

EVAPORATION CONTROL

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Richard D. Reidhead, Jr.

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By

Richard D. Reidhead, Jr.

AN ABSTRACT

Submitted to the College of Agriculture of Michigan
State University of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Resource Development

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Approved A. R. Humphreys

ABSTRACT

Increasing demands for water have brought a need for wise management of this resource. Evaporation represents one of the greater losses of water stored in reservoirs. Evaporation controls may, in certain circumstances, be valuable in increasing water supplies.

The purpose of this thesis was to attempt to bring together a review of the literature on evaporation and the various methods of control. Information regarding how evaporation is effected by the different types of control is reported with a subsequent evaluation of each. The strengths and limitations inherent in these techniques are given along with a brief descriptive account of the control itself.

Effective control of evaporation calls for application of knowledge concerning the basic principles of evaporation. Important among these principles are an understanding of the general structure of water molecules and also of the effects of temperature, wind, and water depth on evaporation.

Various control measures were discussed and evaluated. These included controlling evaporation by: (1) construction of reservoirs with maximum average depth, (2) concentration of water into single reservoirs, (3) the use of windbreaks, (4) elimination of shallow water areas, (5) elimination of aquatic and riparian vegetation, (6) roofs and floating covers, (7) storing water in ground water reservoirs, and (8) evaporation control by monomolecular films.

The reduction of evaporation by methods which limit the amount of water surface exposed to the atmosphere offers considerable promise. Considering evaporation losses in management procedures of reservoir systems may in some instances be profitable. Some degree of

evaporation control can be achieved by designing a reservoir having a maximum average depth, thus having a smaller water surface area per unit of volume.

The reduction of wind over reservoirs will help reduce evaporation but little has been done along this line.

Reduction of aquatic and riparian vegetation will lower the amount of water consumed and lost by relatively low value plants. Experimentation is now being carried on in this field but problems involving the elimination or replacement of riparian vegetation at reasonable prices must be solved before the process can be recommended.

Use of roofs and covers must be limited to small areas because of high costs and construction characteristics.

Underground storage has possibilities where physically possible. Many questions still are unsolved in recharging procedures, pollution possibilities and legal ownership of stored waters.

Because of the limitations of these physical methods of control more attention has been recently directed to the use of chemicals capable of suppressing evaporation. The combination of as many of the physical methods of control as are economically possible with chemical control will undoubtedly be considered more often in the future.

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INTRODUCTION

Water--both too much and too little--is an age-old problem of mankind. Obtaining the necessary quantity and quality of water at a desired place and time has been a concern of civilizations both past and present. There is ample record of the need for adequate water supplies. Lack of water has caused mass migration and starvation as far back as ancient Egypt and there is anxiety today throughout our nation over the adequacy of water supplies. In the Western States this is an acute problem where the present use of water approaches the total available supply. Increased use of water is, however, essential for the growth of population and economy.

Modern civilization has imposed a heavy demand upon water supplies. Of the total liquid water available in the world, only 0.01% is fresh water. The other 99.99% is saline and unusable without complex and expensive purification or conversion. In ancient villages, with pastoral or simple societies, the total daily water requirements were perhaps 3 to 5 gallons per person. Today, in homes with running water, the average daily requirements for household and landscape maintenance is in the order of 60 gallons per day.¹ More water is also needed for use by agriculture, municipalities, industry, and recreation.

The increased use of water for agricultural and industrial purposes has been spectacular over the past two decades. By 1975 in the United States, demands for water are expected to be nearly

¹Water, The 1955 Yearbook of Agriculture, United States Department of Agriculture, p. 4.

double those of 1950--400 billion gallons per day. The extent of the water requirement may be judged when it is realized that an acre-foot of water (325,851 gallons, or the amount of water necessary to cover an acre of ground to the depth of 1 foot) is required to produce 2 tons of dried vegetables, 435 bushels of wheat, 1357 pounds of sugar, 5 tons of oranges, 200 pounds of cotton linters, or 200 pounds of beef. Industrially, an acre-foot of water is necessary to produce $4\frac{1}{2}$ tons of paper, 5 tons of steel, 40 tons of sulfur, 15 tons of synthetic rubber, 1635 pounds of rayon, or 650 yards of wool cloth. One butadiene plant in Texas utilizes 308,000,000 gallons, or 94.5 acre-feet of water per day for cooling purposes only.¹

Perhaps the most significant aspect of the situation at the present time is the trend which is indicated. This much is quite clear--demands are increasing rapidly and as of today, water shortages threaten in certain areas.

In several locations in Arizona, for example, demands have increased above the supply. Surface water provides one-third of the supply and ground water the other two-thirds. In some areas, ground water is being used eighteen times as fast as it is replaced. Such a process can have only one result, that of lowering the water table and increasing pumping costs. Unless a method of conservation of existing water supplies is used, or new sources found, the present economy cannot develop without changing to a less consumptive use of water.

Man has engaged in the control of flowing water since history began. For irrigation, municipal supply, power, or flood control--man has recognized the desirability of adequate and dependable

¹Robert R. Cruse, Final Report on the Southwest Cooperative Project on Reservoir Evaporation Control. Southwest Research Institute, San Antonio, Texas, March 18, 1958, p. 2.

water supplies. Man cannot schedule the occurrence and amount of precipitation effectively, but he has long tried to overcome the variation in the supply of water by storage. Water storage has contributed materially to the development of the United States. The successful agricultural economy in the semiarid sections of the West depends largely on storage of a part of the annual water supply for use during the growing season. The growth of our vast industrial centers has been made possible only by adequate year-round water supplies for municipal and industrial use. Industrial development in many sections has paralleled the increase in available power supplies. The retention of flood flows by flood-control reservoirs has contributed materially to the protection of downstream developments.¹

The rapid development of the arid West near the turn of the century was made possible largely by construction of storage reservoirs. In regions where precipitation was insufficient for agriculture, reservoirs were required to hold the spring floods from melting snow and the quick runoff from short, intense summer storms.

Evaporation represents one of the greater losses of water stored in reservoirs. Water and its wise management and use are vital to the economic stability and growth of the western United States. Evaporation from reservoirs, soil surfaces, and plants does not produce income and it should be investigated to determine ways of preventing this loss.

The Lake Hefner Research² reports that over 30 million acre-feet, or more than twice the flow of the Colorado River, is lost by

¹N. O. Thomas, and G. E. Harbeck, Jr., Reservoirs in the United States, U. S. Geol. Survey Water-Supply Paper, 1360A (1956), p. 2.

²U. S. Geological Survey, Water-Loss Investigations, Vol. 1, Lake Hefner Studies: U. S. Geol. Survey Prof. Paper 269, 1954, p. 1.

evaporation and by transpiration from vegetation along water courses in the 17 western states. This would be enough water to irrigate 15,000 square miles of desert, an area nearly half that of the state of New York or Pennsylvania. Evaporation from reservoirs is approximately 15 million acre-feet. Evaporation uses enough water in the western United States to fill several major reservoirs. This amounts to about the combined storage of such major reclamation storage reservoirs as Roosevelt Lake in Arizona, Lake Shasta in California, Elephant Butte in New Mexico, Hungry Horse in Montana, Seminoe in Wyoming, Lake Mohave (Davis) and Havasu Lake (Parker) on the Colorado River. This is about equal to the total usable storage in California according to figures reported in a recent survey.¹

Evaporation takes a large share of all water supplies even before they arrive at the locations where they are used. Water supplies reach the use areas through systems of natural and cultural storage basins and channels, and along these passages evaporation takes a heavy toll. This lost water would otherwise be available for human consumption, municipalities, industries, or for agriculture.

Evaporation is gradual and often escapes notice; yet over a year's time it takes an important part of the supply. For example, the water lost by evaporation throughout the United States exceeds the amount taken for use in cities and towns.²

In the humid portions of the country, evaporation loss is significant although annual precipitation tends to affect it and it is not so noticeable. This evaporation loss ordinarily is not recognized except during rainless periods such as a drought.

¹Thomas and Harbeck, op. cit., pp. 17, 26, 53, 59, and 94.

²E. D. Eaton, Control of Evaporation Losses-Interim Report. Senate Committee on Interior and Insular Affairs, Print No. 1, 85th Cong., 2d Session, April 14, 1958, p. 7.

Since evaporation from bodies of usable fresh water constitutes a severe water loss to western states, where summer rain storms are few, the figures emphasize the importance of research on possible control of this water loss.

This paper is not an original experiment in the true sense of the word, but is an attempt to bring together a review of the literature available on this problem. It is designed to review the material on the structure of the water molecule, the evaporation process and methods of control. Conclusions are drawn from various sources and are included in the research. A bibliography is also attached.

STRUCTURE OF THE WATER MOLECULE

Evaporation is the process by which water is converted to vapor. The exact laws governing this process are not clearly understood. To obtain the best conception of this phenomenon and the laws governing it, it may be desirable first to review the structure of water.

The water molecules are formed of three elemental particles, or atoms, two of hydrogen (H) and one of oxygen (O)--or, expressed as a symbol, H_2O , which is one of the simplest compounds. The three atoms are held together by two chemical bonds, thus: H-O-H. Atoms consist of negative charges, or electrons (e), moving around a central positive nucleus. The number of electrons in an atom is the atomic number of the element in the periodic system of all the elements. Hydrogen is the first of the elements, and thus has one electron. Oxygen has eight. Chemical bonds are formed by pairs of electrons. The chemical bonds in H-O-H are formed by completion of two pairs, the electron of each H atom associating with each of two unpaired electrons from the oxygen atom. Of the remaining six electrons of oxygen, four are much farther from the nucleus than the other two. The eight outer electrons in H_2O tend to form four pairs of electrons that are as far apart as they can be while still attracted to the oxygen nucleus. Thus they are near the corners of a tetrahedron, a solid bounded by four plane sides.¹

The two hydrogen atoms are attached to the oxygen atom by simple covalent bonding in the manner illustrated below.

