DEVELOPMENT OF AN EVAPORATION MAP FOR THE STATE OF WYOMING FOR PURPOSES OF ESTIMATING EVAPORATION AND EVAPOTRANSPIRATION

by

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This thesis uses May through September Class A pan evaporation values to develop Average Annual Class A pan evaporation, and Average Annual Lake Evaporation maps for the State of Wyoming. These maps are then available for use in estimating evaporation and seasonal evapotranspiration values for water resource studies in the State of Wyoming.

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CHAPTER I

INTRODUCTION

Evaporation is defined in the strictest hydrologic sense as the net rate of vapor transfer to the atmosphere. More simply, "evaporation is the process by which water is transferred from land and water masses of the earth to the atmosphere" (Viessman et al., 1977).

Evaporation constitutes a very important phase of the hydrologic cycle. Together evaporation and transpiration utilize much of the water and natural energy that are available on the earth's surface, thereby influencing all hydrological and most meteorological processes. Accurate estimation of evaporation is important in a number of areas. Evaporation from land surfaces, reservoirs, and other water bodies can amount to a very significant amount. Evaporation from arid areas such as Wyoming, is greater than in humid areas. Evaporation is therefore of more concern to the engineer in arid areas.

The following comments serve to illustrate the significance of evaporation. "Anticipated evaporation is a decisive element in design of reservoirs to be constructed in arid regions. Ten reservoirs the size of Lake Mead would evaporate virtually the entire flow of the Colorado River in a normal year, and normal evaporation from Lake Mead alone is equivalent to almost one-third of the minimum annual inflow to the reservoir" (Linsley, Kohler, and Paulhus, 1975). "The annual amount of evaporation from Lake Mead could meet the water supply needs for New York City for approximately one year" (Viessman et al., 1977).

As a result of its extreme significance, evaporation must be predicted as accurately as possible for the design and development of water resource systems. It is indeed unfortunate that accurate and reliable estimates are difficult to obtain (Viessman et al., 1977). All water present on the surface of lakes, reservoirs, and streams is subject to evaporation. Although virtually nothing can be done to prevent these losses, one must be able to determine their quantitative value in order to design and operate many water resource projects.

Inclusion of evaporation in reservoir operation is necessary for successful operation, just as knowledge of evapotranspiration is essential for successful irrigation scheduling. Knowledge of evaporation amounts enables one to obtain better estimates of unmeasurable terms used in a water budget analysis.

Purpose and Objectives

Direct measurement of evaporation is very difficult. As a result, many equations have been developed for estimating evaporation. These equations are based on a wide variety of climatological factors, such as wind velocity, humidity, and temperature. In order to use these equations one must have available a great amount of climatological data. The primary objective of this study was to develop a map of the state of Wyoming consisting of isoevaporation lines. Once developed this map could be used to obtain a reasonably accurate estimate of evaporation anywhere in the state regardless of the availability of climatological data. The initial objective was to develop a map which would be more accurate than any map previously developed for the State of Wyoming for predicting evaporation. Since the available evaporation stations are widely scattered and the records are incomplete and usually seasonal in nature, a means of interpreting, adjusting, and extending pan evaporation values was also a major objective. A secondary objective was to develop a means of obtaining an estimate of evapotranspiration from this same map.

Before initiating work on this study, an extensive literature review was conducted for purposes of locating any relevant literature. The results of this review are discussed in Chapter II of this thesis.

Once the literature review was completed, work was begun compiling and analyzing data. A discussion of the methodology used for data analysis is located in Chapter III.

Following analysis of the data the results were evaluated and conclusions were drawn so that an evaporation map for the State of Wyoming could be developed. Chapter IV contains an evaluation of the results.

CHAPTER II

REVIEW OF LITERATURE

A synopsis of literature pertinent to this study follows. Subjects to be covered include: (1) Factors affecting evaporation; (2) pan evaporation; (3) pan-to-lake coefficient; (4) evaporation maps; and (5) evapotranspiration.

Factors Affecting Evaporation

Many factors have an effect on evaporation. Included among these are solar radiation, wind, vapor pressure, air and water temperature, atmospheric pressure, water quality, and nature and area of evaporating surface (Linsley, Kohler, and Paulhus, 1949 and 1975; Lahoti, 1968; Chow, 1964; and Burman, 1960).

Solar radiation is one of the most important single factors affecting evaporation (Lahoti, 1968). The reason for this is that natural evaporation is an energy exchange process, and the main source of energy for evaporation is supplied by the sun. Linsley, Kohler, and Paulhus (1975) state that by far the most important factor affecting evaporation is solar radiation if one views evaporation as an exchange process.

Evaporation is dependent on wind. Without wind, evaporation would occur only until equilibrium was achieved between the water body and the surrounding atmosphere. Wind has the effect of removing saturated air and moving in air capable of holding additional water vapor. Reservoir surface area may greatly determine the effect wind will have on evaporation. Wind will have a more pronounced effect on large surface areas. The amount of evaporation normally will increase with wind movement (Burman, 1960).

The rate of evaporation is also dependent upon the difference between the vapor pressure of the water and the vapor pressure of the air above the water surface. If the air is warmer than the water, evaporation will occur until the vapor pressure of the air is equal to the vapor pressure of the water. If the water is warmer than the air, condensation will take place and evaporation will be greatly increased as the fog is dissipated by wind action. Based on these facts, maximum evaporation will occur when the water is warmer than the air (Linsley, Kohler, and Paulhus, 1949).

Temperature is another important factor affecting evaporation. Evaporation is directly dependent on temperature. As the temperature increases, the evaporation rate will also increase. The reason for this is the direct increase in the vapor pressure of the water as the temperature is increased (Chow, 1964).

Evaporation is inversely affected by atmospheric pressure. Therefore, as the atmospheric pressure increases, the evaporation rate will decrease. Linsley, Kohler, and Paulhus (1949) state that, "atmospheric pressure is so closely related to other factors affecting evaporation that it is practically impossible to study the effects of its variation under natural conditions." Thus, while atmospheric pressure is known to affect evaporation, its exact effect has not been clearly established.

The quality of evaporating water appears to have only a slight effect on evaporation. The evaporation rate for salt water is somewhat less than the rate for fresh water, and the rate decreases further as the specific gravity of the water increases. Turbidity alone, however, appears to have no noticeable effect on the rate of evaporation (Linsley, Kohler, and Paulhus, 1949 and 1975; and Chow, 1964).

The final factor to be discussed which has some effect on evaporation is the nature and area of the evaporating surface. There are many different surfaces from which evaporation takes place. Among these are soil surfaces, vegetation, and snow and ice (Linsley, Kohler, and Paulhus, 1949).

The availability of water is the important factor affecting the rate of evaporation from a soil surface. If a soil surface is saturated, the evaporation rate will differ only slightly from that of a water surface at the same temperature. Linsley, Kohler, and Paulhus (1949) state that during the warm summer months, evaporation from a saturated soil surface can exceed that from a water surface. If, however, the soil surface is not saturated, the lack of available moisture will become a factor which limits evaporation.

The availability of water, or evaporation opportunity, is also an important factor affecting evaporation from exposed surfaces of vegetation. A portion of all precipitation retained on these surfaces is returned to the atmosphere by evaporation. The amount of evaporation from vegetation may well be in excess of that from a water surface due to the large surface area present in a bush or tree (Linsley, Kohler, and Paulhus, 1949; and Lahoti, 1968). It has also been shown that the amount of evaporation depends on the roughness of the vegetation. A hydraulically rough surface (alfalfa) will evaporate more than a hydraulically smooth surface (grass) (Jensen, 1973).

It is more difficult to measure evaporation from snow (vaporization or sublimation) than from water surfaces. The maximum temperature which a snow surface can attain is 32°F. Therefore unless the dewpoint is below 32°F, evaporation cannot take place. Under most conditions evaporation from a snow surface is less than from a water surface. The only conditions favoring high evaporation from snow is chinook or similar wind conditions (Linsley, Kohler, and Paulhus, 1949; and Lahoti, 1968).

Pan Evaporation

The most common means currently used for measuring evaporation is the evaporation pan. The evaporation pan has been in use for many years, and will probably continue to be used as it is the cheapest and most generally accepted means of measuring evaporation.

The U.S. Weather Bureau Class A evaporation pan is the officially recognized means of measuring evaporation in the United States and has been for more than 20 years. The Class A pan is circular with a diameter of four feet and a depth of 10 inches, and is supported on a base of 2 x 4 lumber. The depth of water within the pan is supposed to be maintained at a relatively constant level, usually in the range of 7 to 8 inches of water depth, and is measured by means of a hook gage or point gage in a stilling well (Stall and Roberts, 1967). Additional climatological data-measuring equipment necessary at an evaporation station includes a rain gage and an anemometer located 6 inches above the rim of the pan. Wind movement is recorded in miles per day.

Class A evaporation data, although widely accepted as the best evaporation data available, are subject to several limitations. Included among these are: (1) difficulty in establishing an accurate pan-to-lake coefficient for means of relating measured pan evaporation to actual lake evaporation; (2) lack of annual data, as the pan can only be operated during the warm seasons in Northern latitudes; (3) relatively short periods of record available, as very few sites have more than 20 years of record in the United States (Stall and Roberts, 1967); and (4) pan performance is highly dependent on fetch and conditions surrounding the pan (Hounam, 1973; and Jensen, 1973).

Pan-to-Lake Coefficient

Since the rate of evaporation from small lakes is greater than evaporation from large lakes (Chow, 1964), a reduction coefficient is necessary to convert pan evaporation to lake evaporation. An abundance of work has been performed on this subject (Chow, 1964; Linsley, Kohler, and Paulhus, 1949 and 1975; Linsley and Franzini, 1972; Viessman et al., 1977; Brown, 1970; Lahoti, 1968; and Horton, 1943). The results of these analyses indicate that an annual average pan coefficient of approximately 0.7 is applicable for means of determining reservoir evaporation. Linsley and Franzini (1972) state that use of this coefficient should provide estimates of annual lake evaporation within 15 percent if both lake and pan are subjected to similar climatic conditions. An analysis reviewed by Linsley and

Franzini (1972) found that an annual average pan coefficient of 0.7 was obtained from all reliable determinations. Linsley, Kohler, and Paulhus (1949) recommend use of this coefficient because it has "relatively little geographic variation." It is recommended that one deal with annual evaporation rather than seasonal or monthly evaporation. Viessman et al. (1977) state that "ratios of annual reservoir evaporation to pan evaporation are consistent from year to year and region to region, while monthly ratios often show considerable variation."

Evaporation Maps

Numerous annual evaporation maps have been drawn in the past for parts and all of the continental United States (Chow, 1964; Meyer, 1942; Meyers, 1962; Linsley and Franzini, 1972; and Horton, 1943). As stated earlier, the purpose of this study was to obtain an improved evaporation map for the State of Wyoming. Analysis of these earlier maps provides a basis for comparison of results and procedures.

Of these earlier maps, the latest was prepared by the National Weather Service in 1968, and is shown in Figure 1 (Linsley and Franzini, 1972). Although it is the most recent, this map is less detailed than those prepared earlier by Horton (1943), Meyer (1942), Kohler, Nordenson, and Baker (Meyers, 1962), and Viessman et al. (1977) (Figures 2, 3a, 3b, and 4). Kohler, Nordenson, and Baker (Meyers, 1962) show values quite different than Horton (1943) and Meyer (1942), but include more recent and complete pan data, supplemented by estimates of evaporation based on meteorological factors.

