PAPERS ON CLIMATOLOGY IN RELATION TO AGRICULTURE, TRANSPORTATION, WATER RESOURCES, ETC.

STUDIES ON THE PHENOMENA OF THE EVAPORATION OF WATER OVER LAKES AND RESERVOIRS.

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VII.—SUMMARY OF THE RESULTS OF THE SALTON SEA CAMPAIGN.

A brief summary of the general results of the research regarding the laws of the evaporation from large surfaces of water is here presented, in anticipation of the general report upon which they are based. The report contains a description of the stations occupied; the instruments used in the observations; the total monthly amounts of evaporation in different parts of the United States on the pans as located in places of varying environments; the computed values of the C_2, C_3, C_4, coefficients in the Bigelow, Dalton, and Mammoth formulas, respectively; a discussion of the cause of the variation of these coefficients of diffusion with the size of the pans; and the attempt to fix the values of C_2 and C_3 for a very large pan, as the surface of a lake or reservoir. Table 1 contains the annual mean values of these coefficients, which illustrate the leading facts. The report contains the constituent values in the *diurnal* and the *annual* periods, of which these values are the final mean. They are arranged by the diameter of the pans, 2-foot, 3-foot, 4-foot, 6-foot, 12-foot, and the stations are grouped together near the sea-level plane, and on the Rocky Mountain plateau.

TABLE 1.—*Mean values of the C_2-coefficients for pans of different sizes in* $E_0 = C_2 \frac{e_s}{e_d} \frac{de}{dS} (1+.070\,w)$.

Stations.	Pan.	2-foot.	3-foot.	4-foot.	6-foot.	12-foot
Salton Sea, Tower No. 1	1	0.039				
Do	2	0.043				
Do	3	0.044				
Do	4	0.043				
Do	5	0.043				
Salton Sea, Tower No. 2	1			0.036		
Do	2			0.037		
Do	3			0.038		
Do	4			0.038		
Do	5			0.039		
Salton Sea, Tower No. 4	1			0.035		
Do	2			0.037		
Do	3			0.037		
Do	4			0.037		
Do	5			0.036		
Mammoth, Cal		0.034			0.029	
Brawley, Cal		0.033			0.026	
Mecca, Cal		0.039			0.030	
Indio, Cal		0.040			0.032	
North Yakima, Wash			0.037	0.030		
Hermiston, Oreg			0.045	0.039		
Do			0.044			
Granite Reef, Ariz			0.046	0.041		
Do				0.042		
California, Ohio		0.042		0.032*		
Birmingham, Ala		0.041		0.031*		
Dutch Flats, Nebr				0.038		
Minidoka Dam, Idaho			0.046			
Deer Flat, Idaho	A		0.042	0.044		
Do	B		0.044	0.043		
Lake Kachess, Wash			0.042			
Ady, Klamath, Okla	A		0.044	0.033		
Do	B		0.045			
Fallon, Nev			0.038	0.028		
Lake Tahoe, Cal			0.040	0.036		
Elephant Butte, N. Mex			0.044	0.040		
Carlsbad, N. Mex			0.036	0.034		
Do			0.034	0.027		
Lake Avalon, N. Mex			0.038	0.032		
Sand Key, Fla				0.022*		
Eastport, Me				0.023*		
Rangeley, Me			0.022*			
Salt Creek, Cal		0.031*		0.030*	0.026*	0.025*
Means		0.040	0.042	0.037	0.029	0.025

*Floating, or in very humid locations, omitted here.

1. There is no evidence that the water in pans of the same size evaporates faster on the Plateau levels, 4,000 feet, than at sea level, and the formula should not contain any barometric pressure term.

2. The evidence is decisive, by the 3 formulas based upon the terms $\frac{e_s}{e_d} \frac{de}{dS}$, $(e_s - e_d)$, and $(e_t - e_d)$, respectively, that water evaporates much faster from small pans than from large pans. This is because the wind action tends to clear a small pan of vapor, making over it a dryer mixture, than it does a large pan or water surface, where vapor is merely transported from one side of the water area to the other side of it. Especially, over a lake or reservoir the vapor is carried along from point to point without drying the mixture of vapor and air resting on the water surface. This phenomenon is plainly seen at times in the early morning when the fog resting on a lake begins to clear with the increase of temperature, and when the wind is moving the columns of vapor in oblique lines while the evaporation proceeds. It has made our research very difficult to incorporate this fact, because of the necessity of extending the series of coefficients from small pans to a large water surface.

TABLE 2.—*Mean values of the C_3-coefficients for pans of different sizes in* $E_0 = C_2\ 2\ (e_s - e_d)\ (1+.070\,w)$.

