DESIGN INFORMATION FOR EVAPORATION

PONDS IN WYOMING

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ABSTRACT

This publication is a summary of a study to develop design information for disposal of wastewater by evaporation in Wyoming. The specific objectives of the study were to: (1) determine models most suitable to Wyoming for defining evaporation from water, soil, vegetative, and ice surfaces, based on current state-of-the-art procedures and available data, and (2) statistically describe monthly, seasonal and/or yearly variations in evaporation through frequency distributions as well as predict expected average annual evaporation losses. A more detailed presentation of the results of the study are available in the final report (Pochop, et al. 1985) of the project submitted to the Wyoming Water Research Center.

Comparison of equations which estimate evaporation using climatological data showed that the Kohler-Nordenson-Fox equation provided monthly and annual evaporation estimates having statistics more closely resembling those of measured pan data than any of seven other equations tested. Monthly and annual means, standard deviations, and highest and lowest evaporation and net evaporation values have been calculated for seven Wyoming stations.

INTRODUCTION

In semi-arid regions, such as Wyoming, evaporation ponds are a conventional means of disposing of wastewater without contamination of ground or surface waters. Evaporation ponds as defined herein will refer to lined retention facilities. Successful use of evaporation for wastewater disposal requires that evaporation equal or exceed the total water input to the system, including precipitation. The net evaporation may be defined as the difference between the evaporation and precipitation during any time period.

Evaporation rates are to a great extent dependent upon the characteristics of the water body. Evaporation from small shallow ponds is usually considered to be quite different than that of large lakes mainly due to differences in the rates of heating and cooling of the water bodies because of size and depth differences. Additionally, in semi-arid regions, hot dry air moving from a land surface over a water body will result in higher evaporation rates for smaller water bodies. The evaporation rate of a solution will decrease as the solids and chemical composition increase. Depending upon its origin, evaporation pond influent may contain contaminates of various amounts and composition. Decreases in evaporation rates compared to fresh water rates can seriously increase the failure potential of ponds designed on fresh water evaporation criteria. Determination of the effects of water quality on evaporation rate, however, was well beyond the scope of this study. An analysis of the effects of the problem has been included without any attempt to define the amount of the decrease in evaporation.

Designers of evaporation ponds need to know the probability level of their designs being exceeded. Confidence limits for published evaporation normals have not been given, nor have analyses been made of the effects of uncertainty in the estimated normals or of the temporal variation of net evaporation. Definition of the spatial and temporal distribution of parameters such as evaporation and precipitation is difficult in mountainous regions. Data requirements are usually much greater than in non-mountainous regions, yet the density of weather stations is less in Wyoming than in the more populated areas of the United States. The application of many of the empirical equations, based on climatological data, for estimating evaporation have not been thoroughly tested for high altitude conditions. In particular, the ability of these equations for defining the variability of evaporation basically is unknown. Historically, pan data is the most common means for defining free water evaporation. However, the density of evaporation pan stations is much less than that of weather stations.

EVAPORATION ESTIMATES

Many methods exist for either measuring or estimating evaporative losses from free water surfaces. Evaporation pans provide one of the simplest, inexpensive, and most widely used methods of estimating evaporative losses. Long-term pan records are available, providing a potential source of data for developing probabilities of net evaporation. The use of pan data involves the application of a coefficient to measured pan readings to estimate evaporation from a larger water body. Among the most useful methods for estimating evaporation from free water surfaces are the methods which use climatological data. Many of these equations exist, most being based directly upon the equation derived by Penman (1948) which was originally intended for open water surfaces, but is now commonly applied to estimates of vegetative water use. Various versions of Penman's equation have been developed, with that of Kohler et al. (1955) likely being the most widely used.

Pan evaporation is considered an indication of atmospheric evaporative power. Evaporation from a free surface is related to pan evaporation by a coefficient applied to the pan readings. Most evaporation pans n the U. S. are Class A pans made of unpainted galvanized iron or stainless steel 4 feet in diameter and 10 inches deep. The pans are supported on low wooden frames and are filled with 8 inches of water.

A large network of Class A evaporation pans have been set up in the United States. Data from regular reporting pan stations are published in the Climatological Summaries of the National Weather Service (NWS). The number of reporting NWS stations in Wyoming varies with time, but averages near 6. Some additional pan data are available from other agencies such as the U. S. Bureau of Reclamation. A good review of the availability of pan data in Wyoming is given by Lewis (1978). Most pan data are available only for the months May through September.