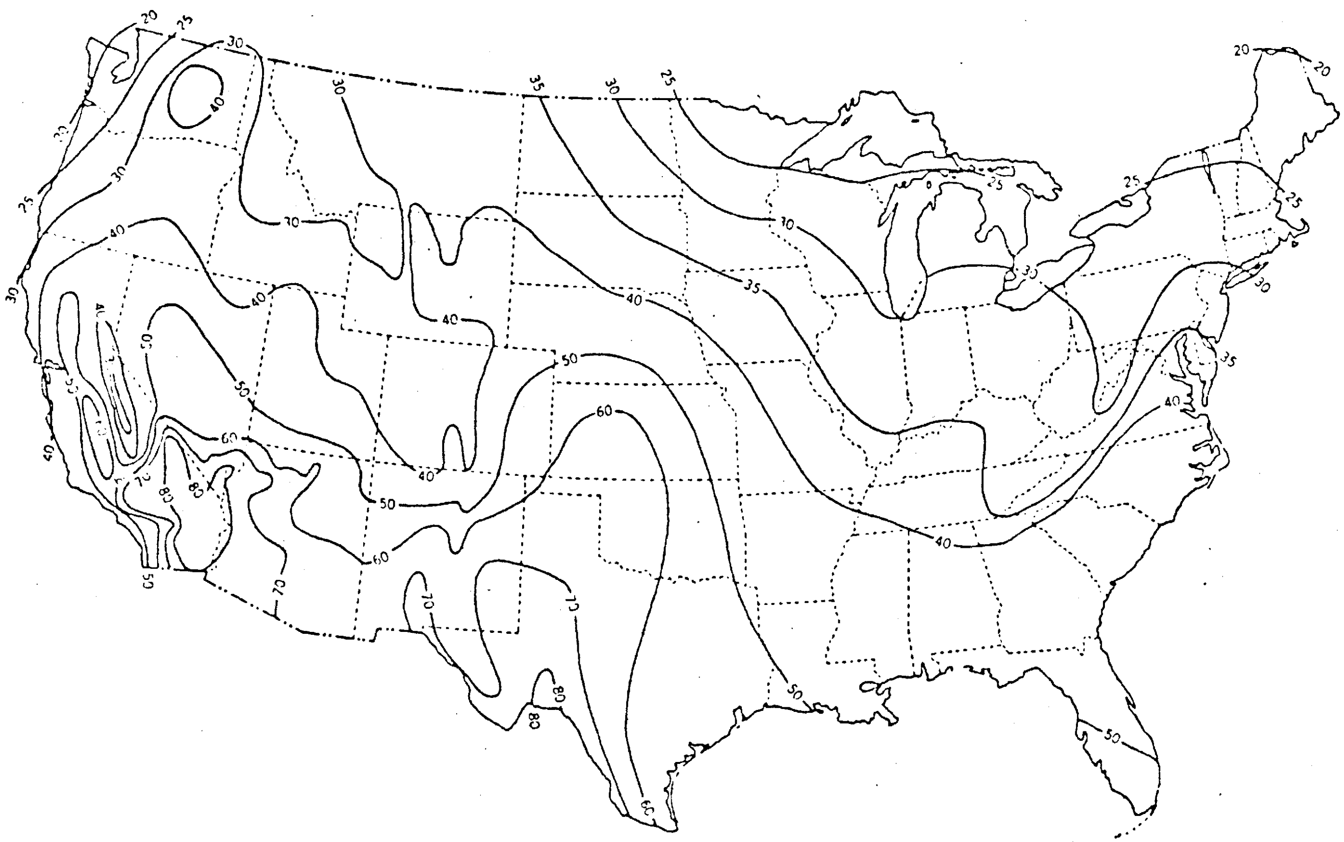


Figure 1. Average Annual Lake Evaporation in inches developed by the National Weather Service (Linsley and Franzini, 1972).

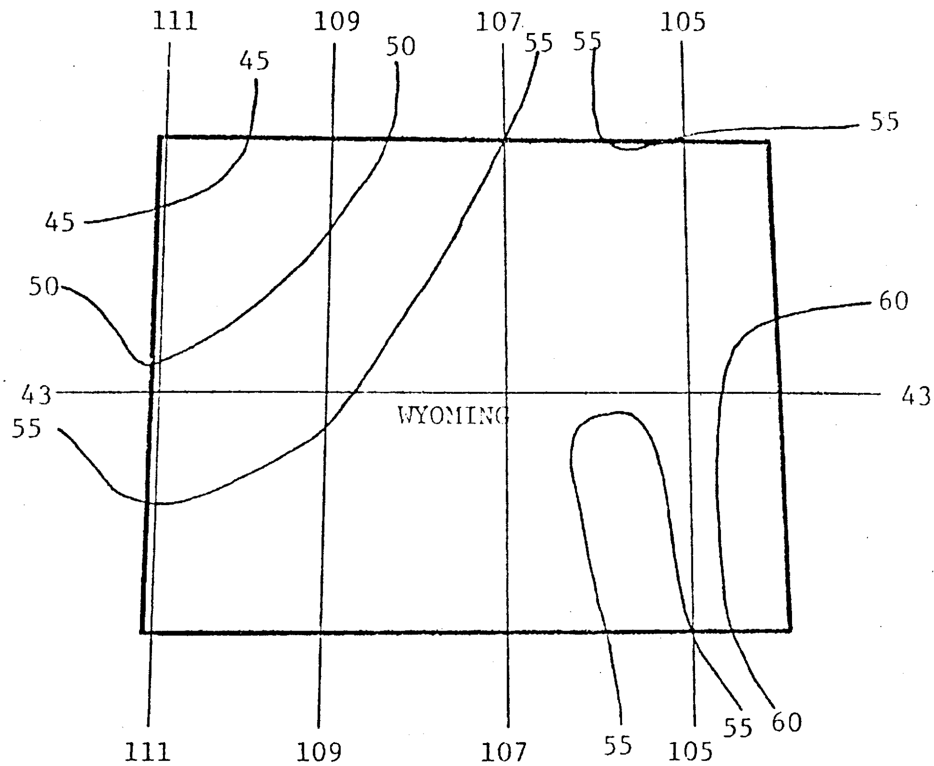


Figure 2. Average Annual Lake Evaporation, in inches (Horton, 1943).

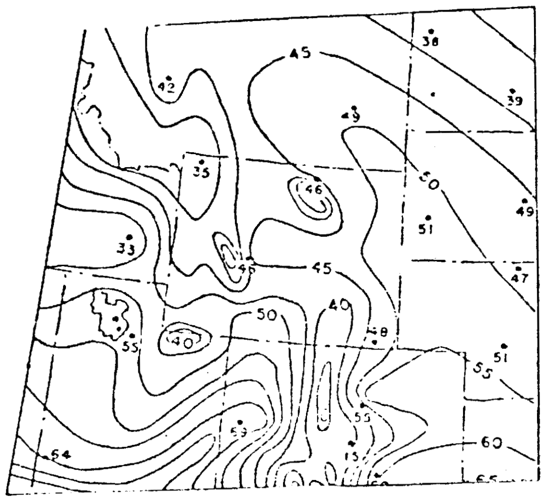


Figure 3a. Mean Annual Evaporation from Shallow Lakes and Reservoirs, in inches. (Meyer, 1942)

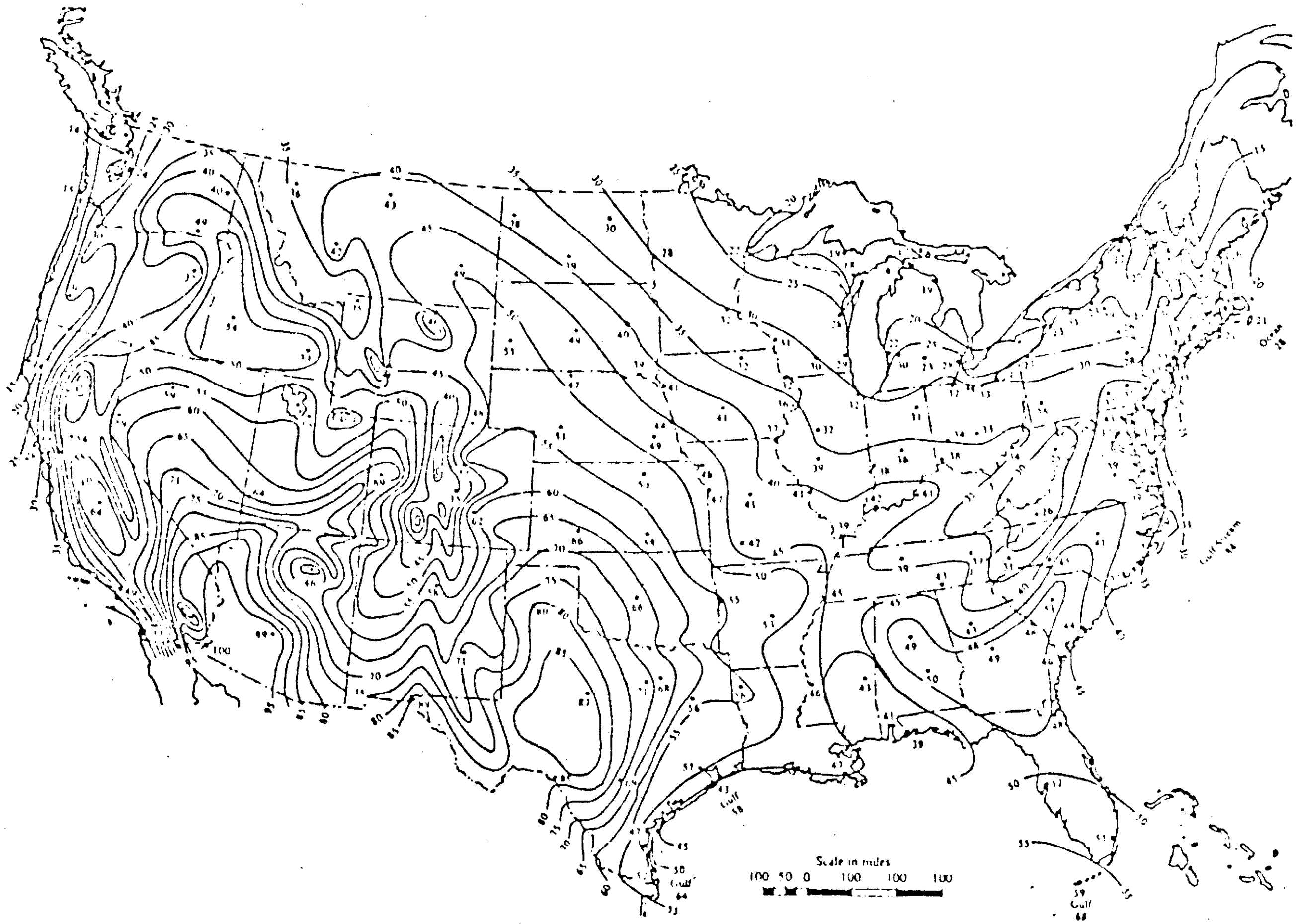


Figure 3b. Mean Annual Evaporation from Shallow Lakes and Reservoirs, in inches. (Viessman et al., 1977)