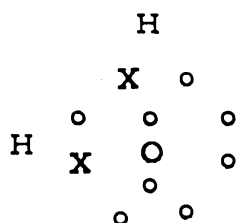


Figure 1. Simple covalent bonding of hydrogen and oxygen atoms.

¹Water, The 1955 Yearbook of Agriculture, op. cit., p. 9.

A further feature of a water molecule is that H attached to O is asymmetrically surrounded by electrons, so that there is a separation of charge or polar character. Because of the strongly electronegative character of the oxygen atom, its nucleus exerts such a strong attractive force on the hydrogen electrons that they are drawn out of their normal position in relation to the hydrogen nucleus. Also, the two hydrogen atoms are bonded to the oxygen atom at an angle of 105° rather than being set in a straight line. As a result of these two factors, a dipole is formed in which the hydrogen end has a positive polarity, while the oxygen end is negative, as illustrated below.¹

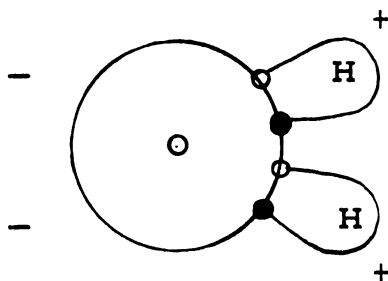


Figure 2. A dipole of hydrogen positive polarity and oxygen negative.

Because the hydrogen electrons are drawn so far out of their normal position, the hydrogen nucleus behaves somewhat like a proton; it may share two electrons with the oxygen atom of an adjacent H_2O molecule, forming what is referred to as a hydrogen bonding. If other molecules with non-binding outer electrons are present, there is a tendency for H to increase the symmetry of its surroundings by approaching a pair of electrons in line with its chemical bond to oxygen, or $2e\text{-H-O}$ in a line. The resulting attraction, in case the $2e$ are on another water molecule,

¹C. R. Sorum, Fundamentals of General Chemistry, (New York: Prentice-Hall, Inc., 1955), p. 192.

is about 6 percent as great as that of the H-O bond.

The properties of water arise from the hydrogen bonding and the tetrahedral arrangement of electron pairs around the oxygen atom.

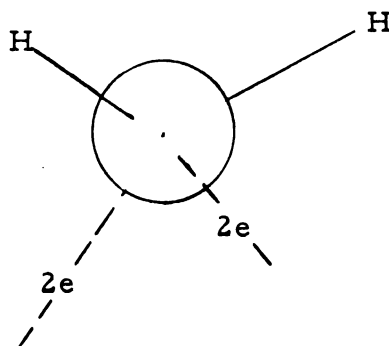


Figure 3. Hydrogen bonding and the tetrahedral arrangement of electron pairs around the oxygen atom.

In the above diagram of the water molecule, the dotted lines illustrate the hydrogen-bonding tendency arising from the diffuse cloud of electrons in the direction of the dotted lines. Several molecules held together by hydrogen bond, as in solid or liquid water, form an assembly of tetrahedral groups; each molecule is bonded to four other molecules.¹

The principles of bonding give the background required in explanation for the properties of water. The properties can be divided into two classes, depending on whether chemical bonds between the H and O atoms are broken, leaving the H₂O molecules intact.

Chemical changes like the rusting of iron are of the first class, in which chemical bonds are broken. Physical changes such as evaporation from a lake are of the second class.

A simple property, a physical one, to consider as a first subject is that water when heated evaporates very slowly as compared with other liquids that have simple molecules. In other words,

¹Water, The 1955 Yearbook of Agriculture, op. cit., p. 9.

the heat of vaporization is high. Vaporization is just the separation of molecules from a liquid to the gas or vapor phase by the attraction between molecules. This transition is the inverse of condensation. The high heat of vaporization is a direct result of the strength of the hydrogen bonding between molecules.¹

The knowledge of the structure of water is important for a fundamental understanding of the process of evaporation. Only with this basic understanding can we effectively approach the subject of evaporation control. (See illustration 4 and 5.) The following figures are not pictured according to scale but do illustrate certain basic relationships.

¹Ibid., p. 10.

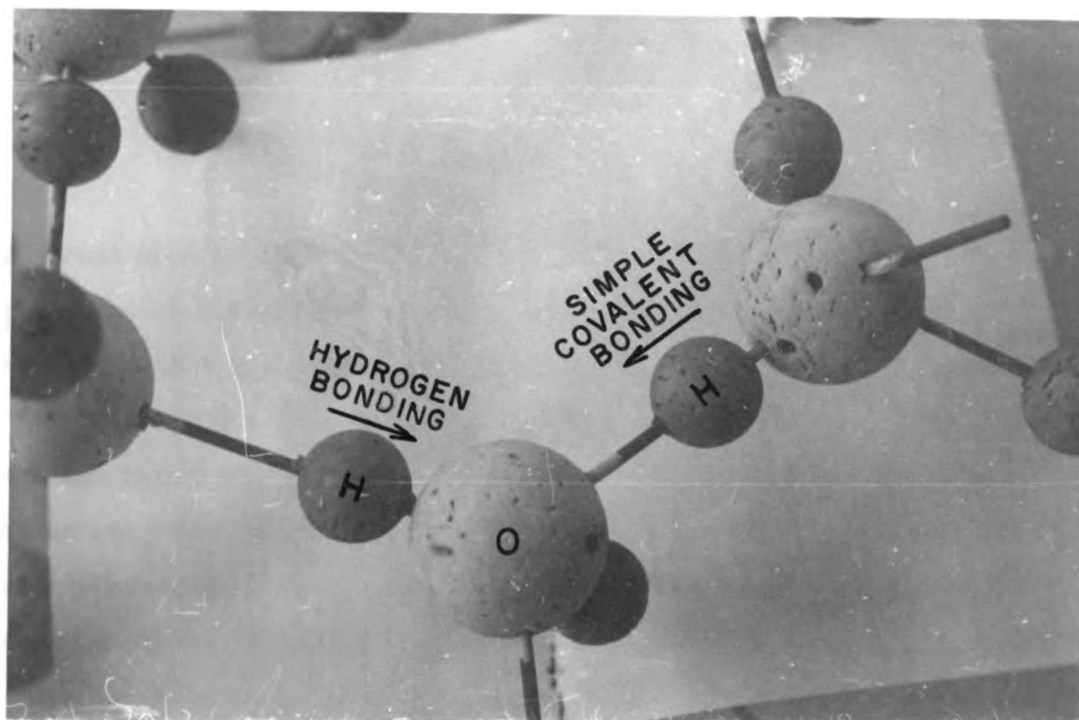


Figure 4. INDIVIDUAL WATER MOLECULE

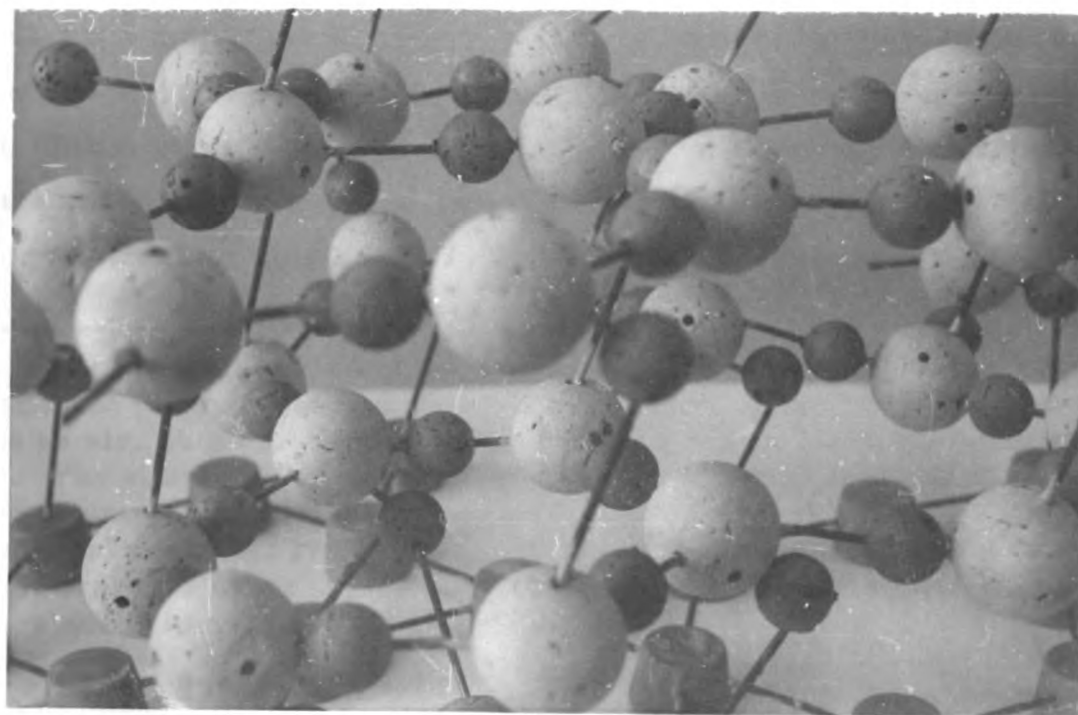


Figure 5. AN ARRAY OF WATER MOLECULES (SIDE VIEW)

EVAPORATION OF WATER

Molecular Approach to Evaporation

A great deal of light could be shed on the processes taking place in evaporation by considering the question from a molecular approach. Suppose we could equip ourselves with supermicroscopic eyes with which to see the detailed structures of gases, liquids, and solids. It is believed that there are trillions of individual molecules of H_2O moving about in an ounce of water. We assume that a very large number of molecules are present in a small volume and that these have considerable freedom of motion. If we could watch one particular molecule we should see it moving about in all directions, now sideways, now up, and now down. The individual molecules do not all move with the same velocity. The average velocity of all the molecules comprising any given mass determines its temperature.