Stations.	Pans.	2-foot.	3-foot.	4-foot.	6-foot.
Salton Sea, Tower No. 1	1	0.0051			
Do	2	0.0055			
Do	3	0.0059			
Do	4	0.0058			
Do	5	0.0059			
Salton Sea, Tower No. 2	1			0.0044	
Do	2			0.0046	
Do	3			0.0048	
Do	4			0.0049	
Do	5			0.0051	
Salton Sea, Tower No. 4	1			0.0047	
Do	2			0.0050	
Do	3			0.0051	
Do	4			0.0050	
Do	5			0.0048	
Mammoth, Cal		0.0050			0.0039
Brawley, Cal		0.0049			0.0035
Mecca, Cal		0.0054			0.0040
Indio, Cal		0.0054			0.0043
California, Ohio		0.0073*		0.0054	
Birmingham, Ala		0.0078*		0.0049	
Sand Key, Fla		0.0042			
Eastport, Me		0.0063			
Rangeley, Me			0.0044		
Means		0.0054		0.0049	0.0039

*Omitted.

TABLE 3.—*Mean values of the C_4-coefficients for pans of different sizes in* $E_0 = C_4 . 2\ (e_t - e_d)\ (1+.070\,w)$.

Stations.	Pans.	2-foot.	Stations.	Pans.	4-foot.	6-foot.
Salton Sea, Tower No. 1	1	0.0044	Salton Sea, Tower No. 2	1	0.0042	
Do	2	0.0046	do	2	0.0038	
Do	3	0.0048	do	3	0.0038	
Do	4	0.0045	do	4	0.0038	
Do	5	0.0047	do	5	0.0036	
			Salton Sea, Tower No. 4	1	0.0046	
			do	2	0.0042	
			do	3	0.0041	
			do	4	0.0039	
			do	5	0.0037	
Mammoth, Cal		0.0039				0.0031
Brawley, Cal		0.0043				0.0032
Mercer, Cal		0.0047				0.0034
Indio, Cal		0.0042				0.0036
California, Ohio		0.0097*			0.0098*	
Birmingham, Ala		0.0107*			0.0082*	
Means		0.0045	Means		0.0040	0.0033

*Means omitted.

3. The Bigelow formula depending on $\frac{e_s}{e_d} \frac{de}{dS}$ has no annual period in the C_2—coefficient; the dinural period is very small, but it shows a slight deficiency in the forenoon when the water temperature is rising, and a small increase in the afternoon when the water temperature is falling. There may be an

interaction of latent and specific heats, so that there is resistance to molecular diffusion in the forenoon, but acceleration in the afternoon. The Dalton formula in (e_s-e_d) is closely in conformity with the Bigelow formula so far as the periodic action is concerned in *dry climates*, but in humid climates the cofficients in the Dalton formula become irregular, especially in the cold part of the day, while the coefficients in the Bigelow formula continue quite steady. The Mammoth formula depending upon (e_t-e_d) has a large annual, and a considerable diurnal period in dry climates; it is erratic in humid climates, and generally the argument is not valuable because the term becomes much too small to compensate for the actual observed evaporation. The Mammoth and the Marvin formulas should not be further considered.

4. The Dalton formula has for one of its implied results the conclusion that evaporation ceases when $e_s=e_d$, while the Bigelow formula admits that it can continue, since $e_s/e_d=1$. This brings up a very difficult point to be determined, and there are two considerations bearing upon it: (*a*) If a water surface evaporates into a *perfect calm* it soon covers itself with a film of vapor, through which further molecular bombardment can not penetrate, so that this layer acts like oil to damp further action. If this film is cleared to any extent by the wind the evaporation will continue, even though $e_s=e_d$. Saturation of air near a water surface does not necessarily imply stagnation of the circulation. Indeed, in the open air stagnation is so rarely a fact that evaporation rarely ceases. (*b*) Direct experiment on evaporation during fogs and rainy intervals proves that evaporation seldom stops in practical open-air conditions. A self-register evaporometer at Los Angeles continued to record to the amount of about 50 per cent of the usual evaporation during the hours marked fog, the registration being for each hour during the day, the record extending from March to June, 1910; at Eastport, Me., evaporation is almost regularly recorded during the dense fogs that prevail in that locality in the spring and summer months; at Rangeley, Me., records of evaporation during rainy intervals were the common rule. These observations were made by 5 different gages at Rangeley and by 3 gages at Eastport, Me., on the same 3-foot evaporation pan, and the harmony of the individual observations excludes all doubt of the fact. These results confirm the observations made by Lehman at Birmingham, Ala., in 1909. They, also, weaken the claim of the Dalton theory of potential-differences as fundamental in practical open-air work, because stagnation rarely occurs, and water seldom evaporates into theoretically saturated mixtures.