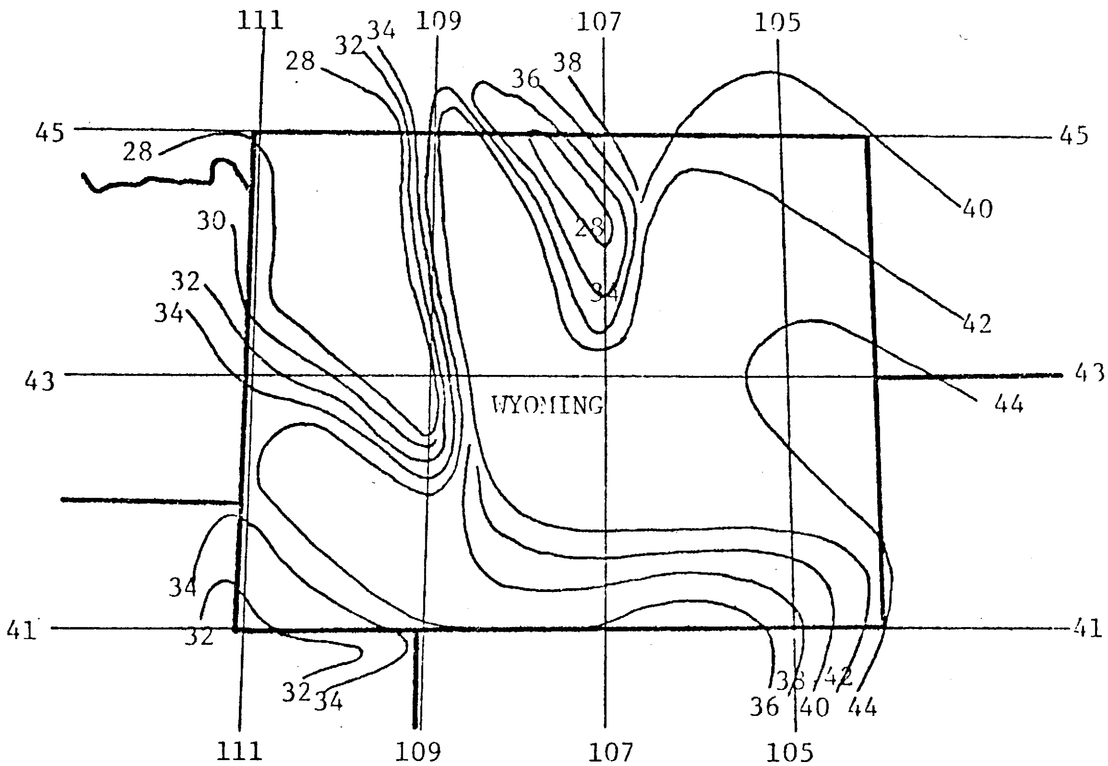


Figure 4. Average Annual Lake Evaporation, in inches, for the 10-Year Period 1946-55 (Meyers, 1962).

Kohler, Nordenson, and Baker (Meyers, 1962) used the following steps in the preparation of their map:

1. The data used were averaged over a 10-year period (1946-55).
2. Meteorological factors were adjusted as required for estimation of evaporation.
3. Monthly and seasonal values of evaporation were adjusted to annual values using relations derived by Kohler, Nordenson, and Fox (Meyers, 1962), and using ratios of annual to seasonal evaporation.
4. Pan-to-lake coefficients were computed using relations from Kohler, Nordenson, and Fox (Meyers, 1962).
5. Values of class A pan evaporation were plotted and isopleths were drawn between the plotted points.
6. Pan-to-lake coefficients were plotted on a similarly scaled map and isopleths were drawn between the plotted points.
7. Values of annual lake evaporation were obtained at any desired point by multiplying values from steps 5 and 6 at that point.
8. Values of annual lake evaporation determined by special investigations such as Lake Hefner and Lake Mead were plotted on another map.
9. A final evaporation map was drawn with consideration being given to the values obtained from steps 7 and 8.

The evaporation rates shown on the final map were recommended for use only as annual values, as they were expressed in terms of the average number of inches for a full year. Use of the map for estimating monthly or seasonal evaporation is possible, but would be applicable only to shallow lakes or reservoirs.

Isopleths were drawn with regard to topography between control points. Therefore, the accuracy is best near control points. The error should be within 10 percent. Somewhat less accuracy, however, can be expected in areas between control points (Meyers, 1962).

Evapotranspiration

Total evaporation is the sum total of evaporation, transpiration, and the amount of water used in building and sustaining plant tissue. From a practical standpoint, total evaporation is taken as the difference between the inflow and outflow of water in a basin. A commonly made assumption is that total evaporation is equal to the difference between precipitation and streamflow. While this assumption gives reasonable long-term averages, it may lead to serious errors if applied for short periods of time to small basins (Linsley, Kohler, and Paulhus, 1949). Total evaporation (consumptive use) and evapotranspiration often are used synonymously in the literature as there is only a slight difference between the two (Linsley, Kohler, and Paulhus, 1975). The term evapotranspiration will be used in the remainder of this discussion.

An engineer may be more concerned with evapotranspiration than he is with either evaporation or transpiration alone. Evapotranspiration, as defined by Linsley, Kohler, and Paulhus (1949), includes all water losses from an area by both transpiration and evaporation and is a quantity necessary for determining the hydrologic balance for a given area. Evaporation, as previously defined, is generally taken as "the process by which water is transferred from land and water masses of the earth to the atmosphere" (Viessman et al., 1977). Transpiration is the process by which water leaves plants and returns to the atmosphere as water vapor (Linsley, Kohler, and Paulhus, 1949). Transpiration often exceeds evaporation in amount and importance. Methods of estimating transpiration are necessary, as it is difficult to measure transpiration loss under natural conditions (Linsley, Kohler, and Paulhus, 1949). Estimating water requirements for crop production is the principal use for evapotranspiration data. Due to economic reasons, it is usually impractical to conduct extensive investigations on small projects. As a result, the water requirement must be estimated.

Several methods have been developed for estimating evapotranspiration from climatological data. Two of these methods chosen for analysis are Thornthwaite and Blaney-Criddle. Thornthwaite's method involves using only temperature and duration of possible sunshine. Blaney-Criddle's method uses the same two parameters, but also involves transposing consumptive use data to irrigated areas with the use of crop coefficients (Linsley, Kohler, and Paulhus, 1975).

The Thornthwaite method was developed in 1948 by correlating mean monthly air temperature with evapotranspiration. The data were based on water balance studies conducted in the east-central United States. An adequate soil moisture was maintained so as not to limit evapotranspiration. The Thornthwaite formula is as follows (Pair, 1975):

$$P.E.T. = 1.6\ L_d\ \left(\frac{10t}{I}\right)^a$$

where P.E.T. = the 30-day value of estimated evapotranspiration, cm;

L_d = daytime hours in units of 12 hours;

t = mean monthly air temperature, °C;

I = heat index obtained by summing 12 monthly indices,

$$i = (\frac{t}{5})^{1.514};$$

and $a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-3} I + 4.9239 \times 10^{-1}$.

Since this method was developed for the east-central United States results could not be expected to be entirely accurate for the arid and semi-arid western United States.

The Blaney-Criddle method was developed in the 1920's and 1930's using soil sampling techniques to make measurements of evapotranspiration. This method has been modified as recently as 1962 for use in its present form. The Blaney-Criddle formula for seasonal estimates is as follows (Pair, 1975):

$$U = KF = \Sigma kf$$

where U = estimated evapotranspiration (consumptive use) in inches for the growing period or season;

K = empirical consumptive use coefficient (irrigation season or growing period);

F = the sum of monthly consumptive use factors, f, for the season or growing period (f = tp/100, where t = mean monthly air temperature in °F, and p = mean monthly percent of annual daytime hours);

and k = monthly consumptive use coefficient.

Use of this method in climatic zones different from those of the western United States may result in less accurate estimates.

An average seasonal consumptive use map has been prepared for the State of Wyoming by Trelease et al. (1970) (Figure 5). This map was prepared for grass, as it is the most widely grown irrigated crop in Wyoming. Evapotranspiration (consumptive use) values were found using the Blaney-Criddle method. Mountainous areas are not represented on the map.

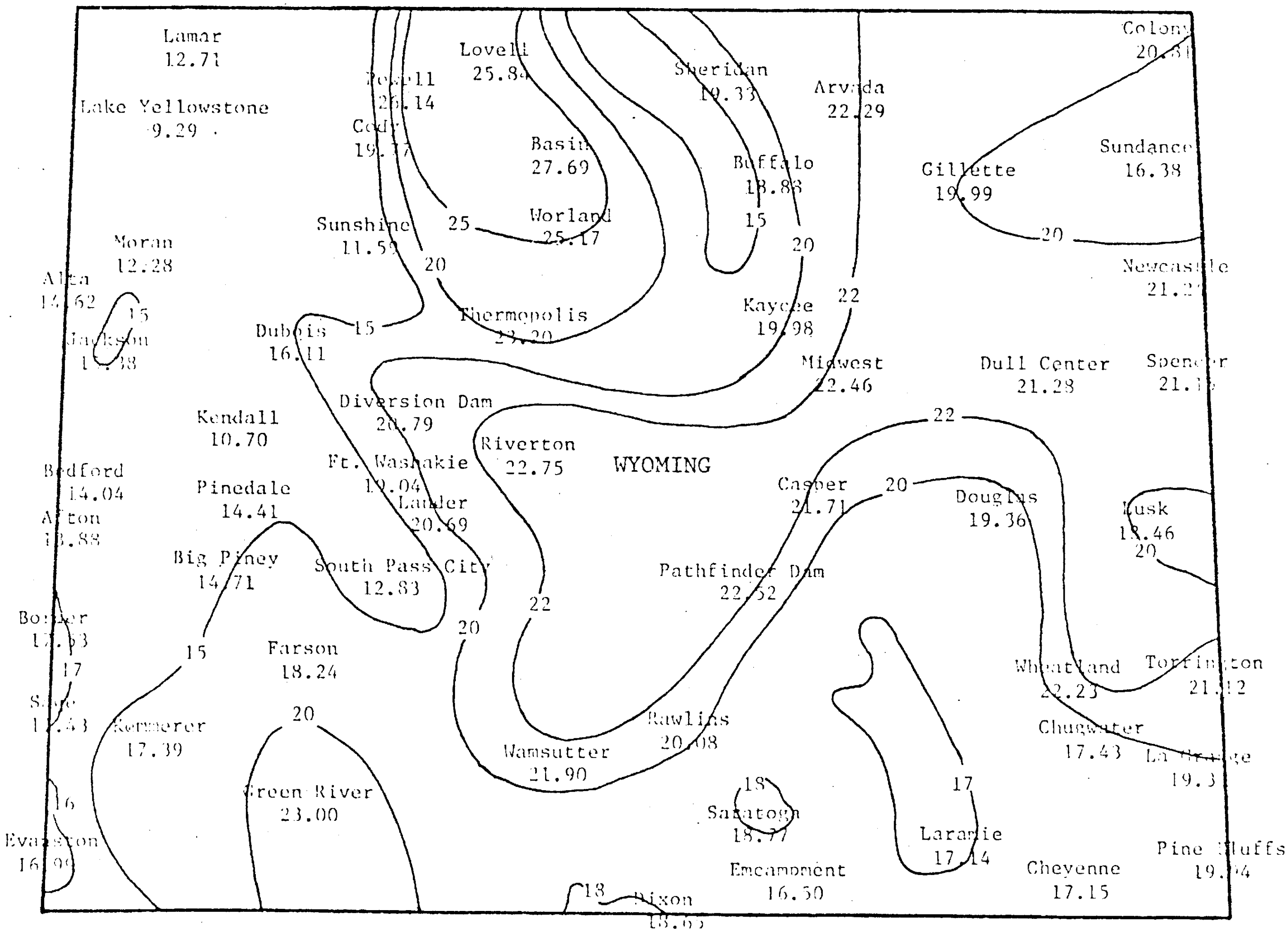


Figure 5. Average Seasonal Consumptive Irrigation Requirement for Grass, in inches (Trelease et al., 1970).