Previous summaries of evaporation in Wyoming (Smith, 1974 and Lewis, 1978) considered only mean annual values of evaporation. Smith used the United States Evaporation Maps of Kohler et al. (1959) to produce a map of average annual gross evaporation estimates for stock-water ponds. Stock-water ponds are similar, with respect to surface area and depth, to many evaporation ponds. Lewis developed a mean annual evaporation map using measured pan evaporation data. He indicated that these evaporation estimates represented annual lake evaporation.

There are five pan stations in Wyoming having 28 years or more of record. Lewis (1978) reported that Whalen Dam and Pathfinder Dam had conditions most closely meeting the definition of a Class A pan station. However, analysis of Pathfinder Dam data indicated a data discrepancy and resulted in the elimination of the years 1949 through 1961. Three stations—Boysen Dam, Sheridan Field Station, and Heart Mountain--were eliminated because of poor pan location, nearby obstacles such as shelterbelts or buildings, or other reasons (Warnaka, 1985). Thus, only one station, Whalen Dam, provided a usable record of over 30 years while Pathfinder Dam retained a usable record of 22 years.

With only two stations in Wyoming having usable records of adequate length, it was not possible to use pan data directly to define the temporal variability of net evaporation. Thus, it was decided to use the limited pan data as a source of evaporation data against which evaporation estimates using the climatological models could be compared.

Because of the many models which exist for calculating evaporation estimates, the selection of the most appropriate method for a given situation is difficult. Selection of a method generally depends upon the availability of data and the ability of the method to estimate both the magnitude and variation of evaporative losses. Unfortunately, for a given situation, no definite guidelines have been given for selecting the method to use.

Data input requirements for the different models vary, ranging in complexity from those that use only temperature data to those that require temperature, wind, humidity, and radiation data. The equations using all four parameters are usually considered the most responsive to climatic variations. The availability of climatic data is a major consideration in selecting a model for calculating evaporation. As many as 100 locations in Wyoming have long-term published records of daily temperature (NOAA) whereas the availability of wind, humidity, and radiation data is very limited as well as quite short-term in some cases. regular published wind and humidity data are available for only four National Weather Service stations in Wyoming. Direct radiation measurements are not currently being published for any Wyoming stations. Thus, radiation estimates need to be made from cloud cover observations or percent sunshine measurements. Again, these are available on a regular basis only at 4 locations in Wyoming.

The problem as viewed from an availability of data standpoint can be seen as a tradeoff between simple temperature models for which data is available at many locations or a more complex model with limited available data. A compromise is to use a complex model with climatic data extrapolated, as needed, from a location where it is available to the location where the evaporation estimate is being made. Basically, this permits use of available on-site climatic data combined with the "best" extrapolation of the other required climatic data.

Eight climatological methods were analyzed for their suitability to predict pond (shallow lake) evaporation in Wyoming. These include the 1) Penman, 2) Kohler-Nordenson-Fox, 3) Kohler-Parmele, 4) Linacre, 5) Priestley-Taylor, 6) Stewart-Rouse, 7) deBruin, and 8) Blaney-Criddle equations. All these formulas except the Blaney-Criddle have a theoretical formulation based on Penman's derivation but, due to different simplifying assumptions, data input requirements vary. Data requirements and a reference for each method are given in Table 1. The Penman and Blaney-Criddle are normally used for estimating vegetative evapotranspiration. However, the potential evapotranspiration estimates are sometimes considered to be equivalent to lake evaporation. They are included here because of their wide use and acceptance. The Stewart-Rouse and deBruin equations were proposed especially for shallow lake and/or pond evaporation estimates.

Table 1. Data Requirements of Evaporation Equations.