Looking first at a gas, a liter of steam¹ for example, we would observe some molecules moving a little faster than others and some moving a little slower but the bulk of them would be moving at about the same speed. In the vapor or gas phase, the molecules are widely separated; they are endowed with high velocities; and they experience frequent collisions with their neighbors.²

¹Steam is the most common example of a vapor, but what one sees issuing from the spout of a teakettle is not steam. Steam is just as invisible as air. A glass teakettle shows nothing inside above the boiling water. The visible cloud at the spout consists of small droplets of condensed steam vapor in which the molecules are no longer in the vapor (or gaseous) phase but are in the liquid phase. The molecules of a vapor are relatively far apart as in a gas, but steam vapor can be easily liquified again, since it is near its condensation point.

²Sorum, op. cit., p. 32.

If we were to heat the steam we would observe that the molecules move faster, if we cool it they move slower. As we cool the steam the molecules move slower and slower. Finally, at 100°C (212°F) we observe that groups of the slowest molecules get together and condense to form drops of liquid water. Within the drop of liquid the H_2O molecules move about continuously. If the cooling is continued the steam is all condensed. If we continue cooling the liquid water we observe that the motion of the H_2O molecules become more sluggish. Finally, at 0°C (32°F) groups of H_2O molecules are observed to orient themselves into definite, rigid masses of ice crystals. If the cooling is continued, the entire mass of liquid water is changed into a solid mass of ice.¹

The molecules that make up the water on the earth's surface and the water vapor in the atmosphere are in ceaseless motion. Some of the molecules of a liquid acquire sufficient momentum to break through the surface and escape into the free air. At the same time some of the molecules of water vapor in the air strike the water surface and are unable to leave it. Strictly speaking, the movement of molecules from water to air is evaporation and the reverse movement is condensation.

A volume is said to be saturated with vapor if no more vapor can be introduced without producing some condensation. Consider a dish of water covered by a large jar. This body of water is exposed in the enclosed vessel. Only a small amount of liquid will change to vapor, regardless of the water temperature, even though the space above the water was originally completely dry. Although the molecules of water vapor entering the space above the water surface are confined by the walls of the vessel, at first there are so few that the number returning to the liquid are limited. Hence, the number of molecules in the enclosed space

¹Ibid.

increases rapidly. With an increase in the concentration of water vapor, there is an increase in the rate of return of the molecules to the liquid. Eventually, the vapor concentration becomes so great that as many molecules return to the water as leave it. At this time equilibrium between the liquid and its vapor is attained, and the rate of evaporation is then equal to the rate of condensation.

If water is placed in an open dish out in the open air it will gradually disappear. An examination will reveal that the molecules of liquid have passed into the air where they exist in the form of gas molecules.

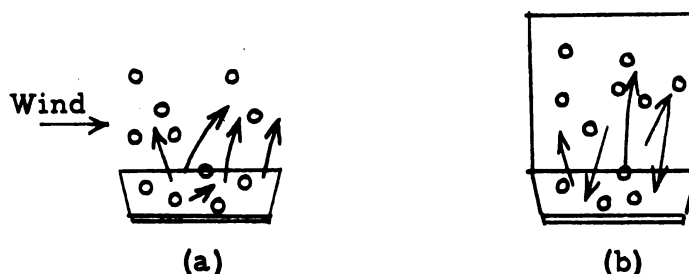


Figure 6. Water in open dish (a) continues to evaporate until all the water is lost. Water in covered dish (b) evaporates until space above is saturated. Then as many molecules fall back into water per second as evaporate.¹

As the temperature increases, the rate of evaporation increases. When the temperature of a saturated volume is lowered, sufficient condensation takes place to establish a new equilibrium state. At the lower temperature, fewer molecules per cubic centimeter are required to produce saturation. On a cold winter day the atmosphere can hold little moisture. On a hot summer day it can hold a great deal more. This means that the higher the temperature, the greater is the vapor density required for saturation. Water continues to evaporate until the atmosphere is saturated for that temperature.

¹Ibid., p. 270.

The amount of water vapor in the air is an important consideration for many scientific purposes as well as for our own comfort. At 30°C (86°F) a cubic meter of saturated water vapor weighs 30 gm. Other values for the amount of water vapor at given temperatures are given in the table¹ below.

TABLE I

MAXIMUM MOISTURE POSSIBLE AT ANY GIVEN TEMPERATURE

$^{\circ}\text{C}$	$^{\circ}\text{F}$	Grams per Cubic Meter
-10	+14	2.1
0	32	4.8
10	50	9.3
20	68	19.1
30	86	30.0

A room of moderate size may easily contain 10 lbs. of water vapor on a hot day. Whether saturated or not, the actual amount of water vapor the air contains is called the absolute humidity. Absolute humidity is defined as the mass of water vapor in the air per unit volume.

On the other hand, relative humidity is defined as the extent to which atmospheric air is saturated with water vapor it could contain per unit volume if saturated at that temperature. Suppose the volume contains one-half the amount of the water vapor that it could contain at a given temperature if it were saturated. The relative humidity is then 50 percent. If it contains one-tenth what it could at saturation, the relative humidity is 10 percent, which it may be in a desert if the air is dry and readily takes up the moisture by the process of evaporation.

¹Ibid., p. 271.

If the humidity is 95 percent and the weather hot, the air is nearly saturated with water and though the process of evaporation is in effect the air around does not absorb moisture as readily. In other words, atmosphere with low humidity will absorb more water by evaporation than under similar conditions with high humidity. Also, the rate of evaporation from a free water surface is usually lower at night than in daytime. The reduction is principally due to the lower night temperature of the air and the resulting increase in relative humidity.

If the humidity is 100 percent the air is saturated with water vapor and the vapor will condense at the slightest lowering of the temperature. If the air is not saturated at a given temperature, a reduction of the temperature will bring it to the point where it is saturated. Further cooling will exceed this saturation point, and moisture will then condense as fog, clouds, or dew on the surface of the earth. When air is saturated with water vapor it is said to be at the dew point, this being the temperature below which further cooling will produce condensation of dew.

Surface Tension of Water

Water particles are attracted to each other. We call this property cohesion. It also is attracted to some surfaces. This is adhesion. The strengths of both cohesion and adhesion in water, of course, are due chiefly to hydrogen bonding.

First let us consider adhesion, the property of adherence to other substances. The wetting of glass--important in the action of a windshield wiper--arises from the formation of hydrogen bonds between the oxygen atoms, which are part of the structure surface of the glass, and the hydrogen atoms of the H_2O molecules.

The principle of cohesion is adequately explained in the following passage.

The forces of cohesion--the tendency of water to stick to itself--between the molecules of a liquid give rise to the phenomenon of surface tension. Because of these forces, the surface of a liquid behaves as if a thin skin were under a state of tension such as to make it tend to contract. However, the tension does not depend on the distance the film is stretched. The measurement of surface tension is defined as the force of contraction acting across an imaginary line of unit length on the surface of a liquid. It is also the force required to break a surface film of unit width. Surface tension is usually measured in dynes per centimeter.¹

Different values of surface tension exist at different temperatures and for various substances as indicated by the table below.

TABLE II²
VALUES OF SURFACE TENSION

Liquid	T (dynes/cm)
Water 15°C	73.5
Water at 80°C	62.6
Alcohol	24.0

The existence of surface tension can easily be demonstrated. If a needle coated with oil (so that the water does not creep up it's sides) is laid gently on water, it will float in spite of the fact that steel is seven times more dense than water. The surface is depressed enough so that the resultant upward force is equal to the weight of the needle. If the needle is heavy enough to break through the surface film, the needle sinks.

¹Rogers D. Rusk, Introduction to College Physics, (New York: Appleton-Century-Crafts, 1954), p. 197.

²Ibid., p. 198.

In other words, a force is required to pull water apart and create two new surfaces. The force, in a sense is opposed by a tension, and this surface tension of water is much higher than that of other liquids because of the hydrogen bonding.

The surface molecules of a liquid are in a state of equilibrium different from those beneath the surface. The latter are surrounded by neighbors on all sides and are pulled equally in all directions as they move about.

For molecules on the surface, there are no upward forces of molecular attraction above them. This causes them to crowd down upon their neighbors below until equilibrium is established. The state of equilibrium of the surface molecules is one in which they are under a kind of pressure which increases their energy in somewhat the same manner that the energy of a spring is increased when it is compressed. To raise a molecule from beneath the surface to a position in the surface film, work must be done on it. Hence, surface molecules are in a higher energy state.¹

Effect of Temperature on Evaporation

As the temperature of a substance increases, the movement of the molecules increases. In a liquid the molecules are darting about, colliding with their neighbors, and sometimes striking the surface of the liquid. If they strike the free surface of the liquid, they may pass on through and escape into outer space, provided they have sufficient speed to overcome the surface attraction.

The rate at which molecules leave a water surface depends solely on the characteristics of the water. Since an increase in its molecular energy indicates a rise in the temperature of the water, the rate at

¹Ibid., p. 200.

which molecules break away from the water surface depends on its temperature.

Since the more rapidly moving molecules are more likely to escape, those that are left are on the average slower moving, possessing less energy and hence, represent a lower temperature. Thus, the remaining liquid is cooler. The cooling due to evaporation can be illustrated in several ways. One of the most common is the method of keeping water cool by placing it in a canvas water bag. The evaporation which takes place causes a reduction of temperature in the water remaining in the bag.

The second result which may be deduced from the molecular theory is that the change of state from liquid to vapor is associated with a definite amount of heat--the so-called latent heat of evaporation. In order to prevent the cooling of the liquid and to maintain its temperature constant, heat would have to be supplied in some way and the amount of heat required would correspond to the amount of vapor formed.

Effect of Wind on Evaporation

Molecules move away from the vicinity of an evaporating surface by the ordinary phenomenon of diffusion. Evaporation by molecular diffusion is an extremely slow process and in the absence of air motion a thin layer of air, the thickness of which is usually measured in millimeters, becomes saturated with water vapor. If this is not removed the molecules from this thin layer of air and the surface layer of the water will interchange with very little water vapor escaping to higher atmosphere. Wind action greatly speeds up the evaporation process by removing this water vapor immediately above the surface and replacing it with air which may have a different temperature or moisture content, usually a dryer air.