CHAPTER III

METHODOLOGY

A description of the types of analysis used to analyze the data relevant to this study are contained in this chapter. Topics to be covered include: (1) Location of Data; (2) Elimination of Data; (3) Methods of Analysis; (4) Factor Analysis; (5) Data Analysis; and (6) Evapotranspiration Analysis.

Location of Data

For purposes of data compilation and analysis, a five-month period from May through September of each year was chosen. Data either were not available or were quite incomplete for the rest of the year at almost all of the stations chosen for investigation. Evaporation information is collected at only a few of the many sites within the State of Wyoming where it is needed. For this information to be of value, one must have means of accurately estimating evaporation at other locations. The purpose of this study, as stated earlier, was to develop such a means of estimation.

A total of 26 stations were chosen for analysis based primarily on data availability. Of these stations, 17 were within Wyoming and nine were in states bordering Wyoming. Table I gives the name, location, and years of evaporation record for all the stations used in this study. Figure 6 indicates the location and distribution of these stations.

TABLE I

STATION INDEX

Station Name	County	State	Latitude	Longitude	Elevation (msl)	Years of Record of Evaporation
Anchor Dam	Hot Springs	Wyoming	43 40	108 50	6460	15
Archer	Laramie	Wyoming	41 09	104 39	6010	17
Boysen Dam	Fremont	Wyoming	43 25	108 11	4642	27
Farson	Sweetwater	Wyoming	42 07	109 27	6595	19
Gillette 2E	Campbell	Wyoming	44 17	105 28	4556	13
Glendo 4SW	Platte	Wyoming	42 27	105 05	4750	17
Green River	Sweetwater	Wyoming	41 32	109 28	6089	16
Guernsey Dam	Platte	Wyoming	42 18	104 46	4355	4
Heart Mountain	Park	Wyoming	44 41	108 57	4790	26
Keyhole Dam	Crook	Wyoming	44 23	104 46	4190	9
Laramie 2NW	Albany	Wyoming	41 21	105 37	7130	9
Lookout 14NE	Albany	Wyoming	41 50	105 38	6965	6
Morton 1NW	Fremont	Wyoming	43 13	108 47	5490	17
Pathfinder Dam	Natrona	Wyoming	42 28	106 51	5930	14
Seminoe Dam	Carbon	Wyoming	42 08	106 53	6838	17
Sheridan Field Station	Sheridan	Wyoming	44 51	106 52	3800	18
Whalen Dam	Goshen	Wyoming	42 15	104 38	4294	27
Flaming Gorge	Daggett	Utah	40 56	109 25	6270	19
Manila	Daggett	Utah	41 00	109 43	6420	16
Wanship Dam	Summitt	Utah	40 47	111 24	5940	18
Island Park Dam	Fremont	Idaho	44 25	111 24	6300	12
Lifton Pumping Station	Bear Lake	Idaho	42 07	111 18	5926	19
Palisades Dam	Bonneville	Idaho	43 21	111 13	5385	18
Yellowtail Dam	Big Horn	Montana	45 08	107 23	3292	7
Pactola Dam	Pennington	So. Dakota	44 04	103 29	4720	18
Mitchell 5E	Scotts Bluff	Nebraska	41 57	103 41	4080	24

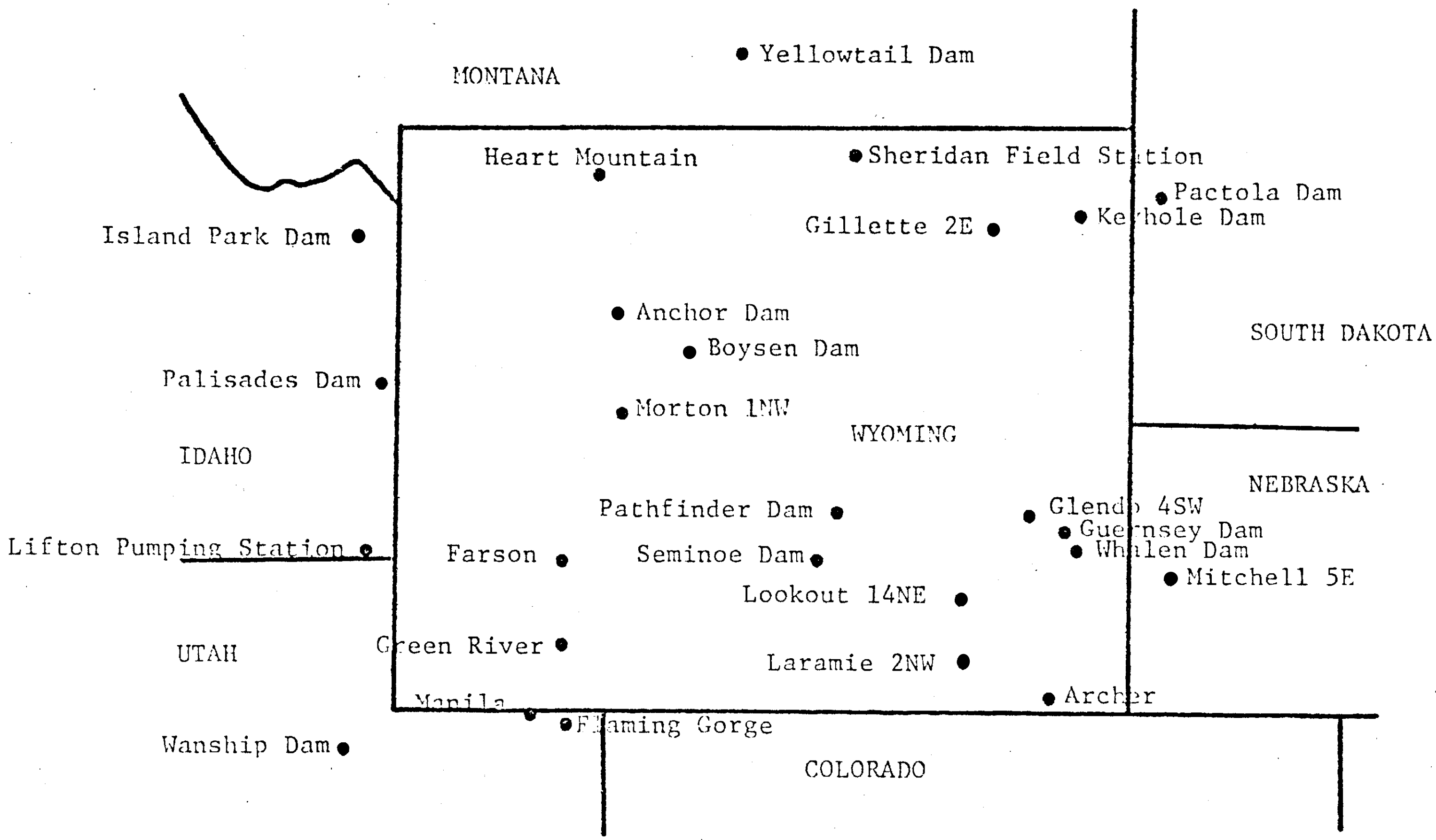


Figure 6 - Location and Distribution of Evaporation Stations

Elimination of Data

Due to lack of data other than evaporation at several stations, and other reasons to be discussed later only 20 of the total 26 stations were used for statistical analysis. The stations which were not used include Seminoe Dam, Glendo 4SW, Guernsey Dam, Boysen Dam, Morton 1NW, and Keyhole Dam. The Seminoe Dam, Glendo 4SW, and Guernsey Dam stations were not used in the statistical analysis because they are U.S. Bureau of Reclamation stations rather than U.S. Weather Bureau stations, and as such only evaporation data were available. Boysen Dam data were eliminated on the basis of its physical setting. From the visual inspection made of this station, it was felt that the evaporation pan was in a poor location and was not representative of the surrounding area. The Morton 1NW station was not used because it was moved twice during a period of eight years, and evaporation values at this station were considerably different from those of other stations in the same general area. The Keyhole Dam data were not included because only two years of record were available within the 20 year period chosen for analysis. It should be noted that all stations were not visually inspected, and some of the stations included in the analysis possibly should have been eliminated. However, since no further reasons for elimination were known, the remainder of the stations were included in the analysis portion of this study.

Methods of Analysis

The available period of record varied considerably from station to station (Table I). However, for statistical purposes, all data were adjusted to a common base period of 20 years. The method of least squares linear regression was chosen for adjustment purposes as this is the most commonly used method for relating two sets of hydrologic data (Klemes, 1973). Another method which was considered for use in adjusting the data was double-mass analysis. However, due to unexplainable changes in slope (breaks in slope, nonlinearities, etc.) on the double mass plots, the method of least squares was felt to be the best method for record adjustment. Computations were performed with the use of the Sigma 7 digital computer at the University of Wyoming and the 'RMDV'-Multiple Dependent variable regression and correlation program.

Before statistical analysis could begin, it was necessary to choose a base station. Once chosen, this station would serve as the independent variable in any regression analysis performed. In order to properly determine which station would best serve as a base station, visual inspection of existing stations was deemed necessary. Having made this decision, a visit to ten evaporation stations throughout the State of Wyoming was made. All but one of the stations visited were official weather bureau evaporation monitoring stations. The official stations visited include Archer, Whalen Dam, Pathfinder Dam, Gillette 2E, Sheridan Field Station, Heart Mountain, Anchor Dam, Boysen Dam, and Laramie 2NW. The one exception was Seminoe Dam, which is operated by the U.S. Bureau of Reclamation. Of the other stations analyzed in this study, all are or were at one time official weather bureau stations except Glendo 4SW and Guernsey Dam, which again are operated by the U.S. Bureau of Reclamation.