5. In order to study the phenomenon of evaporation into varying percentages of mixture of dry air and vapor, as the latter is blown to the leeward side of a pan by the wind, the following experiments were carried out: (1) Four shallow pans 9 inches square were placed in a row on a wind vane, turning into the wind so that one pan was always to windward and the fourth pan to leeward of the row. The last pan evaporated about 90 per cent of the first pan. Similarly, sections on a large circular pan have minimum evaporation on the leeward side. (2) A larger vane, carrying four 2-foot circular pans, indicated a similar result, but less clearly on account of the eddies formed by the circulating wind among the pans. (3) Thirty small pans were set in a nest on a table, in 5 rows containing 6 pans each, but as they were not turned always to face the wind on the same side, and as the sun had too much effect on the south and west outside rows the result was indecisive. It suggested that the minimum evaporation was at a point about two-thirds the distance from the south side to the north side on the central line.

6. A pan of very clear fresh water was evaporated along side of a pan filled with brackish Salton Sea water, which was gradually concentrated by adding water from the sea from November to May without emptying the old water. The brackish water evaporated a little slower than the fresh water, to the amount of *2 per cent* in April and May. No correction has been applied on pans refilled frequently in the usual routine.

7. In order to test the ratio of evaporation from pans of different sizes, our records include the following combinations: (1) A 4-foot pan self-registered hourly and a 2-foot pan along side on the ground near Tower No. 1; (2) a row of 3 pans, 2-foot, 4-foot, 6-foot in diameter, on a platform on Tower No. 3, about half a mile from shore, and as near the water as was practicable; (3) a row of 4 pans 2-foot, 4-foot, 6-foot, 12-foot, on a series of adjoining rafts floating in the Salt Creek slue in calm water. The ratios are quite steady and the results have been incorporated into the final value of the coefficient,

$C_2=0.023\ (1.23)^n$ for 4-hour intervals,

where $n=0$ for large open water areas,
$n=1$ for 6-foot pans,
$n=2$ for 4-foot pans,
$n=3$ for 2-foot pans,
$n=4$ for ordinary dry air.

The value of the coefficient for $n=1$ is fairly well determined, and it is interpolated for $n=4$. These should be further verified if possible.

8. The practical check on $C_2=0.023$ is to be found in the actual evaporation of the Salton Sea itself as measured. In cooperation with the United States Geological Survey, we have the following data for the year June 1, 1909, to June 1, 1910:

	Inches.
1. Actual fall of the Salton Sea level	51.00
2. Inflow through the New and Alamo rivers	12.00
3. Accumulation from annual precipitation	6.00
Total amount due to evaporation	69.00

Taking the daily records of the surface temperatures of the Salton Sea water S_0, and using the values of the vapor pressure e_d and wind velocity w at the pans (1), at the foot of Towers No. 2 and No. 4, as near the water surface as it was practicable to measure air conditions, and assuming various values for C_y, as applied by the formula by adding up to amounts for the intervals throughout the year, it turns out that $C_2=0.022$ or $C_2=0.023$. Since the evaporation in the year ending June 1, 1908, was 51 inches, and for the year ending June 1, 1909, was 59 inches, I am inclined to fix the value, $C_2=0.023$.

The values of C_2 on the 12-foot pan, raised a few inches above the water surface was, $C_2=0.025$, and a probable reduction would bring it to $C_2=0.023$ for a free water surface. The values of C_2 for Birmingham and Cincinnati, in semihumid climates, for a floating 4-foot pan shielded by a surrounding breakwater, was $C_2=0.032$ and by the reduction factor $(1.23)_2$ it would indicate $C_2=0.021$ for an open water surface. In humid climates, especially during the prevalence of fogs and rain, the evaporation is into such an air as always pertains to the *thin layer of vapor resting on the water surface in any climate while undisturbed by the wind.* Our record for the humid stations gives,

for Sand Key, Fla., $C_2=0.022$,
for Eastport, Me., $C_2=0.023$,
for Rangeley, Me., $C_2=0.023$.

It is on the basis of these widely-separated stations that we accept $C_2=0.023$ for the coefficient of evaporation from large water surfaces in 4-hour intervals. For the 24-hours the coefficient is $C_2=0.138\ (1.23)^n$ per day.

