

## THE PRESENT TREND IN EVAPORATION EXPERIMENTS

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The change in the rate of rainfall over wide areas in the United States during recent years has focused attention on erosion control, flood prevention, and irrigation. Likewise, the construction of large hydro-electric plants for the production of cheap power has necessitated the building of great storage reservoirs which, also, are dependent on rainfall. In all these projects the water supply is the most important factor. The loss of water by evaporation materially affects the water supply, and although a great mass of data on evaporation has been collected in the past, the need for more accurate and more complete information has stimulated interest in evaporation studies.

Evaporation studies are of two types. In one the sole purpose is to determine the evaporation loss; in the other it is to find the relation of the evaporation to certain meteorological factors or thermodynamic laws as well as the evaporation loss. Both types of studies serve a useful purpose, but the latter type is of greater value from the scientific standpoint. The present trend is more and more toward this type.

### UNITED STATES WEATHER BUREAU

The principal agency collecting evaporation data in the United States is the U. S. Weather Bureau. The official evaporation pan of the Weather Bureau is the Class A land pan. It is 4 feet in diameter and 10 inches deep and is freely exposed to the air. In 1936 evaporation records were being obtained at 166 Federal Stations<sup>1</sup>, most of which are in the western part of the United States. Seventy-four of these stations are maintained directly by the Weather Bureau or in cooperation with other agencies. At 49 of the Weather Bureau sta-

tions all the meteorological factors are observed, which consist of air and water temperature, rainfall, evaporation, relative humidity and wind velocity. At the remaining stations the only records besides the evaporation are the air temperature and the precipitation.

It is unfortunate that complete records are not taken at all stations because, unless the wind velocity and the relative humidity are known, the evaporation records from a station at one point cannot be used at another point without danger of being seriously in error, even if only a few miles away. A good example of the differences between nearby stations is given by the results from two evaporation pans near Yuma, which are 7 or 8 miles apart. The difference in the annual evaporation from the two pans is 47 inches, which is more than the total annual evaporation at many stations. The records at these stations, however, reveal that the wind velocity at the station with the higher rate is more than twice what it is at the one with the lower rate, and the air temperature is also higher.

The Weather Bureau is at present carrying on a study of the accuracy of different types of rain and snow gages. Since evaporation records must be corrected for precipitation by adding the precipitation to the indicated loss, it is important that the precipitation readings be accurate. In conducting evaporation experiments at Fort Collins, it was frequently necessary to discard records taken during periods of heavy rainfall because the rain collected in the gage differed considerably in quantity from that falling in the evaporation pans.

The Weather Bureau is also planning some special studies on evaporation in addition to the routine observations at the regular evaporation stations. This program will probably include a study of the evaporation from snow and ice, which is very much needed at the present in connection with water supply forecasts from snow course records.

BUREAU OF PLANT INDUSTRY,  
OFFICE OF DRY LAND AGRICULTURE

Evaporation records have been kept at the Field Stations of the Office of Dry Land Agriculture of the Bureau of Plant Industry since most of the stations were started. At the present time observations are being made at 21 stations, although records were obtained at 8 other stations for a portion of the period. A summary of the re-

sults of these evaporation observations for the period from the beginning of the records to 1920, inclusive, is given in Volume 49 of the *Monthly Weather Review*, and the record of the results from 1921 to 1932, inclusive, in Volume 62 of the same journal.

These data are based on records from 6-foot circular tanks, 24 inches deep, sunk into the ground to within 4 inches of the top. Air temperature, wind velocity, precipitation and humidity are observed daily. Water temperature records have not been taken since 1917. It is to be regretted that they were discontinued because the water temperatures have an important effect on the rate of evaporation.