Figure 7. Pathfinder Dam Evaporation Station

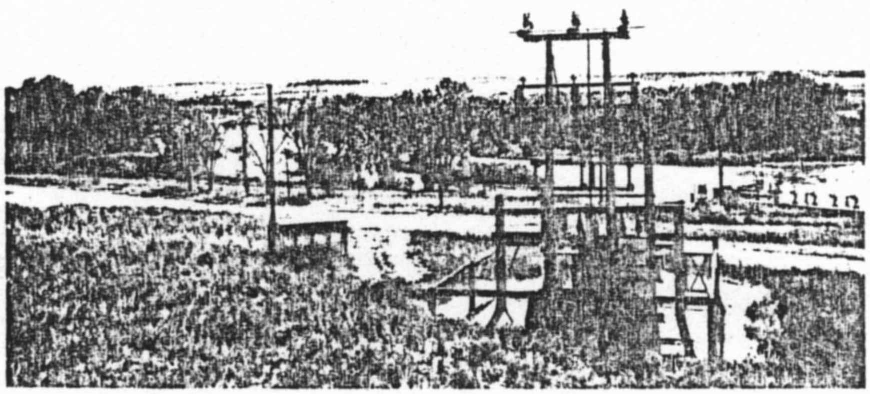
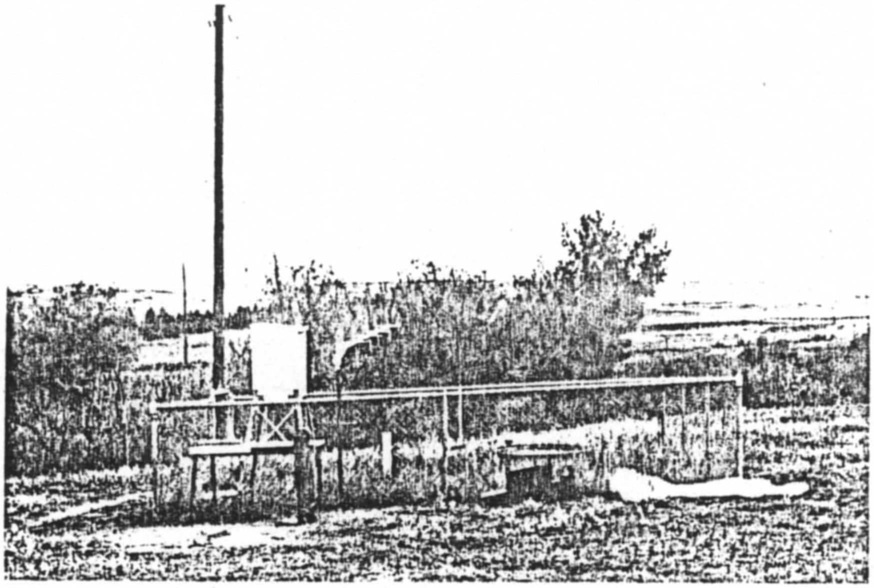
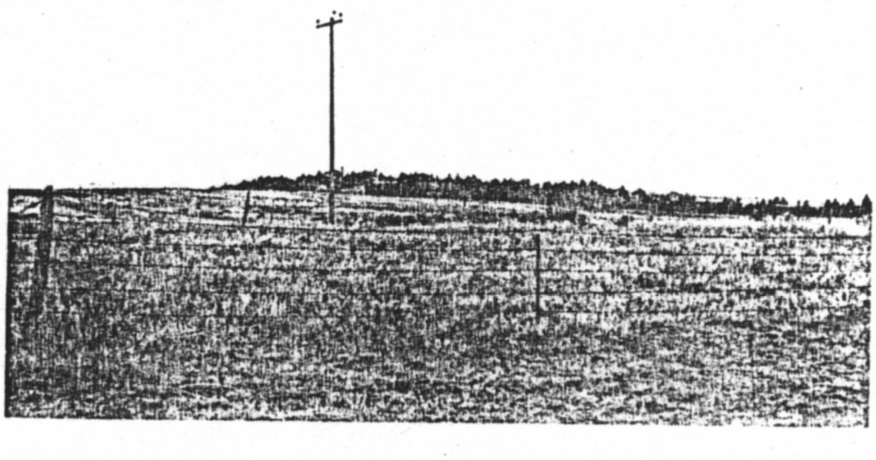


Figure 8. Whalen Dam Evaporation Station



(a)



(b)

Figure 9. Gillette 2E Evaporation Station
(a) Closeup of station looking North
(b) Overall view of station, looking North-west, showing existence of tree shelter-belt

On the basis of this inspection along with investigation of station location and equipment changes, there were two stations which were felt would adequately serve as base stations. Of these two, Pathfinder Dam and Whalen Dam (Figures 7 and 8, respectively), it was felt that Pathfinder Dam was the most suitable. However, further analysis revealed that a noticeable change occurred in the recorded values of evaporation at Pathfinder Dam in 1962. Further investigation revealed that a procedural change had been made in 1962 which accounted for the discrepancy in the data. Because of this change, only Pathfinder evaporation data in 1962 and later years were used in further analysis. This adjustment left only 14 years of evaporation data available at Pathfinder Dam. Since 27 years (1949-1975) of evaporation data were available at Whalen Dam, that station was chosen as the base station for further analysis.

There were several reasons why the remaining eight stations were felt to be unsuitable for use as base stations. These reasons were based on visual inspection of the stations. Archer, Gillette 2E, and Heart Mountain were surrounded by tree shelterbelts and were therefore felt to be unrepresentative of the surrounding country. Figure 9 illustrates the tree shelterbelt effect. Anchor Dam was felt to be unsuitable because it was surrounded on three sides by buildings and immovable vehicles. Also, it was located on the point of a ridge where, according to the operator, the wind blew more than was normal for the surroundings. Sheridan Field Station was surrounded by both tree shelterbelts and buildings and was not protected from animal use by a fence. The location of the Boysen Dam evaporation pan was felt

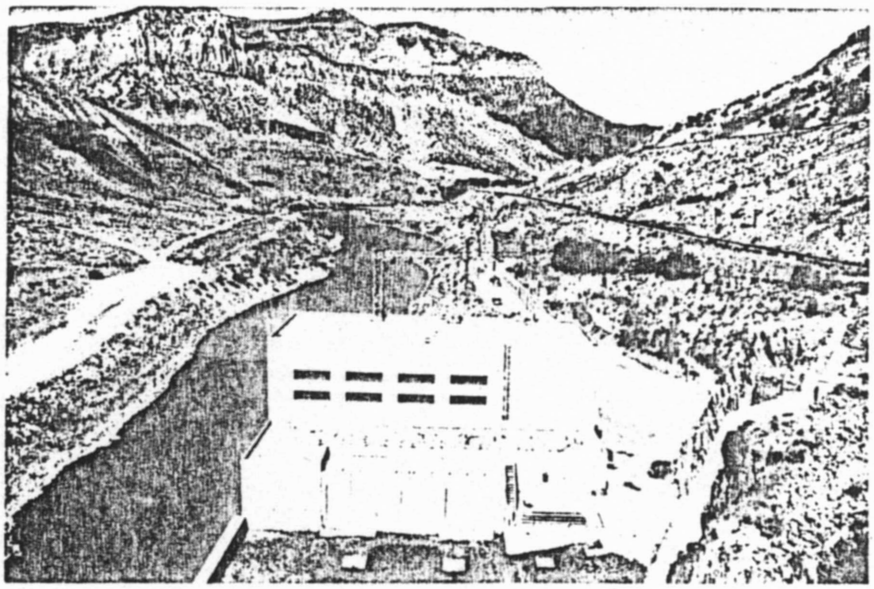


Figure 10. Boysen Dam Evaporation Station

to be the worst of all stations as it was set on an asphalt surface at the bottom of a deep canyon. This location as well as a nearby tree served to protect the pan from natural wind conditions (Figure 10). The Laramie 2NW site was eliminated not so much from a poor location standpoint, but because of the unknown effect of its close proximity to the only sizable body of water in the area, the city of Laramie's sewage lagoon.

Factor Analysis

Determination of which climatological factors are important to evaporation, which of these are currently being measured, and which factors would be used in future analysis, was developed using the following criteria. Available data for significant factors was necessary before proceeding with any analysis. As discussed earlier, many factors have an influence on evaporation. Of these, most are difficult to measure and available data are limited. As a result, wind, temperature, and elevation were the only variables chosen for further analysis because data were readily available. Values of annual precipitation also were analyzed in an attempt to establish a relationship with a correlation sufficient for use in estimating evaporation. The sources for the data analyzed were NOAA's annual summaries of climatological data, and records of the U.S. Bureau of Reclamation.

Data Analysis

Using Whalen Dam evaporation data as the base, double mass plots, statistical analysis, and evaporation adjustment coefficients were used to analyze the available data. Once the data were compiled into usable form, double mass plots were drawn. The double mass plot, "provides a means of determining the consistency of observations collected over a long period of time" (Kohler, 1949). Results from these plots were deemed insufficient to make adjustments in the data. Although breaks (slight changes in slope, nonlinearities, etc.) in slopes did occur on a number of stations, the cause of these breaks could not be ascertained as they did not necessarily correspond with changes in station location or other physical activities. "Neglecting to make a questionable adjustment is a sounder course than adjusting records which may, in reality, be comparable as observed" (Kohler, 1949).

Although the data were not adjusted following double-mass analysis, some adjustment of the data did take place. This adjustment was based on the visual inspection of the stations. This inspection was used to determine if any physical features at the individual evaporation pan sites could be a factor. It was found that several stations were sheltered to a significant degree by tree shelterbelts. Data adjustment for the tree shelterbelt stations was based on an article by Hanson and Rauzi (1977). This study indicated that evaporation from pans protected from the wind by tree shelterbelts was about 14 percent less than that from unprotected pans. "Decreased evaporation leeward of shelterbelts is due to decreased wind velocities, but turbulence is increased, which increases evaporation and, thus, evaporation is decreased proportionately less than are wind velocities" (Hanson and Rauzi, 1977). Based on this study evaporation values at

Archer, Gillette 2E (which was one of two stations included in the study by Hanson and Rauzi), and Heart Mountain were increased by 14 percent before being included in further statistical analysis. The statistical analysis consisted of running multiple linear regression using evaporation as the dependent variable and wind, temperature, elevation, and precipitation as the independent variables. Only 20 of the total 26 stations were used in the statistical analysis for reasons previously mentioned.

Following statistical analysis, the only additional adjustment which had to be made was conversion of the May through September evaporation values to annual values. This adjustment was made using a monthly distribution developed by analyzing annual evaporation data.

It should be pointed out that the May through September evaporation values used for adjustment to annual values were averages over the actual period of record for each station rather than the average over the 20-year extended period of record used for statistical analysis. It was not felt that use of averages over the extended period of record was justified due to the highly variable and generally low correlation coefficients obtained from statistical analysis.

Once annual values were obtained, an average annual pan evaporation map was drawn using isoevaporation lines to indicate the distribution of evaporation across the State of Wyoming. An additional map showing annual lake or reservoir evaporation also was plotted. Values for the lake evaporation map were obtained by multiplying annual pan evaporation by a pan-to-lake coefficient of 0.7.

Listed below is a chronological summary of the steps used in the preparation of the above mentioned evaporation maps:

1. Average evaporation values were determined for each station over the period of record for that particular station. It was not felt that use of extended data would give more accurate results due to the low correlation coefficients obtained from regression analysis.
2. Average May through September evaporation values were extended to annual values using a monthly distribution.
3. Values of Class A pan evaporation were plotted and isevaporation lines were drawn between plotted points. Isoevaporation lines were drawn with regard to known evaporation values only, and did not take topographic effects into account.
4. Values of annual lake evaporation were obtained by multiplying values from step 3 at any point by the pan-to-lake coefficient of 0.7.
5. Values of annual lake evaporation were plotted and isevaporation lines were drawn between plotted points.

Evapotranspiration Analysis

An analysis was performed for the computation of evapotranspiration values at numerous points throughout the state. In performing this analysis, two methods of estimating evapotranspiration were used. These methods, Blaney-Criddle and Thornthwaite, were chosen because the necessary climatic data were readily available. Other methods, including Penman and Jensen-Haise, although accepted as viable methods for calculating evapotranspiration, require solar radiation, which is available at only three stations in Wyoming. These methods therefore were eliminated from this analysis. The purpose of this analysis was to provide the planner with a reliable means of estimating evapotranspiration using the evaporation maps developed.

Blaney-Criddle values of evapotranspiration were obtained from Wyoming Water Planning Report No. 5 (Trelease et al., 1970). Use of the Thornthwaite method of analysis followed a discussion in Sprinkler Irrigation (Pair, 1975).

CHAPTER IV

RESULTS

Evaporation Map

The main purpose of this study was to develop evaporation maps for the State of Wyoming which would be more accurate than other previously developed maps. The increased accuracy was to be due to a larger data base and a study effort which concentrated solely on Wyoming, rather than on a much larger area as was generally the case in previous studies. Before these maps were drawn, the results obtained from the data analysis, as discussed in the methodology section, had to be analyzed and any pertinent results reflected in the final drawing of the maps. Table II contains tabulated values of the data used to draw the maps developed in this study.