The transfer of moisture is accomplished through the irregular or turbulent mixing of the lower air, by which bodies of the moister air from near the surface of the lake are carried upward and replaced by drier bodies brought down from above in the process of turbulent mixing. Actually, the phenomenon of turbulent transfer in the atmosphere is by far the most effective factor in carrying water molecules away from an evaporating surface. Transfer by turbulent mixing is usually at least 25, 000 times as effective as molecular diffusion, and it may be considered almost wholly responsible for any loss of moisture from an evaporating surface freely exposed to the air.¹

The movement of smoke demonstrates plainly the mixing of the air that takes place in the turbulent layer. Where a visible gas, having approximately the same density as the air, is released the effect of turbulent mixing is apparent.

The effect of wind velocity on the evaporation of moisture appears to be primarily its effect in removing the vapor which forms more rapidly over the water surface than can diffuse through the atmosphere above.

The Influence of Water Depth on Evaporation

Evaporation from a lake is affected by the surface water temperatures. These are intimately related to the temperature of the entire body of water, and this depends largely upon the lake depth. The depth has a very pronounced influence upon the rate of evaporation from any large body of water. The explanation of this phenomenon can be found in a comparison of the cycle of events that occurs in a shallow lake with that which occurs in a deep lake.

¹C. W. Thornthwaite and Benjamin Holzman, Measurement of Evaporation from Land and Water Surfaces, U. S. Department of Agriculture, Technical Bulletin No. 817, May 1942, p. 10.

In late winter or early spring the temperature of an entire body of shallow water will be at or near 32°F . As heat received from the sun increases the surface water temperature the weight of this water increases and the warmer water sinks to the bottom. The colder but lighter water rises to the surface where it in turn is warmed to a higher temperature and greater density, and the turnover process is repeated. This continues until the temperature corresponding to the maximum density of water (39.2°F) is reached. From then on, as the surface becomes warmer it also becomes lighter and therefore remains on the surface. The water below the surface heats more slowly by direct radiation and conduction, and by mechanical mixing produced by currents and wave action. Before long the shallow water is soon heated to a temperature closely resembling the temperature of the surrounding air. This means that during the warmer parts of the year a shallow lake will be subject to high evaporation losses.¹

In the fall, the overturning process is repeated in reverse. When the average air temperatures become lower the surface water also becomes cooler and heavier sinking to the bottom, with the warmer water at the bottom rising to the surface. This continues until the entire body of water has a temperature of 39.2°F . After that, as the surface water further cools it becomes lighter and remains on the surface. This explains why, for a given reduction in air temperature, the surface water temperature will drop much more quickly from 39°F to 32°F than from 46°F to 39°F .²

Consider now a deep body of water. Either in spring or in fall, after the temperature of the entire mass has reached 39.2° , further changes resulting from radiation, conduction, and mixing are slow and extend only to a limited depth. Below 200 ft. the temperature remains at or near 40° throughout the

¹C. O. Wisler and F. Brater, Hydrology, (New York: John Wiley and Sons, Inc., 1949), p. 145.

²Ibid., p. 146.

year. However, the amount of heat that is required to raise the temperature of a large mass of water from 39.2° to the temperature which it attains by autumn is enormous, and as a result there is a considerable lag between the temperature of the water and that of the air. The temperature of the water is lower than the air temperature in summer and higher in winter, whereas in shallow bodies of water the mean daily temperatures of the air and water do not differ so greatly.¹

This lag in the temperature of the water in deep lakes behind the temperature of the air above exerts an important influence on the rate of evaporation from lakes. This reduces summer evaporation below and increases the winter evaporation above the observed rates on shallow lakes.

¹Ibid.

EVAPORATION CONTROLS

There are a wide variety of recommendations about the ways in which evaporation could be controlled. This paper will cover several techniques or methods of reducing evaporation. I now will review some of the elementary facts concerning water resources.

First, there is no evidence of any substantial change in the sum total amount of water available on the average, over the years. We as a nation are wasting vast amounts of water. In a number of individual areas throughout the United States, the supply of water is most certainly becoming scarce and the ground water table is being lowered. In such cases further development in municipal growth, in industrial growth, and in population growth will depend upon the economic supply of available water.

There is ample evidence that our total use or consumption of water is increasing steadily and will probably continue to increase. The desirability of reducing evaporation losses in the western states has received much attention in recent years because of the increasing demand for water and the decrease in the supply available due to recent droughts. The increase in demand for water is attributable to many factors, among which the most important are: (1) the rapid growth in population in the far western states since the beginning of World War II, (2) the upsurge in industrial activity in the West, (3) the increase in the acreage of irrigated lands, and (4) the increase in the per capita use of water resulting from a higher standard of living.¹ High evaporation loss in relation to amount used is characteristic of the West. This is the result of the

¹G. Earl Harbeck, Jr., Can Evaporation Losses be Reduced? Proc. Am. Soc. Civil Eng., 84, IRI (1958), p. 1.

climate and the character of the streamflow. The great seasonal variations in streamflow that are common in the West result from extensive surface water being exposed.

Storage reservoirs are a principal means of governing the streamflow in order to increase usable water yield. Reservoirs, however, expose extensive surfaces to evaporation, and thus they are a major cause of water loss. This is true even though reservoirs may lessen natural evaporation by confining floods in deep pools instead of being spread over wide flood plains. The shallowness of some reservoirs together with the extended periods of holdover, increases the evaporation losses of river systems. The net result of reservoir operation is, of course, advantageous in conserving water that would otherwise not be usable.¹

The methods of evaporation control discussed in this paper are:²

1. Construction of Reservoirs with Maximum Average Depth
2. Concentration of Water into Single Reservoirs
3. Windbreaks
4. Elimination of Shallow Water Areas
5. Elimination of Aquatic and Riparian Vegetation
6. Roofs and Floating Covers
7. Storing Water in Ground Water Reservoirs
8. Evaporation Control by Monomolecular Films

¹Eaton, Control of Evaporation Losses-Interim Report, op. cit., p. 12.

²S. W. Freese, "Reservoir Evaporation Control by Other Techniques," First International Conference on Reservoir Evaporation Control, (San Antonio, Texas: Southwest Research Institute, April 14, 1956), p. 45.

S. W. Freese is probably one of the outstanding authorities on reservoir evaporation control. Many thoughts and ideas utilized in this paper on the various methods of evaporation control, with exception of information about monomolecular films, comes from his above cited report.

Construction of Reservoirs with Maximum
Average Depth

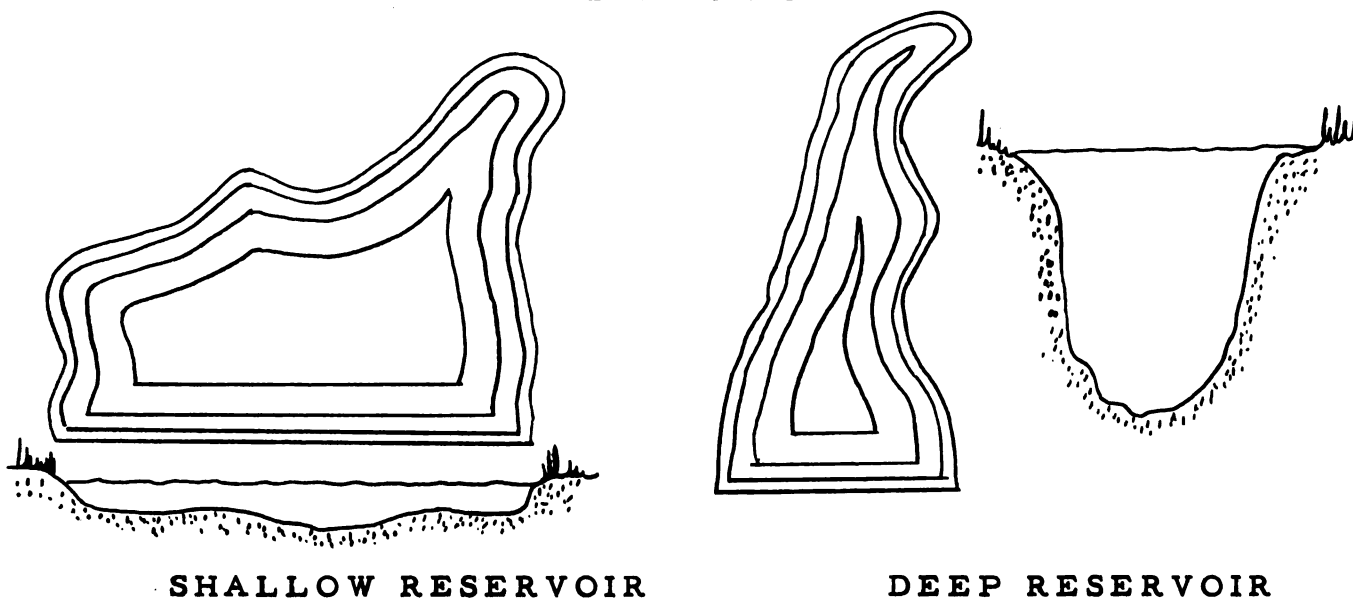


Figure 7. Shallow Reservoir and Deep Reservoir.

Many methods of reducing evaporation losses from reservoirs are known. Project planners and designers are well aware of the desirability of a reservoir having a minimum of surface area for a specified capacity. Evaporation losses are held to a minimum by exposing the least possible water surface area. This means that streams and reservoirs are kept deep and limited in width. Familiar examples are stream channel improvements that permit the water to move at relatively high velocity through a confined channel instead of meandering slowly over a wide stream bed. An even more general practice is to use deep narrow canyons for reservoirs.

A small increase in height in a dam may result in a relatively large increase in storage capacity, but if the surface area is increased disproportionately thereby, a net loss in water may result because of the greatly increased evaporation loss. Evaporation loss is only one of

many factors to be considered in designing a dam and reservoir, and other considerations may dictate a compromise.