The Bureau of Plant Industry is interested in evaporation from the standpoint of its effect on dry land agriculture. So far as is known, no attempt has been made by the Bureau to correlate the evaporation loss and the meteorological factors, the chief interest being in the rate of loss. The evaporation records collected by the Bureau of Plant Industry are useful also to engineers in determining the loss from reservoirs by evaporation because it has been found that the losses from these pans are only slightly greater than the losses from reservoirs, the conversion factor being 0.94<sup>2</sup>; that is, the reservoir evaporation is 94 percent of the pan evaporation.

#### BUREAU OF RECLAMATION

The Bureau of Reclamation of the Department of the Interior, which is responsible for the planning and construction of most of the large irrigation projects completed in recent years, has carried on extensive evaporation studies on these projects for the purpose of assisting in the determination of the quantity of water available for irrigation. At various times they have maintained evaporation pans at 40 different stations. The results of the observations on these pans from the time of installation to 1923, inclusive, have been reported by Houk in Volume 90 of the *Transactions of the American Society of Civil Engineers*.

According to Houk, the U. S. Weather Bureau specifications have usually been followed on land pan installations, although deviations have occurred to meet local conditions. Floating pans used in measuring the evaporations from reservoirs were of the U. S. Geological Survey type, which is 3 feet square and 18 inches deep, and of the U. S. Weather Bureau type, which is the same as the Class A land pan except that it is partially submerged in the water and surround-

ed by a raft which supports the pan and protects it to some extent from the splash of waves.

Most of the evaporation records are for the period from April to October, inclusive, but some of them are for the entire year. Temperature observations were made at all stations and at some of them wind velocities, also, were observed. Direct measurements of the evaporation from reservoirs were not made, so comparisons between the evaporation from land and floating pans and that from the reservoir could not be obtained.

Recently the Bureau of Reclamation installed three floating pans in Lake Mead, one on the Arizona side and one on the Nevada side, both near the dam, and one at Pierce's Ferry, 76 miles above the dam. On shore near the floating pans corresponding land pans were installed, and in addition a pan was installed at Boulder City. All the pans were of the U. S. Weather Bureau Class A type.

The purpose of these evaporation studies is to find out as nearly as possible what the loss is from Lake Mead, so that it will be possible to estimate how much water will be available for irrigation and for power and how much capacity must be provided for flood control. Lake Mead has a capacity of 30,500,000 acre-feet and a surface area, when filled to capacity, of 145,600 acres. The annual evaporation loss is somewhere between 600,000 and 1,000,000 acre-feet. If available for irrigation, it would provide water for from 250,000 to 500,000 additional acres. In terms of stream flow, it is the equivalent of a stream with a flow of from 800 to 1400 cubic feet per second, which is a fair sized river. The importance of evaporation from the standpoint of agriculture is apparent from these figures.

A floating pan of the Weather Bureau type has been maintained by the Bureau of Reclamation since 1911 on East Park Lake at Stonyford, California. Here, in 1930, during July and August, the Bureau of Agricultural Engineering carried on a series of evaporation observations to determine the ratio of the evaporation from various types of pans to that from the reservoir. There was practically no inflow and very little outflow during this period, and what there was could be measured accurately. Evaporation observations were made at three widely separated points on the reservoir by measuring the elevation of the water surface. For comparison, readings were taken on a Class A land and a Class A floating pan, a Colorado sunken pan and a circular sunken pan 4 feet in diameter and 3 feet deep.

During the period of the test, the average evaporation from the reservoir was 69 per cent of that from the Class A land pan, 78 per cent of that from the floating pan, 75 per cent of that from the Colorado sunken pan, and 78 per cent of that from the 4-foot circular sunken pan. A similar comparison by the Bureau of Agricultural Engineering at Fort Collins, Colorado, between the evaporation from an 85-foot circular, copper-lined reservoir and the different types of evaporation pans showed similar results. Experiments at Denver, Colorado, by the Bureau of Agricultural Engineering, and at Milford, Utah, by the United States Geological Survey gave approximately the same results.