Statistical analysis was performed on the climatic factors affecting evaporation using multiple regression. This technique is based on the assumption that certain climatic variables affect evaporation in such a way that the relationship of this effect can be discerned by this type of analysis. The results of the statistical analysis are shown in Table III, and the data used for the analysis can be found in Table IV.

Average evaporation values over the actual period of record (May through September) for each station were used in drawing the evaporation maps rather than the extended data used for statistical analysis. An interesting point, however, should be made. There was

TABLE II

COMPARISON OF MAY THROUGH SEPTEMBER PAN EVAPORATION, ANNUAL PAN EVAPORATION AND LAKE EVAPORATION

Station	Total May-Sept Pan Evaporation $Evap_o$	Annual Evaporation $Evap_o \div .688$	Lake Evaporation Annual Evap. x 0.7
Laramie 2NW	48.90	71.08	49.75
Pathfinder Dam	46.15	67.08	46.95
Boysen Dam	42.55	61.85	43.29
Whalen Dam	43.45	63.15	44.21
Heart Mountain	41.00	59.59	41.72
Anchor Dam	40.30	58.58	41.00
Green River	50.45	73.33	51.33
Keyhole Dam	40.30	58.58	41.00
Gillette 2E	46.90	68.17	47.72
Sheridan Field Station	42.05	61.12	42.78
Archer	46.05	66.93	46.85
Farson	43.80	63.66	44.56
Lookout 14 NE	48.35	70.28	49.19
Seminoe Dam	42.15	61.26	42.89
Glendo 4 SW	47.55	69.11	48.38
Guernsey Dam	43.60	63.37	44.36
Morton 1NW	34.50	50.15	35.10
Yellowtail Dam	44.25	64.32	45.02
Pactola Dam	26.45	38.44	26.91
Mitchell 5E	39.90	57.99	40.60
Wanship Dam	32.40	47.09	32.97
Flaming Gorge	40.70	59.16	41.41
Manila	42.75	62.14	43.50
Lifton Pumping Station	35.30	51.31	35.92
Palisades Dam	39.15	56.90	39.83
Island Park Dam	29.05	42.22	29.56

All values listed are in inches.

TABLE III

RESULTS OF STATISTICAL ANALYSIS

Variable	Multiple R	R-Squared	Sample R	B
Wind	.54241	.29421	.54241	5.912×10^{-4}
Precipitation	.69833	.48767	-.53976	-7.677×10^{-2}
Temperature	.72888	.53127	.21541	1.632×10^{-1}
Elevation	.74929	.56144	.16609	3.238×10^{-4}
(Constant)				6.047×10^{-1}

TABLE IV

DATA USED FOR STATISTICAL ANALYSIS
1956-1975

Station	Ave. May-Sept Evap.[1]	Ave. May-Sept Wind[2]	Ave. Annual Temp.[3]	Total Annual Prec.[4]	Elevation (msl)
Whalen Dam	8.71	1937	47.5	12.84	4294
Green River	10.12	1792	42.3	7.68	6089
Laramie 2NW	9.77	4547	38.7	11.74	7130
Farson	8.64	1744	37.4	7.32	6595
Lookout 14NE	10.06	4163	40.5	13.04	6965
Heart Mountain	7.59	1327	44.3	8.51	4790
Anchor Dam	8.44	1560	41.4	15.35	6460
Gillette 2E	9.28	1622	44.8	15.86	4556
Sheridan Field Station	8.40	1527	43.7	14.97	3800
Archer	9.21	1416	45.7	14.35	6010
Pathfinder Dam	9.21	2529	44.9	9.71	5930
Flaming Gorge	8.12	1413	43.9	12.54	6270
Palisades Dam	7.81	3406	43.6	19.60	5385
Lifton Pumping Station	7.03	1523	41.0	9.80	5926
Pactola Dam	5.25	1518	41.8	20.27	4720
Manila	8.69	1046	45.1	9.89	6420
Yellowtail Dam	9.01	2083	49.6	20.66	3305
Wanship Dam	6.49	913	43.6	15.68	5940
Island Park Dam	5.76	461	36.4	32.62	6300
Mitchell 5E	7.89	1775	47.1	13.01	4080

[1] All values listed are in inches.

[2] All values listed are in miles per day.

[3] All values listed are in °F.

[4] All values listed are in inches.

little difference between the average value of the actual measured data and the average value of the extended data at any given station. The maximum difference observed was 8 percent and the average difference was less than 2 percent. From this one can infer that on the average, evaporation at a point does not change significantly from year to year over the May through September period.

The climatic factors evaluated in this analysis included wind, temperature, precipitation, and elevation. Wind was found to be the most significant variable for estimating evaporation, followed by precipitation, temperature, and elevation, respectively. Since data for these factors are readily obtainable from U.S. Weather Bureau stations throughout the state, one can easily use the following relationship developed from the above statistical analysis as an evaporation prediction equation for the State of Wyoming.

$$E = K(5.9 \times 10^{-4}W - 7.7 \times 10^{-2}P + 1.6 \times 10^{-1}T + 3.2 \times 10^{-4}H - 6.0 \times 10^{-1})$$

where E = Average annual lake evaporation, inches;

W = Average wind, May through September, miles per day;

P = Total annual precipitation, inches;

T = Average annual temperature, °F;

H = Elevation, feet;

and K = 1.02, a constant to convert average May through September pan evaporation to average annual lake evaporation.

Care should be exercised in using this relationship, however, as it predicted observed values of evaporation for all stations in Wyoming with a correlation coefficient of only .75. It is recommended that evaporation values be taken from the isoevaporation lines on the evaporation map developed rather than by use of the equation, as the isoevaporation lines drawn on the map are based on actual evaporation values and are felt to be more accurate. Since a correlation of only .75 was achieved, it was not felt that values predicted by the resultant equation would be sufficiently accurate for use in defining isoevaporation lines for the state evaporation maps. As a result, only average values of measured evaporation were used in the construction of the maps.

The final annual pan evaporation map (Figure 11), therefore, was drawn with regard to measured evaporation values only. Figure 12 indicates the amount of annual lake evaporation. Topographic effects were not taken into account when drawing the maps since their effect on evaporation is not known. As indicated earlier, the relationship of evaporation to increasing elevation is uncertain due to the many contradictory factors involved. Evaporation at a particular elevation has been found to depend on temperature, atmospheric pressure, exposure, and aspect of slope. Although several major attempts have been made to study the relationship of evaporation with elevation, no general definitive results have been obtained which can readily be applied to areas other than the ones studied with any degree of confidence (Blaney, 1960; Peck, 1967; and Horton, 1934). Some studies have found evaporation to increase with elevation, and others have found it to decrease with elevation.

Available data from studies performed in the past with regard to evaporation at high elevations are limited. These results may,