Method	Data Required Temp	Hum	Wind	Rad	Reference
Blaney-Criddle	X				SCS, 1967
Linacre	X				Linacre, 1977
Stewart-Rouse	X			X	Stewart & Rouse, 1976
Priestley-Taylor	X			X	Priestley & Taylor, 1972
DeBruin	X	X	X		deBruin, 1978
Penman	X	X	X	X	Jensen, 1973
Kohler-Nordenson-Fox	X	X	X	X	Kohler et al., 1955
Kohler-Parmele	X	X	X	X	Kohler and Parmele, 1967

The Kohler-Nordenson-Fox equation provided the best estimates of the means and variability of pan evaporation. The equation requires four climatic inputs. In order to use the equation, the wind, humidity, and radiation data were taken from nearby first order stations. Despite this extrapolation of data, the equation provided better evaporation estimates than the other equations. The two equations requiring only temperature data as input were the Blaney-Criddle and Linacre equations. Either of these equations would have the advantage of using climatic data much more readily available than that required for the Kohler-Nordenson-Fox equation. The Blaney-Criddle predicted low means and did not adequately define the variability of monthly evaporation. The Linacre equation did relatively well in predicting the variability of evaporation, but estimated very high means. Thus, both were eliminated for use in this study.

VARIABILITY OF NET EVAPORATION

Monthly evaporation estimates have been made at seven locations using the Kohler-Nordenson-Fox equation with a pan coefficient of 0.7. The Kohler-Nordenson-Fox equation is based on Penman's equation (1948) which describes evaporation as the combination of water loss due to radiation heat energy and the aerodynamic removal of water vapor from a saturated surface. The general form for the combination equation is

$$E = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} E_a$$

where E is the evaporation in inches per day, Δ is the slope of the saturation vapor pressure curve at air temperature in inches of mercury per degree F, γ is the psychrometric constant in inches of mercury per degree F, R_n is the net radiation exchange expressed in equivalent inches of water evaporated, and E_a is an empirically derived bulk transfer term of the form

$$E_a = f(u)\,(e_s - e_d)$$

where f(u) is a wind function and $(e_s - e_d)$ is the vapor pressure deficit.

Kohler-Nordenson-Fox (1955) evaluated the aerodynamic term using pan data resulting in the form

$$E_a = (0.37 + 0.0041\,U_p)(e_s - e_a)^{0.88}$$

where E_a is in inches of water per day. Up is the wind speed 2 feet above the ground expressed in miles per day, and e_s and e_a are the saturation vapor pressures at mean air and mean dew-point temperatures, respectively, expressed in inches of mercury. For development of the wind function, Kohler-Nordenson-Fox made an adjustment in the psychrometric constant to account for the sensible heat conducted through the sides and bottom of the pan. However, the psychrometric constant used in the final equation is the standard value given by

$$\gamma = 0.000367P$$

where P is the atmospheric pressure in inches of mercury.

Kohler-Mordenson-Fox calculated lake evaporation by applying a pan coefficient of 0.7 to the above equation. A more complete summary of the development of the Kohler-Nordenson-Fox equation is given by Warnaka (1985).

Monthly estimates were calculated for each of 35 years or more at the four first-order stations of Casper, Cheyenne, Lander, and Sheridan; at Rock Springs using Rock Springs' temperature, humidity, and wind data and radiation data from Casper; and at Whalen and Pathfinder using on-site temperature data and the other climatological data from Casper and Lander, respectively. Whalen and Pathfinder were included since long-term pan data for the months May through September were available at these locations.

Monthly and annual means, standard deviations, and highest and lowest evaporation values for the years of record were calculated for each location (Table 2). High, low, and mean values for pan coefficients other than 0.7 can easily be obtained from the data of Table 2 by dividing the values by 0.7 and multiplying by the desired coefficient. However, the standard deviations will change somewhat for different pan coefficients. The range of annual values average approximately 15% of the mean annual values. The greatest variation is at Rock Springs with the highest and lowest annual values 19% greater and 21% less than the mean annual value, respectively. The least variation is at Sheridan with the highest and lowest annual values about 13% above and 7% below the mean annual value, respectively.

Monthly and annual means, standard deviations, and highest and lowest net evaporation values for the years of record were calculated for each of the seven locations (Table 3). Again, a pan coefficient of 0.7 was used. The greater variability of net evaporation as compared to

Table 2. Means, Standard Deviations, and High and Low Evaporation Values (in inches) from Estimates Using the Kohler-Nordenson-Fox Equation With a Coefficient of 0.7.