The comparisons show that there is apparently a very definite relation between the evaporation from the different types of pans and that from a large body of water; and as shown by Sleight<sup>3</sup> in his work at Denver, the ratios are constant regardless of the size of the lake or reservoir, if 12 feet or more in diameter.

#### BUREAU OF AGRICULTURAL ENGINEERING

The question has been raised, however, as to whether these ratios remain constant throughout the year. Observations made in California indicate that these ratios are not constant and therefore the Bureau of Agricultural Engineering started several years ago to make observations in California to determine what these monthly ratios are. This work is being carried on by Mr. A. A. Young at Fullerton and Baldwin Park. Comparisons are being obtained between the evaporation from the various types of standard pans and that from a 12-foot circular sunken pan at Fullerton and a 6-foot circular sunken pan at Baldwin Park. Both pans are 3 feet deep. Comparison of records from the 12-foot pan and the Class A Weather Bureau pan at Fullerton show that for California conditions the ratio is 0.77, as the average for the entire year, and 0.79 for the period from April to November, inclusive, instead of 0.70 as was found at Fort Collins. At Baldwin Park the results found were not consistent. The observations at Fullerton indicate that in general the ratio increases in the summer with the increase in temperature and decreases in the winter with the decrease in temperature.

Other studies being carried on by the Bureau of Agricultural Engineering in California are: (1) the relation between the evaporation from a U. S. Weather Bureau Class A land pan and from a desert

lake without known inflow or outflow, and probably without seepage loss; (2) the effect of shade on the evaporation from small pans; (3) the variation in evaporation at different points in a reservoir or lake; (4) the effect of salt solutions on the rate of evaporation; and (5) the influence of color of pan on the rate of evaporation.

A study was carried on several years ago by Mr. Young to determine the evaporation loss from covered reservoirs by comparing the evaporation from a pan floating in the reservoir to the evaporation from a pan fully exposed nearby. Both pans were of the Weather Bureau type. The reservoir, which had a capacity of 200,000 gallons, was completely covered by a circular frame building with a conical roof, and the only ventilation was from a 14-inch screened strip at the top of the wall, just under the eaves. The water supply was from underground sources and consequently had a very uniform temperature, ranging from 74 degrees in summer to 70 degrees in winter.

As would be expected, the evaporation from the floating pan in the reservoir was less than that from the land pan outside, but the interesting fact was that the evaporation from the pan in the reservoir was a minimum in August when the evaporation from the outside pan was a maximum, and was highest in the winter when the evaporation from the pan outside was a minimum. In the winter the rate from the pan in the reservoir exceeded not only the rate of the pan outside, but also its own summer rate by a wide margin.

Mr. Young concludes from this study that from the standpoint of reducing the evaporation loss, the expense of building a shelter is not justified. However, other factors such as elimination of contamination and reduction in the growth of algae may be controlling factors in deciding whether to cover a reservoir.

#### OTHER GOVERNMENT AGENCIES

Evaporation investigations are also conducted by the United States Forest Service, the Tennessee Valley Authority, and the United States Geological Survey.

The United States Forest Service is carrying on extensive studies in range and forest management and in watershed control over a wide range of conditions, and in both the ecological and the hydrological studies, evaporation plays an important role. The Forest Service makes evaporation observations at 50 stations in the National Forests, and in addition maintains a large number of lysimeters for

the purpose of studying evaporation and transpiration rates. Twenty-three of the stations are first class stations, where complete meteorological records are kept. At the remaining stations only the evaporation and the air temperature are observed. The pans are of the U. S. Weather Bureau Class A type.

The Tennessee Valley Authority is making observations on evaporation from pans at four different locations in the valley. The observations are made daily throughout the year, and complete meteorological records are kept. The purpose of this study is to derive an evaporation formula applicable to the Tennessee Valley which may be used in computing reservoir evaporation from the meteorological data.