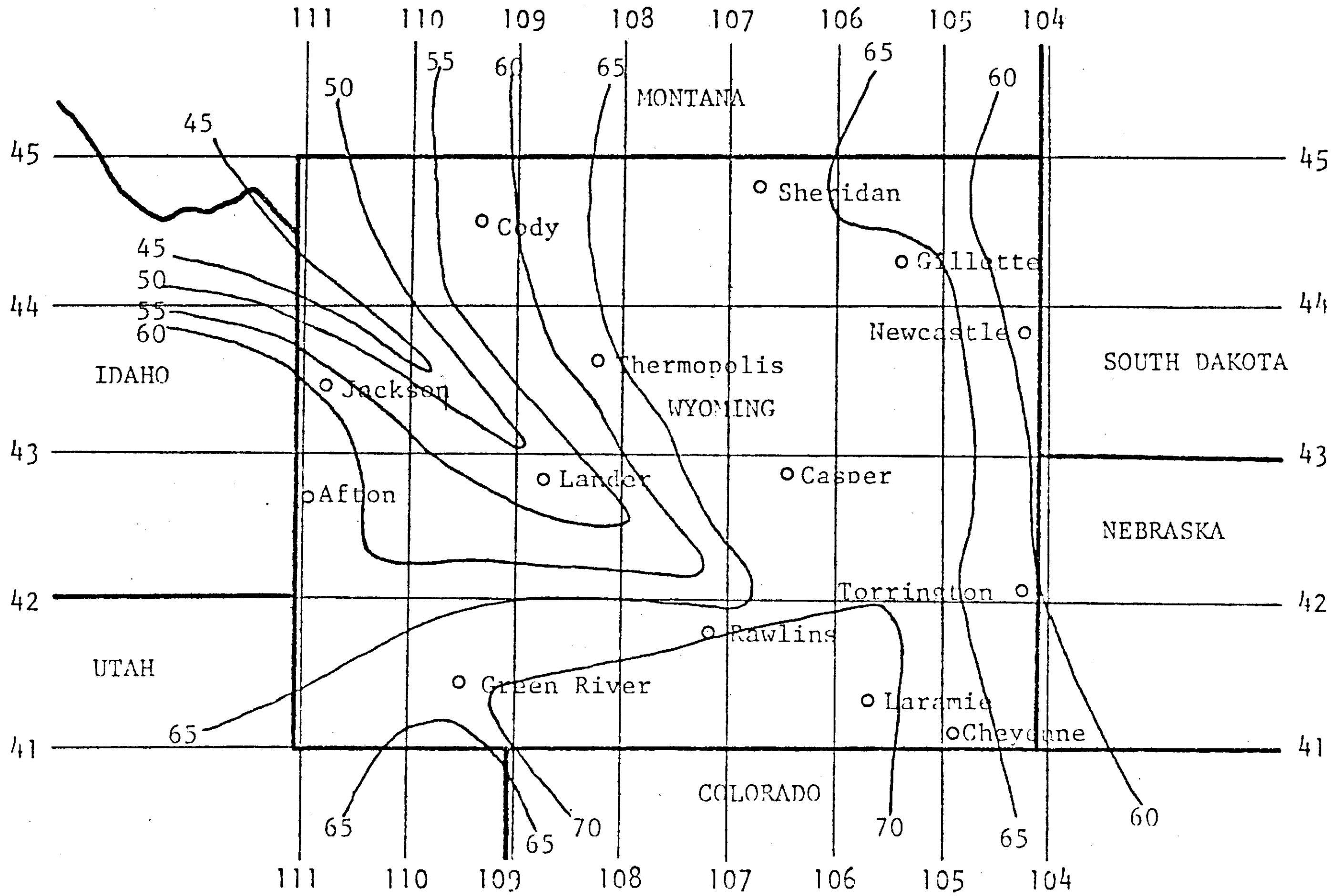


Figure 11. Annual Pan Evaporation, in inches

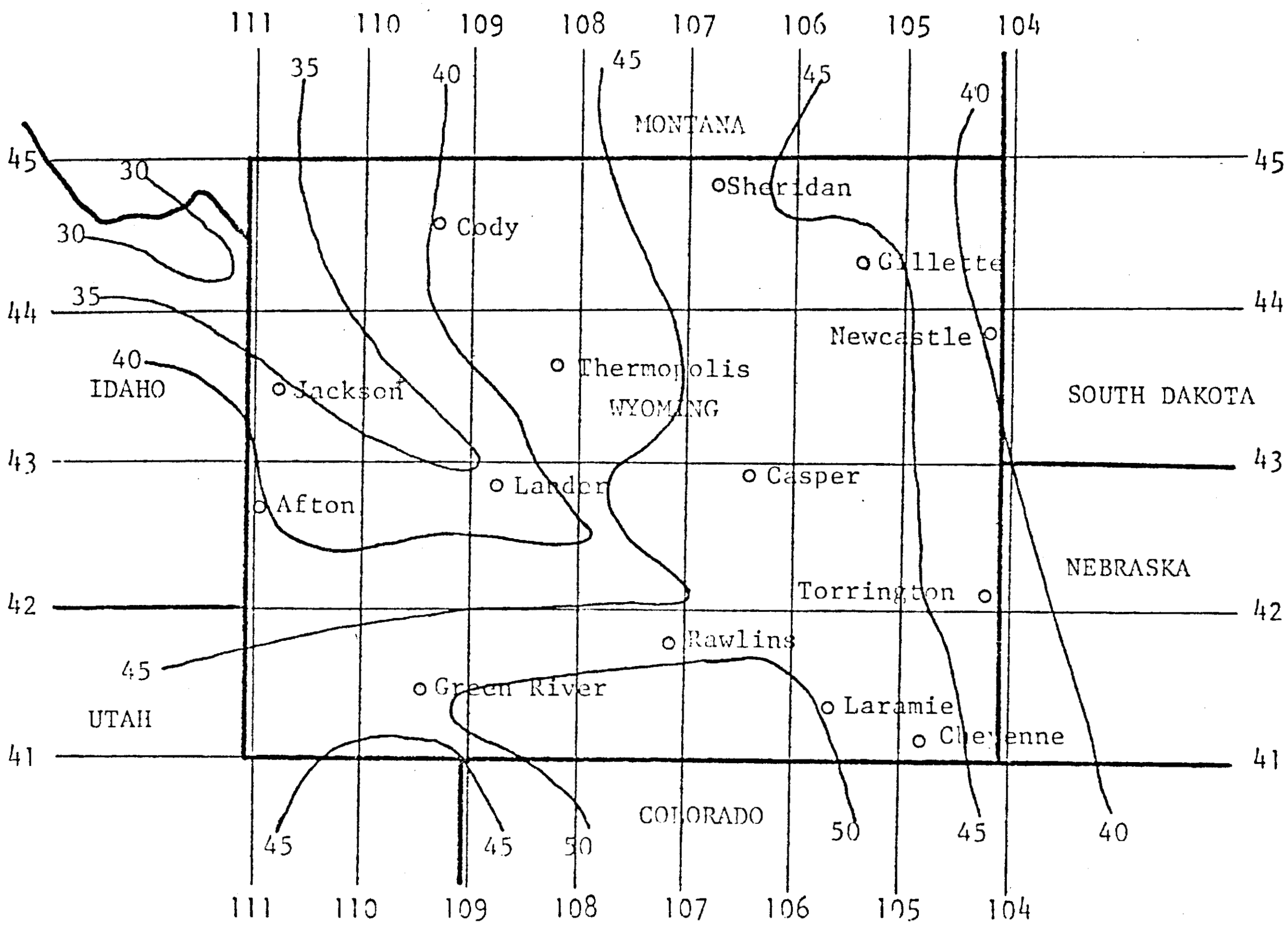


Figure 12. Annual Lake Evaporation, in inches

however, provide a better estimate of mountainous evaporation than could be obtained by using the maps developed in this study, since the station of greatest elevation used in this study was Laramie 2NW at an elevation of 7130 feet. Previous studies performed in northern Colorado and northeastern Utah may be applicable to Wyoming. A general discussion of the effect of elevation on evaporation follows, since it was felt that such a discussion might prove beneficial to the reader.

One study conducted in Colorado is known as the Wagon Wheel Gap Experiments (Horton, 1943). These experiments were conducted on two different drainage basins on the east slope of the Continental Divide. The data base was from October 1910 to September 1926, inclusive. The mean elevations of the two basins were 10,209 feet and 10,133 feet, and ranged from 9,245 feet to 11,355 feet. The mean annual total evaporation values for the two basins were 14.95 inches and 14.29 inches, respectively. From these results one might infer that a good relationship exists between evaporation and elevation. This is not the case for other studies conducted by Blaney (1960) and Peck (1967) which found no definitive relationship between evaporation and elevation. The Wagon Wheel Gap results are mentioned because the study site was close to Wyoming; the study was conducted under climatic conditions similar to Wyoming; and the data base was over a longer period than that used in other studies. The only conclusion that can be drawn from comparing results of all studies investigated is that no general relationship for evaporation and elevation has yet been established.

Another study, conducted on Mount Whitney in California, resulted in the development of an evaporation profile (Blaney, 1960). Although based on only six stations, this study is one of the few sources for evaporation data at altitudes up to and exceeding 14,000 feet. As such, these results are listed in Table V for the reader's information.

These earlier studies also have shown that evaporation at high altitudes is greatly influenced by slope orientation. Southern slopes are subject to greater evaporation since they receive more solar heat. Evaporation from high ridges on southern slopes and from exposed steep slopes is higher than evaporation at the same elevation on protected slopes and northern slopes, and appears to decrease slightly with increasing elevation. Evaporation for sites where strong nighttime winds occur, along southern slopes and on well-exposed ridges, was found to have no discernable variation with elevation (Peck, 1967). The reader should be reminded that the results given for mountainous evaporation rates by Blaney (1960) were not obtained in Wyoming, and should be used only for general information in planning if better information is not available.

Evapotranspiration Estimates

As explained in the previous chapter, two methods of evapotranspiration analysis were used in this study. The purpose of the evapotranspiration analysis was to develop a factor which, when multiplied by an average May through September value of evaporation, would give the seasonal evapotranspiration for an area. It is felt that one may use the May through September evaporation map (Figure 13) to determine evapotranspiration with a high degree of confidence by applying the

TABLE V

MOUNT WHITNEY EVAPORATION PROFILE

Station Name	Elevation (feet)	Mean Daily Evaporation (feet)
Soldiers Camp	4515	0.223
Junction of South Fork and Lone Pine Creek	7125	.170
Hunters Camp	8370	.147
Lone Pine Lake	10,000	.136
Mexican Camp	12,000	.134
Summit of Mount Whitney	14,502	.140

(Blaney, 1960)

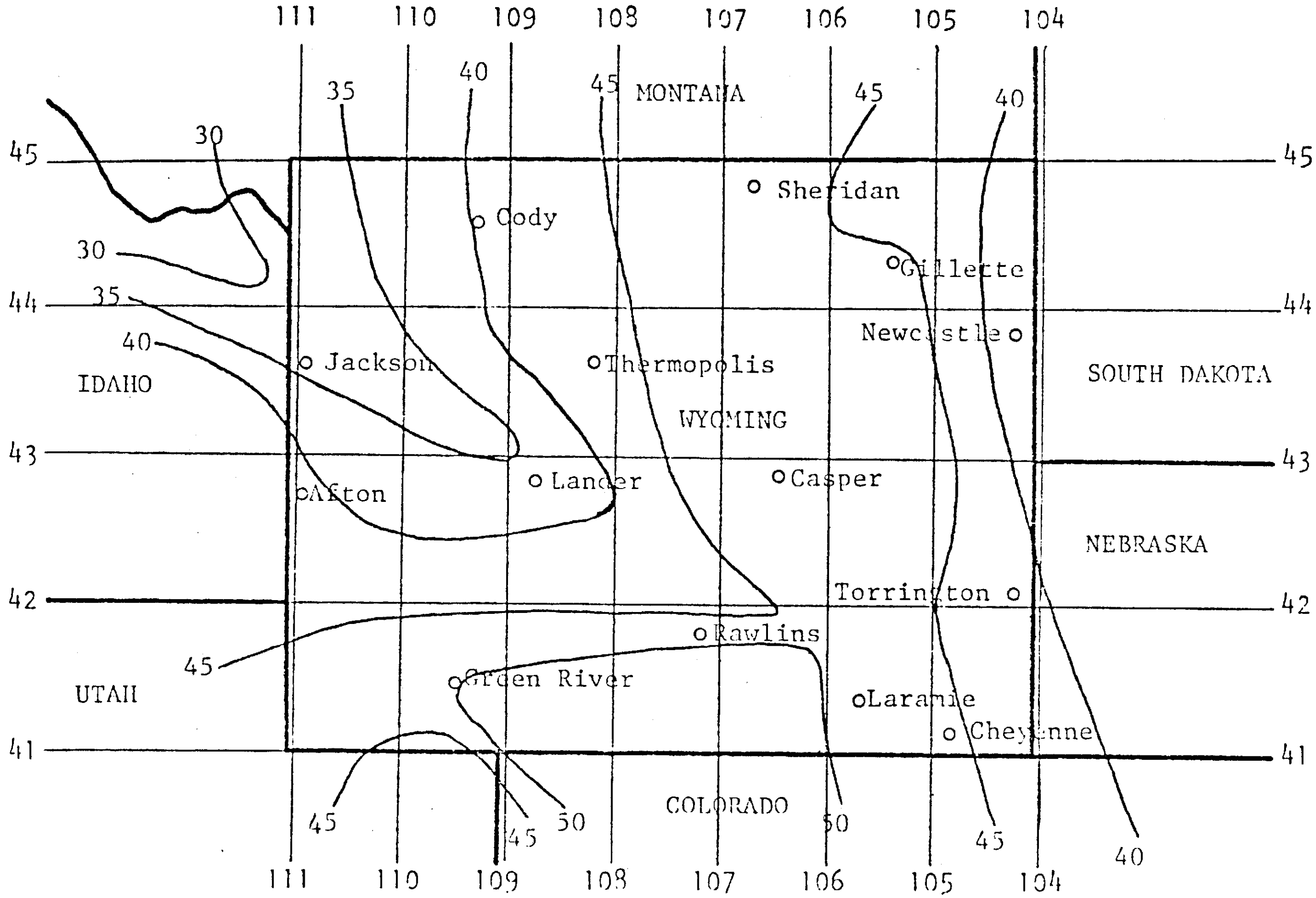


Figure 13. May through September Pan Evaporation, in inches

appropriate factor. The development of the two factors can be found in Tables VI and VII. It is recommended that a factor of 0.47, obtained by the Blaney-Criddle method of analysis, be used for evapotranspiration estimation purposes. The Blaney-Criddle factor was chosen since that method was developed for use in the western United States, and the Thornthwaite method was developed for the east-central United States (Pair, 1975).

Distributions

Although the evaporation maps developed in this study are not an entirely new development, the distributions developed are new. The distributions referred to are those used to convert May through September evaporation to annual evaporation (developed with Pathfinder Dam evaporation data) and the mean monthly distribution developed for Wyoming stations for the months May through September (Tables VIII, IX, and X). Table X shows the development of the May through September evaporation distribution developed by analyzing evaporation data from 12 Wyoming evaporation stations.

The Pathfinder Dam annual evaporation distribution was used for extending data to annual values because the distribution of May through September evaporation of other distributions developed previously by the U.S. Bureau of Reclamation (Lahoti, 1968) and Brown (1970) did not compare favorably with the May through September distribution developed for the 12 Wyoming stations (Tables IX and X). A comparison of the various distributions available for extending data to annual values is shown in Table XI.

TABLE VI

BLANEY-CRIDDLE EVAPORATION-EVAPOTRANSPIRATION COMPARISON

Evaporation Station	May-September Pan Evaporation	Consumptive Use Station	Seasonal Consumptive Use	Factor (cu/Evap.)
Archer	46.05	Cheyenne AP	17.15	.37
Farson	43.80	Farson	18.24	.42
Gillette 2E	46.90	Gillette 2E	19.99	.43
Green River	50.45	Green River	23.00	.46
Laramie 2NW	48.90	Laramie	17.14	.35
Pathfinder Dam	46.15	Pathfinder Dam	22.52	.49
Heart Mountain	41.00	Powell	26.14	.64
Sheridan Field Station	42.05	Sheridan AP	19.33	.46
Anchor Dam	40.30	Thermopolis	23.20	.58
Mean	45.07		20.75	0.47
Standard Deviation	3.52		3.13	0.09

cu values listed are average seasonal consumptive irrigation requirements for grass, in inches

Pan evaporation values listed are in inches.