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Casper	Mean	1.2	1.4	2.1	3.1	4.3	5.9	7.2	6.5	4.6	3.1	1.7	1.3	42.4
	StDv	0.4	0.4	0.5	0.6	0.6	0.9	0.6	0.7	0.6	0.6	0.4	0.5	2.6
	High	1.9	2.2	3.1	4.1	6.1	8.2	8.6	8.0	5.4	4.1	2.4	2.2	47.1
	Low	0.6	0.8	1.1	2.2	3.2	4.2	5.8	4.8	3.1	1.5	0.8	0.8	36.2
Cheyenne	Mean	1.7	1.9	2.7	3.8	5.0	6.2	6.9	6.2	4.6	3.3	2.0	1.8	46.1
	StDv	0.4	0.5	0.6	0.7	0.8	0.9	0.7	0.7	0.6	0.6	0.5	0.3	3.4
	High	2.8	3.6	3.9	5.0	6.6	8.2	8.7	7.8	5.9	4.3	3.7	2.5	53.6
	Low	1.1	1.0	1.5	2.4	3.0	4.4	5.9	5.0	3.2	1.9	1.3	1.3	37.7
Lander	Mean	0.7	1.1	2.2	3.5	5.0	6.5	7.5	6.5	4.3	2.5	1.1	0.8	41.7
	StDv	0.3	0.3	0.5	0.6	0.7	0.9	0.6	0.6	0.7	0.5	0.3	0.2	2.8
	High	1.4	1.9	3.3	4.8	6.6	8.3	8.8	7.7	5.3	3.4	1.9	1.2	47.8
	Low	0.2	0.6	1.3	2.3	3.3	4.4	6.1	4.6	2.8	1.2	0.6	0.3	32.9
Sheridan	Mean	0.7	0.9	1.8	3.3	4.7	5.6	7.2	6.3	4.0	2.6	1.2	0.8	39.1
	StDv	0.2	0.3	0.4	0.7	0.7	0.9	0.7	0.7	0.6	0.6	0.4	0.3	2.6
	High	1.5	1.9	2.5	4.6	6.7	7.7	8.5	7.9	5.0	3.6	2.2	2.0	44.2
	Low	0.3	0.4	1.3	2.0	3.6	3.6	5.7	4.9	2.4	1.7	0.5	0.4	36.5
Rk Sprs	Mean	1.2	1.5	2.4	3.7	5.1	6.6	7.7	6.8	5.0	3.3	1.7	1.2	46.2
	StDv	0.3	0.4	0.5	0.6	0.6	1.1	0.7	0.7	0.7	0.7	0.6	0.4	4.6
	High	1.8	2.7	3.5	5.2	6.2	9.4	9.7	8.1	6.2	4.9	3.2	1.9	55.2
	Low	0.4	0.7	1.6	2.0	3.8	3.9	6.3	5.1	3.6	1.8	0.8	0.6	36.4
Pathfind	Mean	0.9	1.1	2.1	3.5	5.0	6.5	7.5	6.6	4.5	2.6	1.3	0.9	42.5
	StDv	0.2	0.3	0.5	0.6	0.8	0.9	0.6	0.6	0.7	0.5	0.2	0.2	2.4
	High	1.2	1.8	3.3	4.9	6.3	8.3	8.9	7.9	5.4	3.4	1.9	1.3	46.2
	Low	0.5	0.6	1.4	2.2	3.5	4.5	6.2	4.9	2.8	1.4	0.7	0.6	35.5
Whalen	Mean	1.7	1.9	2.6	3.5	4.7	6.3	7.6	6.9	5.1	3.6	2.2	1.8	47.9
	StDv	0.5	0.5	0.6	0.6	0.6	0.9	0.6	0.7	0.7	0.7	0.4	0.4	3.0
	High	3.3	3.0	3.7	4.6	6.4	8.7	8.7	8.3	6.7	4.8	3.3	2.6	54.5
	Low	0.7	1.1	1.2	2.4	3.6	4.8	6.1	5.2	3.3	1.9	1.5	0.9	40.2

Table 3. Means, Standard Deviations, and High and Low Net Evaporation (in inches) from Estimates Using the Kohler-Nordenson-Fox Equation With a Coefficient of 0.7 for Evaporation