There are limitations also on the opportunities for management of surface reservoirs to hold storage at maximum depths, although this method is widely and successfully practiced. There are only relatively few deep, narrow reservoir sites at suitable locations, with acceptable geology, and not pre-empted by railways, highways, and other essential developments. Another limitation of the canyon type sites is that it does not provide adequate capacity in the canyon section. In practice, reservoir operation must contemplate a substantial amount of water to be stored at relatively shallow depths with correspondingly large water exposure.¹

Often, there is little choice as to available reservoir sites on a particular stream. Either there is only one site meeting the various needs of the case or several possible sites having about the same area-capacity characteristics. Where there is a choice of sites from the standpoint of average depth, the difference in evaporation losses should certainly be evaluated.

Freese² cites a comparison of two reservoirs in West Texas, each with about 60,000 acre-feet capacity, and located only 30 miles apart. At the 60,000 acre-foot point, one reservoir has an area of 5300 acres and an average depth of 11.3 feet whereas the other reservoir has an area of only 3580 acres and an average depth of 16.8 feet. At an average operating capacity of 40,000 acre-feet, the difference in surface areas between the two lakes is 1275 acres. The average net evaporation (that is, after rainfall) in this particular area of West Texas is about four feet per year. The difference in evaporation between the two lakes is,

¹Eaton, op. cit., p. 15.

²Freese, op. cit., pp. 45-46.

therefore, approximately 5,100 acre-feet per year or 405 million gallons per day.

Fortunately, the city which has a lake with less favorable area-capacity characteristics has ample water and there is no need within the foreseeable future, for more water than is now available. Under these circumstances, it is difficult to place a value on the water lost by reason of the unfavorable average depth. At a cost of \$.05 per 1000 gallons, an acceptable figure for water from a lake in West Texas, the loss amounts to \$82,000 per year.

It is possible to figure more accurately the saving to the city which has a lake with the more favorable area-capacity characteristics. In this case, the city is confronted with the necessity of securing an additional water supply and the water will cost \$.10 per 1000 gallons delivered into the lake under consideration. The saving to the city by reason of the more favorable evaporation characteristics, is \$164,000 per year.

A deep reservoir with a limited amount of surface area will thus evaporate less than an equal amount of water stored in a shallow reservoir which has a large water surface area.

Concentration of Water into Single Reservoirs

Water concentrated within a large reservoir usually has a great advantage over storing in several smaller and shallower storage basins. The advantage being that water from several storage areas may be gathered together increasing the depth and decreasing the total area covered by the water.

More energy from the sun is required to evaporate water from a deep reservoir as compared with a shallow storage reservoir.

The reduction in surface area exposed to the evaporation process also reduces evaporation. Reducing evaporation losses by this method may be accomplished by diverting water from one watershed into a single reservoir on another watershed or by operating a reservoir system on the same drainage basin in order to concentrate the water into a lower reservoir.

Operational procedures will in some measure reduce evaporation losses from stored bodies of water. When a reservoir is kept empty at all times losses due to evaporation are at an absolute minimum. This, of course, defeats the purpose of constructing the reservoir, which was to store water for controlled release. An operational schedule consisting of a full reservoir in the winter when evaporation is low and empty reservoirs in the summer when losses are high would reduce the amount of water evaporation from the lake. Unfortunately, this type of scheme is generally not practicable, especially in the West, where much of the runoff occurs in the spring as a result of the melting mountain snowpack. In many instances, control of evaporation by this process must first consider the water requirements of important water users such as municipalities, irrigators, industries, and power companies.¹

An example of diverting water from one watershed into another in order to concentrate the amount storable in one reservoir is given by Freese.² He states that water in two watersheds could be combined into one reservoir. The normal 2/3 capacity operating level of two Texas lakes on different watersheds, have a combined water surface area of 7,450 acres. This water could be stored in one reservoir with

¹Harbeck, op. cit., p. 2.

²Freese, op. cit., p. 47.

a total water surface area of 5,800 acres, with a reduction of 1,650 acres less of exposed water. The net evaporation that prevails in that part of the country is approximately 4.5 feet per year. Using the figure already used of water valued at \$.05 per 1000 gallons the saving resulting from the use of one reservoir instead of two, amounts to \$120,000 per year.

Windbreaks

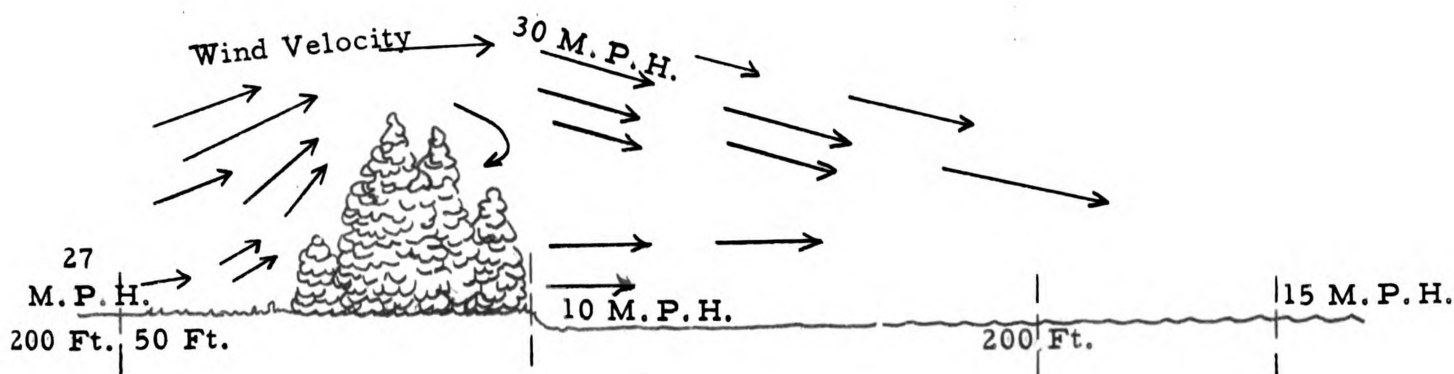


Figure 8. Effect of tree plantings on wind-velocity.¹

The effect of air movement on evaporation has been given a widely different value by various writers. I feel that a reduction in wind velocity over a reservoir will reduce evaporation, although wind above some limiting velocity, perhaps 25 miles per hour, may have no additional effect on evaporation. For winds sufficiently strong to remove all vapor as rapidly as it may be formed, additional wind velocity may produce no further effect. Of course, such a limiting velocity may vary

¹Conservation Soil and Water for the Public Schools, State of North Dakota 1948, Issued by Department of Public Instruction, Garfield B. Nordrum, Superintendent, p. 70.

with other factors affecting evaporation. Below the limit where additional wind cannot remove more water vapor, a correction factor may be applied. In this range of wind velocity any reduction in wind speed would also decrease the amount of evaporation.¹

Although many reservoirs already have windbreaks around them it is very difficult to evaluate the benefits of wind protection. There seems to be a lack of experimental data on the effect of windbreaks on reservoir evaporation.

Windbreaks act as barriers to reduce wind currents. The tree windbreak as shown in illustration (8) will reduce wind currents to a practical degree for a distance of about 20 times the height of the trees. Thus, a windbreak 30 feet high would slow down wind velocity to a distance of 600 feet. This would result in some reduction of evaporation losses.

A windbreak should be constructed to accommodate the water area and wind direction. Windbreak plantings would also increase the amount of moisture lost by transpiration. New experimental data would be needed to determine the net saving of water.

An additional advantage of a windbreak may be in improving the multipurpose use of a reservoir in protecting small game or by creating shade for recreation.

Elimination of Shallow Water Areas

Reducing the surface area to a minimum is another method of lowering reservoir evaporation. This is quite important especially in the arid West, where losses may represent an appreciable part of the available water supply. In the Southwest, evaporation losses may

¹Adolph F. Meyer, Elements of Hydrology, (New York: John Wiley and Sons, Inc., 1928), p. 195.

average as high as 72 inches per year, equivalent to 6 acre-feet of water for each acre of pond area and generally about half of this loss will occur in the four summer months of May to August, inclusive. For such regions, it is evident that reservoirs having the greatest possible mean depth and least surface area will be the most efficient for storage purposes.

In some places evaporation may set a limit on the extent to which a proposed reservoir might be raised in capacity without an increase in evaporation greater than the intended gain in water supply. Lake Worth in Texas was built with substantial shallow water and swampy areas at the upper end. A study was conducted of Lake Worth for the purpose of eliminating, within economic limits, the shallow water areas and the water vegetation in order to reduce evaporation and transpiration from the lake.

It was found that by regulating the flow of water from Lake Eagle Mountain which is above Lake Worth, a saving in evaporation could be obtained. A reduction in the normal Lake Worth operating level by 4 feet reduced the water surface area approximately 700 acres. With a net evaporation from the lake of 3 feet per year, at a cost of \$.05 per 1000 gallons the saving, due to the elimination of 700 acres of evaporation surface, amounts to \$34,000 per year.¹

Freese also states that two to three feet is considered the minimum depth above the normal water level deemed necessary to control the growth of willows and swamp land vegetation. With an evaporation rate of 4 feet per year, the value of water at \$.05 per 1000 gallons and the cost of fill being \$.25 per cubic yard, one could be able to economically add earthen fill from a depth of .72 feet below normal water level to

¹Freese, op. cit., p. 48.

2½ feet above normal water level. The value of the water saved from this method of control of evaporation would pay for the cost of fill in 20 years.

Elimination of Aquatic and Riparian¹ Vegetation

Reservoir evaporation control is closely tied to the control of transpiration by lake vegetation. A short section on the reduction of non-beneficial consumption of water by aquatic and riparian vegetation is required. It is a well-known fact that water associated vegetation such as water lilies, cattails, and riparian phreatophytes (salt cedar, willows and cottonwoods) use and transpire large quantities of water each year. The amount would depend on the type of plant and the conditions under which it is grown. A conservative estimate of three to five feet of water is transpired by each acre of water-loving plants and produces little economic value.

Techniques of clearing and removing vegetation from shallow water and swamps are being perfected, and continuing research promises further improvements. The high costs involved and the general need for repeated treatment is still a major problem.