The United States Geological Survey carried on evaporation experiments for a period of years at Milford, Utah, and at Austin, Texas. The experiments at Milford are of particular interest. They were made on a Class A Weather Bureau land pan and a buried tank 12 feet in diameter and 3 feet deep, for the purpose of determining the factor to use in converting Class A pan evaporation records into reservoir evaporation. The conversion factor obtained was 0.67, which compares with a ratio of 0.69 found at Stonyford, California, and 0.70 at Fort Collins and Denver, Colorado. The work at Milford has been discontinued.

#### UNIVERSITY OF IOWA

The University of Iowa, in co-operation with the Flood Forecasting Branch of the U. S. Weather Bureau and other agencies, is making a study of the effect of insulation on Class A Weather Bureau pans at Lake Okoboji. They are also preparing to study the effect of difference in water level on the rate of evaporation from Weather Bureau pans. Mariotte constant level tanks will be used for controlling the water level in these pans, one at the maximum level and one at the minimum level permitted in Class A stations. A third pan will be allowed to fluctuate between these limits in the normal manner.

#### COLORADO EXPERIMENT STATION

In May, 1890, evaporation records were started on a buried tank 3 feet square and 3 feet deep at the Colorado Experiment Station, by Professor L. G. Carpenter. These observations have been continued ever since and now constitute what is believed to be the longest record of evaporation in the United States.

## GREAT LAKES SURVEY

In the study of the hydrology of the Great Lakes, the most important factor is the evaporation from the water surface. Colonel Pettis<sup>4</sup>, in making a quantitative study of the hydrology of Lake Superior, found that the total annual contribution to the lake from all sources was 62.6 inches, of which 35.6 inches, or 57 per cent, was lost by evaporation. Freeman<sup>5</sup>, in his report on the regulation of the Great Lakes makes the statement that "for long periods each year more water is evaporated from the lake surfaces than goes over Niagara Falls."

The Lake Survey has maintained five evaporation stations of the Weather Bureau type on the lakes since 1937. The pans are insulated and an attempt was made to keep the water temperature the same as the lake temperature. However, in doing this they were not entirely successful. Complete meteorological records were kept. The results of this study are reported in the April, 1939, *Proceedings of the American Society of Civil Engineers*. The rate of evaporation from these pans indicated that there was no correlation between humidity and evaporation and that it was an effect of evaporation rather than a cause. Our experiments, however, under controlled conditions in the laboratory at Fort Collins, showed that the evaporation was directly proportional to the difference in vapor pressure, which is a function of the relative humidity, the air and water temperature.

Folse<sup>6</sup> of the Carnegie Institute, working on the evaporation from the Great Lakes concluded that the evaporation varied with the difference in vapor pressure, but that the wind did not increase the evaporation until it was greater than 10.8 miles per hour. Obviously, such contradictory conclusions cannot all be correct. They indicate that information available on evaporation from large bodies of water is unsatisfactory. The conclusions of Folse were based on a statistical study of the water levels of the lakes.

## SCRIPPS INSTITUTION OF OCEANOGRAPHY

In the evaporation studies previously referred to, the evaporation was investigated in relation to the meteorological factors that influence the rate of evaporation. There is, however, a noticeable tendency at present to abandon this method of approach and to study evaporation in relation to the aerodynamic and thermodynamic prin-

ciples involved. Studies are being conducted for the purpose of determining the correlation between evaporation and the rate of diffusion of the vapor layer that lies immediately above the water surface or the rate at which the vapor layer further removed from the water surface is dispersed by eddy conduction or convection. This principle was utilized by Sverdrup<sup>7</sup> of the Scripps Institution of Oceanography in computing the evaporation from the ocean. Where the evaporation was known as shown by pan records on shipboard, there was a reasonably close agreement between the observed and the computed evaporation.