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Casper	Mean	0.7	0.8	1.1	1.7	2.1	4.6	6.1	5.9	3.7	2.2	1.0	0.8	30.9
	StDv	0.6	0.5	0.9	1.2	1.8	1.6	1.1	1.1	1.4	1.0	0.6	0.4	4.5
	High	1.7	1.9	2.5	3.7	5.8	8.1	8.3	8.0	5.2	3.7	2.2	1.8	38.3
	Low	-0.8	-0.1	-1.2	-1.3	-2.6	1.1	3.8	2.2	-0.2	-0.2	-0.7	-0.4	20.6
Cheyenne	Mean	1.2	1.5	1.7	2.3	2.6	4.0	5.0	4.8	3.6	2.6	1.5	1.4	32.0
	StDv	0.9	0.7	1.1	1.5	1.8	1.9	1.6	1.2	1.4	1.2	0.8	0.5	6.3
	High	2.5	3.5	3.8	4.2	6.4	6.9	7.9	7.8	5.6	4.0	3.6	2.4	43.3
	Low	-1.7	-0.1	-0.6	-1.2	-2.4	-0.6	1.1	2.9	-1.1	-0.8	-1.2	0.2	18.7
Lander	Mean	0.2	0.5	1.0	1.1	2.3	4.8	6.9	6.1	3.2	1.2	0.3	0.3	28.1
	StDv	0.6	0.7	1.1	1.8	2.1	2.2	1.0	1.1	1.6	1.4	0.8	0.5	5.7
	High	1.1	1.8	3.0	4.3	5.8	8.3	8.5	7.7	5.3	2.9	1.9	1.1	41.3
	Low	-1.5	-1.4	-1.6	-3.0	-2.8	-1.9	5.0	2.6	-1.5	-1.8	-1.5	-0.9	12.2
Sheridan	Mean	0.1	0.4	0.9	1.5	2.1	2.6	6.2	5.3	2.6	1.5	0.4	0.3	23.7
	StDv	0.5	0.4	0.7	1.4	1.9	2.6	1.4	1.3	1.4	1.2	0.6	0.5	4.4
	High	1.3	1.4	2.1	4.2	6.5	6.9	8.0	7.5	4.7	3.3	2.1	1.9	34.7
	Low	-1.0	-0.5	-1.2	-1.9	-3.1	-4.1	2.3	1.1	-0.5	-1.2	-1.4	-0.9	14.4
Rk Sprs	Mean	0.8	1.1	1.9	2.7	3.8	5.5	7.1	6.1	4.3	2.6	1.2	0.7	37.7
	StDv	0.5	0.6	0.7	1.1	1.4	1.9	1.0	1.2	1.3	1.2	0.8	0.5	6.6
	High	1.7	2.6	3.4	5.1	5.7	9.4	9.1	8.1	6.1	4.8	3.1	1.7	51.1
	Low	0.7	0.0	0.6	0.7	0.6	0.6	3.9	3.3	0.3	0.2	0.0	-0.3	21.0
Pathfind	Mean	0.6	0.7	1.5	2.2	3.5	5.1	6.8	6.0	3.7	1.7	0.9	0.6	33.3
	StDv	0.4	0.5	0.7	1.1	1.6	1.7	0.9	1.1	1.2	1.1	0.4	0.3	4.0
	High	1.0	1.7	2.6	4.5	5.9	8.3	8.4	7.8	5.3	3.1	1.9	1.1	39.9
	Low	-0.9	-0.2	-0.2	0.5	0.1	1.1	5.0	2.4	1.0	-0.8	-0.2	-0.4	19.8
Whalen	Mean	1.3	1.5	1.9	2.0	2.5	3.9	5.9	5.9	3.7	2.9	1.7	1.3	34.8
	StDv	0.4	0.6	1.0	1.2	2.1	2.2	1.5	1.1	1.6	1.1	0.5	0.5	5.5
	High	2.0	2.8	3.5	4.0	6.3	7.7	8.5	8.0	5.6	4.4	2.6	2.2	45.3
	Low	0.4	0.6	-0.4	-0.2	-3.7	-0.9	2.6	3.5	-1.1	0.1	0.8	0.2	21.6

evaporation is shown by the values of Tables 2 and 3. The range of annual net evaporation values average 34% above and 42% below the mean annual values (Table 3). These are over twice the magnitude of the percentages for evaporation (Table 2). The standard deviations of the annual values are also near twice the magnitude for net evaporation than for evaporation.