9. The final formulas become,

$$\text{Bigelow, } E_{0\,(\text{day})}=0.138\ (1.23)^n \frac{e_s}{e_d}\frac{d_e}{dS}\ (1+.070)\ w \text{ in centimeters.}$$

$$\text{Dalton, } E_{0\,(\text{day})}=0.036\ (1.23)^n\ (e_s-e_d)\ (1+.070)\ w \text{ in centimeters.}$$

In the semihumid and humid climates the values of the C_2 coefficients in the Dalton formula are much looser, and not so much evidence exists of the reliability of this coefficient. Indeed, it is doubtful whether any constant can be found for this formula.

10. Careful experiments made at Rangeley with the several types of gages for measuring the water heights in pans come to the following conclusions: The improved form of still-well, with heavy base and small intake pipe, is as satisfactory as possible. It does good work in ordinary winds, and it may not be practicable to make one that is any better. *The several types of gajes give substantially the same results in ordinary or calm winds when the illumination is good.* In night work, or in dark or dusky weather, it sometimes becomes very difficult to see the setting point of the contact gages when in contact with the water surface, so that the burette tubes then assert their general superiority. The magnifying burette tube has some features which render its record less accurate than the plain burette tube. All these instruments require good observing to measure the tenth millimeter on the water height. The following precautions are suggested: (1) *Plain burette tube.*—Lay a piece of black-surfaced canvas down under the place where the meniscus is read against the sky line, and the apparent lowest edge will look like a *fine black line* against the millimeter scale. After filling the tube lift it to the point of best illumination as the *same level* with the eye to avoid a parallax in reading the curved meniscus. The tube should be *wet above* the reading height, and the water should always flow *upward* to the gravity level. The handling and the reading of the tube must habitually be done in precisely the *same way* at the different observations. The mean of three readings is usually an accurate measure of the water height to the *tenth millimeter*. (2) The magnifying burette tube is easily read, so far as scale is concerned. However, it has a short range, and would not cover 36-48 hours' evaporation, Saturday to Monday, or longer, in the arid, hot climates of the Southwest. The neck should reach lower into the pan in order to avoid the surface surgings in high winds on large pans; the valve should be made to turn horizontally in order to avoid the vertical jump in closing, which may become very irregular whenever it sticks a little or becomes clogged in dirty and alkaline waters; the drip must be handled in a uniform manner from one observation to another. (3) The micrometer gage is very easy to read, and it is an excellent instrument when the seeing and illumination is good. In some kinds of light it is very difficult to recognize the disturbance rings, and in reading large pans, as 6-foot pans when the point is beyond ordinary eye focus length, it often happens that an observer can not tell the instant of contact. If an observer has a poor eyesight, if the larger pan is rocking behind a heavy breakwater, it becomes exceedingly difficult to make the required setting with accuracy. In these cases the plain burette tube is of advantage, because it is filled quite mechanically and lifted for reading into the most favorable light on the level with the eye. (4) The vernier hook gage with *point moving upward* is an excellent instrument in places convenient to the eye, and with good illumination, but has the same difficulty as mentioned with the micrometer gage. (5) The vernier hook gage, with *flattened point moving downward*, is superior to the preceding type, because the water hollow which follows the retreating wire end, and is preserved to the depth of about one millimeter, suddenly snaps at a given level in a very conspicuous manner. This phenomenon makes it very easy to read the contact height under conditions not favorable to the gages 3 and 4. It may be said that evaporation work in windy places is much easier with the plain burette tube than in calm, foggy, or rainy places with the venier hook gages.

11. It is evident that the research of the Salton Sea campaign, while settling a number of important points in evaporation, has raised a series of difficult questions. The theoretical side of the problem, the application to the thermodynamic theories, has not been attempted as this would require an exclusive study under laboratory conditions and processes. Practically it seems necessary for engineers to adopt a standard pan and reduce the observed readings to the open water surface. Thus the evaporation from a 4-foot standard pan, when corrected for temperature and wind and multiplied by the factor 66 per cent is about what observation suggests. If a water thermometer on a small raft in the lake measures S_0, and a sling psychrometer measures e_d through t and t_1, and an anemometer placed as near the water as possible is used for the wind velocity, then the coefficient is $C=0.138$ for 24-hour intervals. For the formula, use the mean values of S_0, e_s, e_d, w, taken at readings made about 6 a. m. and 2 p. m., the times of minimum and maximum meteorological conditions. If any reservoir, where the inflow is measured accurately and the rainfall can be fully accounted for, can be observed for some time it may be possible to further check the accuracy of this formula. Since local conditions count so much on the action of an evaporation pan it would not be possible to improve this formula by any small number of observations. The formula can easily be extended to working tables whenever it is felt that the adopted coefficients of this report are reliable.