UNIVERSITY OF CALIFORNIA

Another series of tests in which a different method of approach was used was carried on at the University of California recently. In this series the correlation between the evaporation and the difference in vapor concentration near the water surface and far away was studied under controlled conditions in quiet air. Of particular interest in this study was the method used in measuring the evaporation loss which consisted of an optical wedge by which the drop in the water surface was indicated by the change in the number of interference bands produced when a ray of green light was projected onto the wedge.

The drop in the water surface

$$\Delta H = \Delta n \frac{L\lambda}{L_1^2}$$

where,  $\Delta n$  = change in number of interference bands

$L$  = length of lever arm

$L_1$  = distance between etched marks on glass

$\lambda$  = wave length of light used.

This method was very effective in measuring very small losses, but it could not be used when evaporation was occurring at a rapid rate because the interference bands changed so rapidly that they could not be counted.

SCRIPPS INSTITUTION OF OCEANOGRAPHY;  
CALIFORNIA INSTITUTE OF TECHNOLOGY

Experiments have also been carried on to determine the relation between evaporation and solar radiation or insolation. This work was done at the Scripps Institution of Oceanography and the Cali-

ifornia Institute of Technology by Cummings, Richardson, Bowen and McEwen. Since the sun is the source of the heat necessary to vaporize the water lost by evaporation, it would seem to be quite a simple problem to determine the evaporation if the solar radiation for the area is known. However, not all the radiation from the sun falling on a body of water is used for evaporation. There is a definite loss by back radiation, some loss by conduction, and in the spring when the water is warming up, there is a large amount of heat stored in the water, which is given up in the fall when the water starts to cool. The air in contact with the water surface also carries off some of the heat absorbed from the sun. According to Richardson<sup>8</sup>, evaporation utilizes only about 50 percent of the insolation at the water surface. The remainder is lost in the manner just described. Of these losses, back radiation is the most important item and is usually more than all the others combined. Most of these losses can be evaluated with a reasonable degree of accuracy, if the necessary data are available.

#### SOIL CONSERVATION SERVICE

The Soil Conservation Service, in connection with its soil erosion studies, is also conducting evaporation experiments in which a new method of attacking the problem based on aerodynamic theory is being utilized. The vapor gradient above the surface studied and the turbulence are the factors involved in this method. The procedure used was developed by Thornthwaite and Holzman. The vapor pressure is determined at two different levels by means of hygrothermographs and the rate of movement of the air and vapor is determined by anemometers at these levels. From the anemometer readings and the temperature and humidity record, it is possible to compute the vapor content of a given mass of air at each level and also the rate of vapor transfer. This is a measure of the rate of evaporation from the surface being studied. It is expressed by the formula

$$E = 17.1 \frac{(e_1 - e_2) (u_2 - u_1)}{T + 459.4}$$

where  $E$  = evaporation in inches per hour;

$e_1, e_2$  = vapor pressure in inches of mercury at the two levels;

$u_1, u_2$  = wind velocity in miles per hour at the two levels;

and  $T$  = temperature.

The Soil Conservation Service is investigating the evaporation and transpiration from different types of cover, but the principles

could be applied just as well to the evaporation from water surfaces. Equipment for making the observations has been installed over 5 different types of cover at Beltsville, Maryland, 5 sets of equipment have been installed in the Muskingum valley in Ohio, and 10 more sets are now being installed. One set is being sent to Berkeley, California, to measure the amount of water accumulated by condensation on plants and on the ground. A more detailed description of this method appears in the January, 1939, issue of the *Monthly Weather Review*.

#### CONCLUSION

As a result of the evaporation studies being conducted by these agencies, more accurate and more complete information is becoming available as to rate of evaporation in different parts of the United States. At the same time, the laws governing evaporation are becoming better known and new facts based on the fundamental relationship between evaporation and the physical factors are being discovered. At the present time, the opinions as to the effect of the various factors on evaporation are many and diverse. It is hoped that the present studies will help to reconcile these diverse views, when possible, and permanently eliminate those views that are found to be in error.

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