The elimination of shallow areas as already discussed would change the environment so that many water plants could not flourish, thus saving valuable water.

Roofs and Floating Covers

City waterworks use concrete and steel roofed tanks throughout the country. True, this is not for the prime purpose of preventing

¹Riparian vegetation is plant growth on the shores of a lake or stream.

evaporation losses but to protect the quality of the enclosed water. A roof over water does prevent some evaporation because of lower water temperatures and reduced action of wind.

A concrete roof to cover a large tank is estimated to cost two dollars per square foot or \$87,000 per acre. Using seven per cent per year rate of interest, amortization, and maintenance, the annual cost would be \$6,000 per acre of roof. This is beyond the most marketable value of saved evaporation water. Assuming that a roof would eliminate four acre feet of water per year, water being valued at \$.15 per 1000 gallons due to its purity and possible domestic market, the value of the water lost when compared with an uncovered tank would be less than \$200 per year per acre of water surface. This amount compared with the annual cost of a roof is certainly uneconomical for a large reservoir.¹

Floating covers could also limit the evaporation process. For example, a plastic sheet may be stretched over a small area to reduce the evaporation. Cost and maintenance would probably limit this method of control to experimental stages for sometime.

Storing Water in Ground Water Reservoirs

The term ground water reservoir is commonly used as that area of water bearing material or aquifer beneath the root zone of plants. Water at this depth is affected very little if any, by the process of evaporation. However, large amounts of ground water are being removed by pumping especially in areas where surface waters do not satisfy the needs of municipal, industrial, and irrigation users.

¹Water, The 1955 Yearbook of Agriculture, op. cit., p. 63.

The selection of ground water as a supply, rather than the surface water sources, has generally been on the basis of one or more of the following advantages:

1. Ground water may be reached within a few hundred feet of the place where it is to be used, and on the same property, whereas surface water may require pipelines and right-of-way over stretches of several miles.
2. Ground water may be available for use in areas where the water in streams and lakes has already been appropriated by other users.
3. Yield from wells and springs generally fluctuates less than streamflow in alternating wet and dry periods.
4. Ground water is more uniform in temperature and soluble mineral load than surface water, and is generally free of turbidity and bacterial pollution.¹

Pumping usually reduces the depth of the ground water much faster than it is supplied by the natural process of nature. This leaves large areas which are capable of storing surface water. These areas are larger in many cases than existing surface reservoirs. There are also other underground spaces where water could be stored, as in certain limestone formations.

Artificial recharge or depositing water in subsurface storage basins has had various degrees of success. Failure to understand the location of suitable storage formations and the movements of ground water has led some to disappointment.

High quality water must be used for recharging ground water aquifers in order to protect future users. There are also legal problems concerning the withdrawal of water stored underground. New legislation must be enacted or the underground storage basin confined to the use of persons authorized to make withdrawals.

¹Freese, op. cit., pp. 50-51.

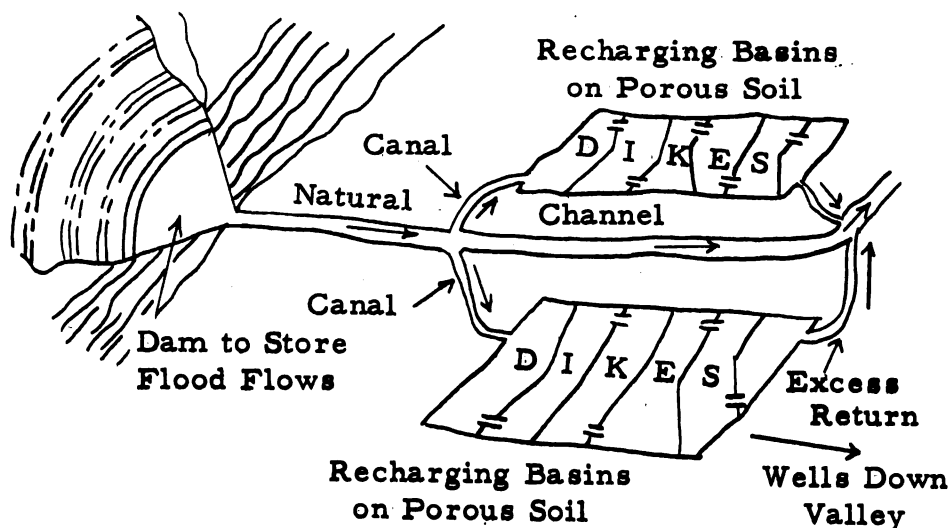


Figure 9. Methods of recharge.¹

Methods which induce the water to infiltrate through the soil into the waterbearing formations are the basin, furrow, and shaft or pit process. The water is diverted to a place suitable for recharging and allowed to infiltrate into the soil. Exposing shallow water over a large area allows for considerable water loss by evaporation. But with new technological methods it is certain that more water on the infiltration bed will reach the ground water aquifer.

Another method is the injection well method. This is a special well designed and adapted for injecting water. This is very effective if impermeable strata or layers exist between the surface of the land and the water bearing formation. It is also useful if land is too valuable to set aside a large tract for surface methods of recharging. The amount of water injected into the aquifer is limited by the opening of the well

¹Dean C. Muckel, Replanishing Underground Water Supplies on the Farm, Soil and Water Conservation Research Division of Agricultural Research Service, U. S. Department of Agriculture, Leaflet No. 452, September, 1959, p. 3.

and much care must be taken to prevent pollution and siltation. As the number of available sites for large surface reservoirs decrease, more attention will be given to the use of underground storage.

The cost of spreading water for recharging the ground water varies. One rocky area absorbed 10 to 100 cubic feet per second of base flow for about 85 cents per acre-foot. The San Gabriel River Basin was recharged using a canal and basin system. The cost varied from \$3.25 to \$5.25 per acre-foot for annual operation and maintenance plus an average annual capital expense of \$2.00 per acre-foot. Experience in Los Angeles County indicates rates of infiltration may vary from 1.5 to 10.0 acre-feet per acre per day. This is cheap storage, because frequently in Southern California ground water has a value of \$35 to \$40 per acre-foot.¹

Freese² believes that a city could economically afford to spend about \$.01 per 1000 gallons to filter, chlorinate, and recharge by gravity underground aquifers. This would be feasible if a city were losing 25% to 33% of its stored water by evaporation and this evaporation water could be saved by recharging ground water aquifers.

¹George D. Clyde, "Utilization of Natural Underground Water Storage Reservoirs," Journal of Soil and Water Conservation, January, 1951, p. 15.

²Freese, op. cit., p. 50.

Evaporation Control by Monomolecular Films

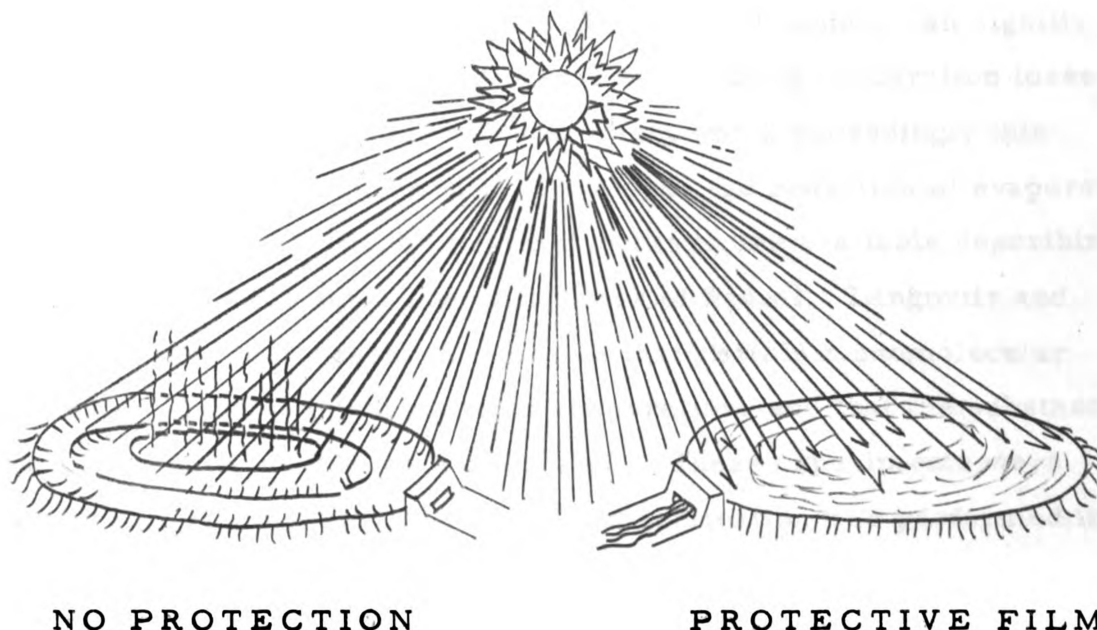


Figure 10. Reservoirs with and without protection of monomolecular films.

Introduction to Monomolecular Films

In recent years the increasing demand on available water supplies all over the world has focused attention on the possible use of monomolecular films to conserve this valuable and essential resource. The method for chemical protection of water surfaces gives promise of effective evaporation control. In field tests as well as in the laboratory, monomolecular films, such as that derived from hexadecanol,¹ significantly reduce evaporation losses. This method, while still in the stage

¹Cetyl alcohol is another name for this material. Although in the ordinary sense of the word it is not an alcohol but a wax. It is a white, waxy, crystalline-like solid. The structure of the atom consists of a long-chain primary hydrocarbon with 16 carbon atoms attached to an OH group. This is generally available in flake or powder form. It is relatively tasteless and odorless. Hexadecanol is derived from materials such as tallow, sperm oil, or coconut oil.

of testing and development, appears to be susceptible to a practical application at costs within economic limits. Investigations by a number of governmental and private organizations support the expectation that monomolecular films along with conventional techniques, can significantly increase the usable water supply by reducing evaporation losses.¹

A realization of the tremendous effect which exceedingly thin layers of certain substances might have upon the reduction of evaporation of water is not new. There is extensive literature available describing research on this subject. The early work of Rideal,² Langmuir and Langmuir³ and other research indicates that certain monomolecular films were effective in suppressing evaporation, and that the substance most likely to be useful was hexadecanol. These experiments were confined to a laboratory. The first field application was performed in 1952 by Mansfield,⁴ an Australian physical chemist.

