinds and quantities of fertilizer, pest and disease controls and the like. Hence the negative answer to the earlier question. Still, something can be done with ratios. There is reason to believe potential transpiration is a fairly constant fraction of the solar radiation income. Combining this fact with the relation between potential transpiration and total crop growth, it is possible to derive a connection between growth rate and utilization of water, assuming that unlimited water is available (by inference, there would be a similar response to timely irrigation). In what may seem too precise a form, the answer is that the increase in yield (t) equals $.39\varepsilon$. Here ε represents efficiency and t can be read, according to preference, as metric tons per hectare per centimeter of water applied or as tons per acre per inch of water. Considering the fivefold (or perhaps tenfold) world variation in efficiency, some uncertainty in the multiplying factor is unimportant; others may prefer, or find, a different value. Taking the illustration already given, suppose the area involved is one acre and the efficiency is exactly or almost 100 per 10,000. The predicted increase in yield in response to water, *applied when it is needed,* is .39 ton of dry matter per acre per inch of water. In terms of fresh weight the gain is about 1.5 tons per acre per inch. This is the kind of response obtained in experiments with irrigated potatoes in Britain.

There are some countries where the value of ε is small because of lack of water, but there are many, including several of the rice-growing nations, where the small value of ε is more truly a measure of the inefficiency of the farming system itself. To get the most out of water, whether it comes from irrigation or from rainfall, the standard of performance elsewhere in the system must be improved: better varieties, better soil management, better crop husbandry, better plant hygiene and better pest control. Then water may be the driver of nature in agriculture as well as in the atmosphere.

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Problem: lubricate a submarine 3 miles under the sea.

The submarine: *Aluminaut*, Reynolds' $3,000,000 craft designed to plumb the ocean as deep as 15,000 feet.

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Both tend to increase lubricant resistance at great sea depths.

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And after months of testing they proved out one for lubricating the *Aluminaut's* controls.

They also came up with a hydraulic oil for the sub's external dual manipulators (arms) which will perform as well at 15,000 feet down as it has in aircraft 30,000 feet up.

But a submarine without a smooth-closing, tight hatch is about as useful as a parachute made from lace doilies.

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