TABLE VII

THORNTHWAITE EVAPORATION-EVAPOTRANSPIRATION COMPARISON

Evaporation Station	May-September Pan Evaporation	Consumptive Use Station	Seasonal Consumptive Use	Factor (cu/Evap.)
Gillette 2E	46.90	Gillette 2E	21.61	.46
Green River	50.45	Green River	20.24	.40
Laramie 2NW	48.90	Laramie 2NW	18.41	.38
Pathfinder Dam	46.15	Pathfinder Dam	15.92	.34
Heart Mountain	41.00	Heart Mountain	20.83	.51
Sheridan Field Station	42.05	Sheridan Field Station	21.39	.51
Anchor Dam	40.30	Anchor Dam	19.29	.48
Whalen Dam	43.45	Whalen Dam	23.61	.54
Mean	44.90		20.16	0.45
Standard Deviation	3.76		2.32	0.07

cu values listed are 30 day values of estimated evapotranspiration, in cm.

Pan evaporation values listed are in inches.

TABLE VIII

PATHFINDER DAM ANNUAL EVAPORATION DISTRIBUTION

Month	% Of Annual Evaporation
January	2.7
February	2.5
March	3.9
April	8.0
May	11.5
June	13.1
July	17.1
August	15.6
September	11.5
October	7.6
November	3.9
December	2.6

TABLE IX

MAY THROUGH SEPTEMBER MONTHLY EVAPORATION DISTRIBUTION

Month	% Of May Through September Evaporation
May	17.5
June	20.3
July	24.4
August	22.4
September	15.4

TABLE X

DEVELOPMENT OF MAY THROUGH SEPTEMBER EVAPORATION DISTRIBUTION

Station	May[1]	%[2]	June[1]	%[2]	July[1]	%[2]	August[1]	%[2]	September[1]	%[2]
Laramie 2NW	19.6	12	21.0	3	22.8	7	21.3	5	15.3	1
Pathfinder Dam	16.8	4	19.2	5	24.2	1	22.9	2	16.9	10
Boysen	17.2	2	20.7	2	24.6	1	22.7	1	14.8	4
Whalen Dam	18.0	3	20.8	2	24.4	0	22.1	1	14.7	5
Heart Mountain	18.8	7	20.3	0	24.3	0	21.9	2	14.7	5
Anchor Dam	17.1	2	21.1	4	24.4	0	22.0	2	15.4	0
Green River	18.3	5	20.7	2	24.7	1	21.5	4	14.7	5
Keyhole Dam	16.5	6	19.5	4	25.2	3	22.7	1	16.1	5
Gillette 2E	16.6	6	19.0	6	24.9	2	24.2	8	15.3	1
Sheridan Field Station	16.0	9	19.0	6	24.8	2	24.5	9	15.7	2
Archer	17.2	2	20.3	0	23.1	5	22.9	2	16.5	7
Farson	17.4	1	22.1	9	24.8	2	20.5	8	15.2	1
Average (May through September Evaporation)	17.5		20.3		24.4		22.4		15.4	
Standard deviation	1.04	3.29	0.96	2.64	0.71	2.13	1.15	3.02	0.73	2.95

[1] Values listed under months are percent of total May through September evaporation which occurred in that month over the period of record at a given station.

[2] Values listed in % columns are the percent that a given monthly value differs from the average value for that month for all stations.

TABLE XI

COMPARISON OF ANNUAL EVAPORATION DISTRIBUTIONS

	% Of Annual Evaporation		
Month	U.S. Bureau of Reclamation (Lahoti, 1968)	Brown (1970)	Pathfinder Dam
January	2.7	4.8	2.7
February	3.4	3.1	2.5
March	6.3	2.6	3.9
April	9.3	7.5	8.0
May	12.0	13.0	11.5
June	14.3	13.0	13.1
July	15.5	14.7	17.1
August	13.5	13.9	15.6
September	10.4	10.5	11.5
October	6.7	9.2	7.6
November	3.4	3.9	3.9
December	2.5	3.2	2.6

The Pathfinder Dam annual evaporation distribution was developed by analyzing annual evaporation values collected at the Pathfinder Dam evaporation station for the period 1962 to 1969. An average value for each month over the period of record was found. The distribution was then obtained by determining the percentage each monthly value comprised of the sum of the monthly averages. The May through September distribution was developed using 12 Wyoming evaporation stations. An average value for each of the five months (May through September) was found. The values in the monthly distribution shown in Table IV are the percentage each monthly average comprised of the sum of the monthly averages over the period of record. This distribution predicted May through September evaporation within 10 percent of the average value over the period of record at any station in any month.

CHAPTER V

DISCUSSION AND CONCLUSIONS

Evaporation varies much less on a yearly basis than either streamflow or precipitation. Extreme variations in annual total evaporation are within 25 percent of the mean annual value. Pan evaporation values also fall within this range (Linsley and Franzini, 1972). Therefore, one can use values from the maps developed in this study with confidence that they will not differ drastically from the average values used as data for this study. Evaporation maps similar to the one developed in this study are generally accepted as one of the best methods currently available for estimating evaporation. "These annual evaporation maps provide the most accurate generalized estimates of evaporation available" (Peck, 1967).

The annual lake evaporation map developed from this study is similar to ones developed earlier by Meyer (1942) and Viessman et al. (1977). This map was based on a larger data base than previous studies, and on an intensive investigation of primarily Wyoming evaporation data. Since results of this study are similar to those of earlier studies it is indicated that no serious errors were made. It is felt that the development of a more accurate map is not possible at this time. A more accurate map would involve using estimated evaporation values at locations other than evaporation stations. Use of climatological factors for estimation purposes would not be acceptable since a correlation of only .75 was obtained from statistical analysis between evaporation and selected climatological factors. Therefore, until more data become available or a more accurate means of estimating evaporation is developed the maps developed in this study are as accurate as any available.

Use of Results

The maps developed in this study, Figures 11, 12, and 13, can be utilized in a variety of ways, and might prove to be quite useful to the engineer. Evaporation and evapotranspiration values are necessary whenever one wishes to derive a water balance. Some of the instances in which these values might be used include: (1) conducting reservoir operations; (2) establishing a hydrologic monitoring system; (3) determining the hydrological balance for a drainage basin; (4) determining water rights, and water right transfers including computations of consumptive use for such transfers; and (5) water resource planning of all kinds at all levels--federal, state, and local.

The evaporation values shown should be used only as annual values as they are expressed in terms of the average number of inches for a full year. Monthly or seasonal values of evaporation can be obtained by multiplying the value of annual evaporation shown on the maps (Figures 11 and 12) by the appropriate percentage obtained from the Pathfinder Dam annual evaporation distribution (Table VIII). More accurate results can be obtained for the period May through September using the distribution shown in Tables IX and X, in combination with the Pathfinder Dam distribution, Table VIII.

One may also use the May through September pan evaporation map (Figure 13) for estimating seasonal evapotranspiration for irrigated grass, hay, and pasture. To do this one multiplies values obtained from Figure 13 by 0.47. Figure 13 is a map showing pan evaporation values for the period May through September, which corresponds roughly to the period during which seasonal evapotranspiration occurs. One should keep in mind that the evapotranspiration factor of 0.47 was developed using irrigated grass, hay, and pasture as the vegetation being considered. Evapotranspiration values obtained are not precise values and should be used for planning purposes only.

An example should serve to illustrate how one would use these results. Assume one was concerned with a point designated as Latitude 42, Longitude 109. The following procedure would provide the information desired. Using Figure 12, one finds that the average annual lake evaporation for this point is 45 inches. To find a value for evaporation in April, one multiplies 45 by 0.08, with 0.08 being obtained from Table VIII and representing the percentage of annual evaporation that normally occurs in April. This calculation shows that one can expect 3.60 inches of evaporation in April. Assuming a reservoir surface area of 1000 acres, this means that one could expect evaporation to amount to about 300 acre-feet for the month of April. Use of Table IX is preferable to Table VIII if a monthly evaporation value is desired for the period May through September as more accurate results should be obtained. Use of Table IX is preferred since the May through September distribution contained therein was developed using data from 12 Wyoming evaporation stations while the distribution contained in Table VIII was based on data from only one station. If May rather than April evaporation was needed, one would obtain the percentage 17.5 from Table IX. This means that 17.5 percent of the evaporation occurring during the period May through September will occur in May. Summing values from Table VIII, it is seen that 68.8 percent of the annual evaporation will occur during this five month eriod. To find May evaporation, then, one multiplies .688 by .175, and this value by 45 inches. May evaporation is therefore equal to 5.42 inches.

If a seasonal value for evapotranspiration is required, one begins by multiplying the value obtained from Figure 12, 45 inches, by 0.688 and dividing by 0.70 to convert annual lake evaporation to May through September pan evaporation. An alternate procedure would be to use Figure 13 to obtain a value for May through September evaporation. Once a value of May through September evaporation has been found, 44.23 for this example, a value for seasonal evapotranspiration is obtained by multiplying this value by the evapotranspiration coefficient of 0.47. Thus for the point being considered in this example, one would expect seasonal evapotranspiration to be approximately 20.8 inches.

Limitations of Results

The results presented in this study are believed to be sufficiently accurate for use by the engineer for determining average annual evaporation and average seasonal evapotranspiration for Wyoming. It is believed that the results obtained are as accurate as any previously developed, and may be as accurate as any which can be developed with the available data. There are limitations to the use of these results of which the engineer should be made aware.

These results should not be applied to areas which are not representative of the surrounding countryside. This would affect the use of these results over small areas only, however. Since the engineer will usually be concerned with an entire drainage area, this limitation is of minor importance.

Use of these results for mountainous areas will introduce some amount of error as mountainous area effects were not included when drawing the final evaporation maps. If values are needed in a forested area of high elevation, one could decrease the values found in this study by 14 percent to account for tree shelterbelt effects, and obtain values more applicable to forested areas.

One should also be reminded that values obtained from the evaporation maps developed from this study are average values, and therefore will not give exact results. Annual evaporation values obtained may vary by as much as 25 percent from the actual evaporation in any one year, and seasonal evaporation values may vary even more. Therefore, the greatest accuracy should be expected when results are to be used for determination of a long term water balance.

Conclusions and Recommendations

Several conclusions can be drawn based on the analysis conducted and the results obtained from this study. These conclusions are:

1. Results presented are believed to be as accurate as any previously developed. The engineer should be sufficiently confident to use these results for water resource planning purposes.

2. The average annual lake evaporation map developed in this study is similar to earlier work done by the U.S. Department of Agriculture (Viessman et al., 1977) and Meyer (1942), but differs considerably from results obtained by Kohler, Nordenson, and Fox (Meyers, 1962), the National Weather Service (Linsley and Franzini, 1972), and Horton (1943).
3. An effort should be made to relocate many of the evaporation pans so they will be more representative of the surrounding countryside. Relocated sites should be established as far as possible from tree shelterbelts and other structures, either natural or manmade.
4. Additional research is indicated for seasonal pan-to-lake coefficients so that more accurate monthly or seasonal values can be obtained.
5. Additional research is indicated for evaporation in mountainous areas.

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