Interest in this method of control has increased in the last few years. For this reason more attention is devoted to this factor as an evaporation control method than any of the others. This also holds promise as an evaporation retardant.

Theory of Monomolecular Films

A simple manner to explain how a film will control evaporation is to remind the reader of his last bowl of soup which contained a fatty

¹Eaton, op. cit., p. 15.

²E. K. Rideal, "The Influence of Thin Surface Films on Evaporation of Water," J. Phys. Chem., 29, 1585 (1925).

³Irving Langmuir and D. B. Langmuir, "The Effect of Monomolecular Films on the Evaporation of Ether Solutions," J. Phys. Chem., 31, 1719-1 (1927).

⁴W. W. Mansfield, "Effect of Surface Film on the Evaporation of Water," Nature, 172, 1101 (1954), p. 16.

layer on the surface. Under these conditions the soup will remain hot and the water does not evaporate. If one wants to cool the soup quickly by evaporation, he sticks a spoon in it and breaks the film of oil by agitation. All have seen the clouds of condensed steam come from hot soup when it is stirred. Also, if one blows on the soup it will cool more rapidly than if it stands undisturbed. This simple experiment illustrates how a fatty film slows the process of evaporation.¹

In this case the film is sufficiently thick to be observed directly. The extent and nature of any spreading on the water of monomolecular film may be followed visually by methods such as noting the movement of talc powder dust on the film surface.

Certain types of organic compounds possess the property of forming a film one molecule in thickness when applied to a water surface. We find that those organic chemical molecules that are good retardants of evaporation also furnish a very interesting story about their molecular structure. The retardation of evaporation by a film depends largely on the molecular architecture.

We were taught in chemistry that the hydrocarbons could be very long-chained molecules, one carbon atom following another in a long chain with hydrogen atoms attached to each carbon. The short-chained hydrocarbons of 1, 2, 3, or 4 carbon atoms carry the names of methane, propane, ethane and butane. For the long chains, the nomenclature becomes very complicated. In general, we have given up the use of long names and have adopted the policy of saying for example, C_{12} , C_{13} , or C_{14} , that is, the number of carbon atoms in the chain of hydrocarbon, acid, alcohol, or ester.

¹V. K. LaMer, "The Physical Chemical Basis of Water Evaporation Control by the Monomolecular Film Technique," First International Conference on Reservoir Evaporation Control, (San Antonio, Texas: Southwest Research Institute, April 14, 1956), p. 7.

A hydrocarbon forms a lens and does not spread on the water surface. In order to make the hydrocarbons spread, we have to attach an OH group at one end of the molecule. Acids, alcohols, and esters do spread because they contain an OH group in their molecule which is attracted to the water molecules which also contain OH groups.¹ The result is that a droplet of an acid, an alcohol, or an ester spreads out and forms a monomolecular film on the surface of the water.

Certain classes of organic compounds known as polar compounds possess the evaporation suppressing effect. These polar compounds have a hydrophylic² (water attracting) and a hydrophobic (water repelling) portion comprising their molecular structures and possess the property of being able to spread out on the water surface. The hydrophobic portion of the molecule consists of a hydrocarbon structure and for the purpose of retarding evaporation should contain 10 to 18 carbon atoms.³

The reduction of evaporation takes place when the monomolecular layer is compressed. When a monomolecular layer of certain polar compounds is compressed, the molecules of water which are moving about under the impulsive effects of heat within the body of water, are unable to break through the compressed layer into the air but are retained by the body of water. Therefore, an evaporation reducing effect is produced.

¹See Illustration.

²The hydrophylic end of the molecule is a functional group, usually characterized by the OH group. It has a great affinity for water, so that when the substance is in contact with water, the molecules tend to align themselves always with one end in the water and the remainder of the molecule out of the water.

³The hydrophobic residue should contain at least 10 carbon atoms, as a smaller residue implies a compound quite soluble in water. Those chain lengths having over 18 carbon atoms generally form too brittle a film and it will not reform well when ruptured by rain, boats, or other causes.

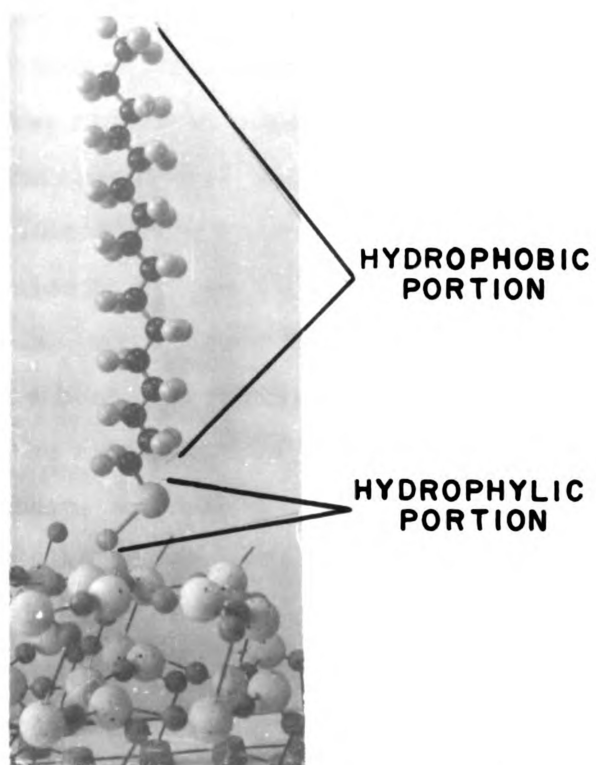


Figure 11. STRAIGHT-CHAIN MOLECULE

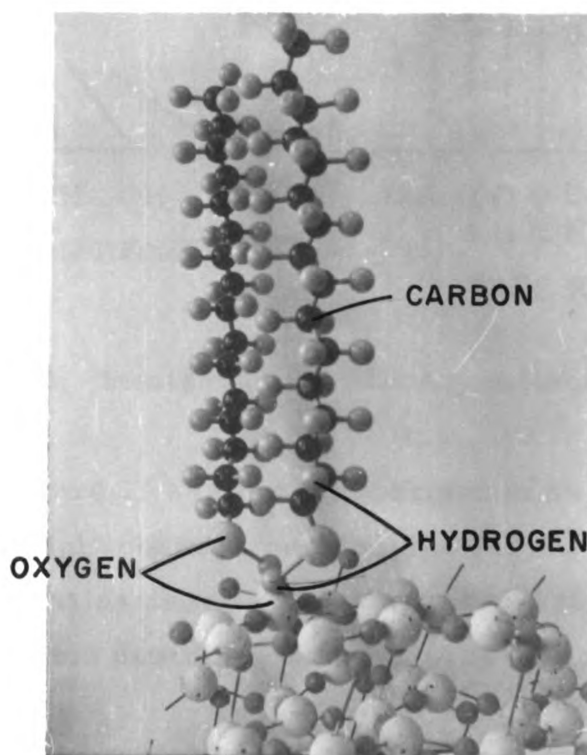


Figure 12. RELATIONSHIP OF STRAIGHT-CHAIN MOLECULES

For a water molecule to evaporate, it is necessary for this molecule of water to break through these chains in the monolayer. It should be evident that the higher the compression of the monolayer the more difficult it would be for the molecules of water to thread their way between the fatty acid molecules to escape and evaporate as vapor.

The hydroxyl compounds, particularly the straight-chain primary alkanols, were found to be the best compounds to use as evaporation retardants. Comparison of the orientation of the molecules of various types of alkanols (straight-chain, secondary and tertiary) in a monomolecular film, the primary alkanols by nature of their chemical structure, will form the most effective evaporation retardant film. The straight-chain primary structure is capable of forming a more highly compressed film than the secondary, tertiary, or branched-chain compounds.¹

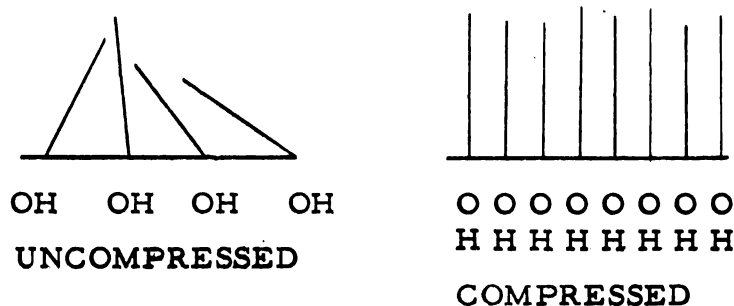


Figure 13. Straight-chain primary molecule.

Illustration Figure 13 shows a comparison of an uncompressed and compressed straight-chain primary molecule. As noted, the uncompressed long chains do not stand erect on the surface but are tilted to a certain extent depending upon the pressure to which the film

¹Cruse, op. cit., p. 9.

is subjected. As the film is compressed, the angle of the tilt increases until finally the molecules are packed very tightly together and are precisely perpendicular to the surface of the water. The molecules are then compressed against each other like safety matches in their packet.

Thus, when packed together, the molecules stand on end, closely packed, and form a film which helps resist evaporation of the water thus covered. Chemical materials of this type applied to the surface of water will, by their own special nature, spread continuously unless confined by the physical barriers such as shore lines or reservoir walls. At any time a material is present in excess of the amount necessary to form a compressed film one molecule deep, the film-forming material may function as an effective evaporation retardant.¹

Qualifications of an Effective Monomolecular Film

1. A monolayer film will need to restrict the rate of evaporation effectively by providing a greater resistance to the passage of water vapor molecules from the water surface into the air than are normally present.
2. It must be a non-toxic, odorless, and an invisible substance.
 - a. It should not harm or otherwise affect fish and aquatic life.
 - b. The material used should be agreeable and safe for human health.
3. The film should be lighter than water so that it can float but not be overly soluble.
4. The film must spread easily and possess self-sealing properties. This includes resisting the action of dust and wind.
5. Only the compounds forming liquid films at normal temperatures can be considered.
6. The length of the effectiveness of a monomolecular film will determine its value as a suppressant. Therefore, resistance to oxidation or degradation by fish and aquatic life is desirable.

¹B. W. Beadle and R. R. Cruse, "Water Conservation Through Control of Evaporation," Southwest Water Works J., 38, No. 9, 1956, p. 398.

7. The initial cost of the material and the cost of the application must be economically feasible.

Effectiveness of Monomolecular Films

The type of material used for a monomolecular film will be a determining factor in the amount of evaporation retarded. Hexadecanol was one of the first products used to produce a favorable monolayer to control evaporation and many of the experiments are centered around this product. Its value as a retardant, and the readily available supply of cetyl alcohol, has caused it to be used almost entirely in projects determining control of evaporation on large reservoirs.

Hexadecanol has proved to be a good performer in reducing evaporation. It has usually satisfied the requirements for effective monomolecular films. C_{16} is a straight-chain fatty alkanol with theoretical superiority. Despite the theoretical superiority, those straight-chain alkanols having an even number of carbon atoms are susceptible to bio-chemical oxidation and some consumption by aquatic life. Oxidation not only takes place on the film after formation, but on the reserve supply if it is stored on the water surface. Other fatty alcohol combinations have shown in screening tests¹ to be more effective at higher temperatures in reducing evaporation.

An evaporation reduction investigation conducted at Lake Hefner in 1958 shows the importance that other products may have in relation to cetyl alcohol. Screening tests were conducted on 22 promising fatty alcohol combinations. The material used in the large field test with a composition of C_{12} -1.0%; C_{14} -4.0%; C_{16} -93%; and C_{18} -2% ranked fifteenth in effectiveness out of 22 materials tested. Therefore, 14 other

¹Screening tests are usually considered to be small laboratory tests which determine if a product would be worthy of a more extensive test on a large body of water. They are usually conducted out-of-doors in 4 foot diameter U. S. Weather Bureau class "A" evaporation pans.

materials have now been found superior to the hexadecanol product used at Lake Hefner. This standing was based upon the evaporation reduction factor at 82.5° F, the highest temperature for the test. The three materials at the highest temperature were about 1.5 times as effective as the material used at Lake Hefner. Higher temperatures will cause larger amounts of evaporation and therefore, the use of materials other than hexadecanol may produce a greater result in evaporation savings.

Lake Hefner field investigations clearly demonstrated that it is possible to apply a monomolecular film to a large lake.¹ The studies were for an 86 day period in 1958. Treatments were made on only 55 days of this period because of high winds and other conditions making it unfeasible to make applications on 31 days. The average coverage for the 86 days is an indication of the degree of successful establishment of a visible layer under the conditions that prevailed during the summer of 1958 with the techniques used. The average coverage for the 86 days of the investigation was 10 percent and the overall evaporation savings for the same period was 9 percent or a total savings of 450 acre feet of water. The maximum savings that could have been expected with hexadecanol at the temperatures prevailing was 35%.²

Under usual conditions where water saved from the process of evaporation can be used and has value, the costs should not exceed benefits.³ The Lake Hefner studies were the first of its kind on a large lake and techniques of application and the type of equipment best suited

¹Lake Hefner has a surface area of approximately 2500 acres.

²Water-Loss Investigations; Lake Hefner 1958 Evaporation Reduction Investigations, Report by the Collaborators, June 1959, p. 43.

³Conditions will be considered later where the value of the water saved from evaporation may not be the most important item.

for the work were unknown. Therefore, the costs would probably be higher than on a later test of the same nature.

Meticulous records were maintained on the costs of (1) hexadecanol applied, (2) gasoline, oil, and repairs for operation of boats, (3) salaries and wages of operators and laborers, (4) motor vehicle operation, (5) rental of barge, (6) equipment depreciation, and (7) miscellaneous expenses.¹

The total cost of the Lake Hefner tests was \$27,542.42. The 9% reduction of water that would have otherwise evaporated amounted to 450 acre-feet. When this is divided into the total cost, the average cost was \$61.21 for every acre-foot of water saved.² The largest single cost during this time was for 40,040 pounds of hexadecanol. The cost that was paid was \$0.515 per pound for a total of \$20,620.60. This is approximately 3/4 of the total field cost, and therefore any significant reduction of material costs would have an important effect on the reduction of the overall costs of the field operations.

Reports based on discussions with manufacturers representatives show that they anticipate that material costs may be reduced as much as 50 percent of present costs. The reason for a reduction in cost will be available when a standardized material can be used in large quantities. Lake Hefner used hexadecanol in finely powdered form instead of the granular or flake form. It required special processing by the manufacturer and therefore an increase in cost to the consumer. Once a large market for similar forms and types of material is available the price would seem to be reduced. The development of synthetic materials also indicates a substantial saving as compared with the use of the natural product.³

¹Water-Loss Investigations; Lake Hefner 1958 Evaporation Reduction Investigations, op. cit., p. 89.

²This compares with the value of raw water in Lake Hefner which is about \$60 per acre-foot, as reported by the city of Oklahoma City.

³Water-Loss Investigations, Lake Hefner 1958 Evaporation Reduction Investigations, op. cit., p. 91.

Improved techniques, both in the manufacture and field application could be expected to further reduce these costs. Increased efficiency of the monolayer, whether it be an improved material or application, would increase the evaporation savings and thereby effect a lower unit cost.

The large potential market for materials used as evaporation retardants does not displace any other chemical or process now on the market. Robert R. Cruse states that in Texas alone there is the market potential for 38,400 tons per year of a qualifying evaporation retardant.¹ Upon consideration of the possibilities for the potential market of evaporation retardants throughout the western states, as well as many other localities throughout the world, one can see at once why many chemical firms might be interested in the success of such a product.

Test results indicate that under certain conditions a successful degree of evaporation reduction is possible for small reservoirs.² Many problems still must be solved before the process can be recommended for general use. Among these are a simple effective method of application and maintenance of the chemical film on the water surface in order to reduce the amount of material required. The product used should satisfy all the requirements of a monomolecular film. These should reduce evaporation losses, cause no adverse effects, have a relatively long life, and resist oxidation or consumption by aquatic life. Tests must be conducted for a sufficient time and under varying conditions to gain data that may be used in making an analysis of the economics of evaporation retardation for particular localities. It is hoped that research will help supply the needed information that will make evaporation control by films a practical reality.

¹Cruse, op. cit., p. 6.

²Commonwealth Scientific and Industrial Research Organization, Saving Water in Dams, The Mansfield Process, C.S.I.R.O. Leaflet 15, Melbourne, Australia, 1956, p. 1.

CONCLUSIONS

Water, a great natural resource, should be managed wisely, especially when the supply of available water may be the limiting factor of growth. Economic growth whether in areas of irrigation, industry, or cities may be hampered by water shortages. Many localities find it necessary to place severe restrictions on water usage during long hot dry periods. Population needs and demands for dependable supplies of high quality water are steadily growing while the supply of available water is not increasing. Where the available supply of water is the limiting factor of growth, research directed towards all phases of water conservation is appropriate whenever possible.

Reduction in evaporation losses will benefit the entire nation. The Southwestern United States will benefit most, due to the present high rate of evaporation losses and the limitation of growth that a shortage of water has placed upon it. The humid portion of our country can benefit also by retarding evaporation losses. Decreasing losses from storage basins may be equivalent to increasing the size of the watershed by a similar amount. This increase would be welcomed by many water boards in cities throughout the United States, especially those which suffer from recurrent water shortages. Many individually owned supplies could also profitably conserve water through evaporation control.

Water in some reservoirs contains high amounts of dissolved solids, especially in the Southwest. Evaporation, in removing only the pure water, serves to concentrate the dissolved materials already present. The high salinity in certain reservoirs due to evaporation losses makes the water unusable. Reduction of evaporation may not only save valuable water but also render the water usable from the entire reservoir.

Where there is only a slight difference in the amount of pure water that can be removed from a lake before it is considered for rejection as a water supply, evaporation retardation will generally be economically feasible.

Our world has areas where rainfall and ground water are not available throughout the year. Here, people depend entirely upon the reservoir storage supplies during the periods of low rainfall. Evaporation controls may extend the water supply in these reservoirs. Economics at critical low water levels may be a secondary consideration, especially when needed for only a short period until additional precipitation becomes available.

The reduction of evaporation by methods which limit the amount of water surface exposed to the atmosphere offers considerable promise. Considering evaporation losses in management procedures of reservoir systems may in some instances be profitable. Some degree of evaporation control can be achieved by designing a reservoir having a maximum average depth, thus having a smaller water surface area per unit of volume. However, this approach is limited by such factors as topography, accessibility, availability of dam sites and costs involved. Many of the most desirable sites have already been used or are unavailable for reservoir use.

Reduction of aquatic and riparian vegetation will lower the amount of water consumed and lost by relatively low value plants. Experimentation is now being carried on in this field but the development of replacing this vegetation with less water consumptive plant users in a reasonable price range will need to be solved before the process can be recommended.

The reduction of wind over reservoirs will help reduce evaporation (but to my knowledge, little has been done along this line).

Roofs and covers on which some research is now underway, obviously must be limited to small areas because of costs and construction characteristics.

Underground storage has possibilities where physically possible. Many questions still are unsolved in recharging procedures, pollution possibilities, and legal ownership of stored waters.

Because of the limitations of these physical methods of control more attention has been recently directed to the use of chemicals capable of suppressing evaporation. This affords considerable promise and has the possibility of developing into a very profitable conservation practice. The combination of as many of the physical methods of control as are economically possible with chemical control will undoubtedly be considered more often in the future.

Suppression of reservoir evaporation offers considerable promise as means of conserving available water supplies. It is in the dry arid portions where a monofilm technique will be of most value. Where ample water is available or high humidity prevails, evaporation retardants do not appear to be economically feasible.

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