The spatial variations of estimated evaporation and net evaporation are indicated by the values of Tables 2 and 3. Mean annual values of estimated evaporation range from a low of 39.1 inches per year at Sheridan to a high of 47.9 inches per year at Whalen. That is, the annual mean at Whalen is about 22.5% higher than the annual mean evaporation at Sheridan. Mean annual net evaporation ranges from a low of 23.7 inches per year at Sheridan to a high of 37.7 inches per year at Rock Springs. As can be seen, the spatial variation of net evaporation, in particular, is quite large. The spatial variations of mean annual values are similar to those shown by the maps of Lewis (1978) and Smith (1974).

EFFECTS OF WATER QUALITY, ICE, AND VEGETATION

Very little information is available concerning the effects of many of the common wastewaters on evaporation rates. It is known that the evaporation rate of a solution will decrease as the solids and chemical concentrations increase. However, the overall effects on evaporation rates of dissolved constituents as well as color changes and other factors of wastewater are unknown.

A series of field tests were conducted to investigate the influence that different types of wastewater might have on evaporation rates. These tests were investigative in nature and results cannot be considered as confirmation of rates to be expected in evaporation ponds. The objective was to obtain preliminary data on the magnitude of the potential effect of contaminants.

Field tests were conducted during the period from June 20 through October 29,1984. Plastic buckets with a diameter of 1 foot and a depth of 9.5 inches were filled to a depth of 8 inches with wastewater from various types of operations. These included municipal, coal mining, oil shale, uranium, and trona wastewaters. In addition, evaporation rates for tap water were measured. Specific gravities and total suspended and dissolved solids concentrations of each are given in Table 4. A comparison of evaporation for each treatment versus the evaporation for tap water is shown in Table 5. For the entire period of June 20 through October 28, municipal, coal and oil shale wastewaters averaged somewhat higher evaporation while uranium and trona averaged lower evaporation as compared to tap water. Evaporation rates ranged from -19% lower to 12% higher than tap water rates. Whether similar percentages apply to wastewater ponds and/or at different times of the year is unknown.

Table 4. Specific Gravities, Total Suspended Solids, and Total Dissolved Solids of Field Treatments.

Wastewater Source	Specific Gravity	Total Suspended Solids (ppm)	Total Dissolved Solids (ppm)
Tap Water	0.998	35	1010
Municipal	1.060	160	52900
Coal	0.998	10	626
Oil Shale	1.066	48	74200
Uranium	1.043	200	54100
Trona	1.000	170	2310

Table 5. Comparison of Evaporation Rates of Various Wastewater to the Evaporation Rates of Tap Water.

Period	Tap Water (Inches)	% Above or Below Tap Water Rates				
		Municipal	Coal	Oil Shale	Uranium	Trona
Jun20-Jun26	1.34	16	31			
Jun27-Jul 4	3.10	5	8			
Jul 5-Jul10	1.49	18	17			
Jul11-Jul17	2.27	19	19	- 9		
Jul18-Jul22	0.74	- 4	-11	- 1		
Jul23-Jul29	1.42	2	22	27		
Jul30-Aug 5	1.48	1	5	16		
Aug 6-Aug12	2.02	17	3	16	-35	
Aug13-Aug19	1.55	5	3	3	15	13
Aug20-Aug26	1.35	13	17	16	0	-61
Aug27-Sep 3	2.06	- 4	1	16	- 3	-29
Sep 4-Sep 9	2.17	1	1	12	0	-19
Sep10-Sep16	0.95	- 3	9	7	2	-19
Sep17-Sep23	1.35	6	8	15	13	-18
Sep24-Sep30	0.96	0	-13	20	- 7	-15
Oct 1-Oct 7	0.47	4	- 4	17	- 2	-13
Oct 8-Oct21	1.34	0	- 1	14	5	13
Oct22-Oct28	0.56	2	5	23	-11	5
Overall		6	8	12	- 3	-19

Evaporation ponds are usually designed on the basis of estimates of annual net evaporation. Calculation of annual evaporation rates requires estimates during periods when the surface may be frozen. Most studies related to cold weather evaporation have been concerned with snow rather than ice. In general, the evaporation from a snow pack is usually much less than the amount of melting that occurs. Considering the large percentage of the annual evaporation which occurs during the warmer months and the overall uncertainties involved in estimates of evaporation from water surfaces, the amount of evaporation from frozen ponds during winter can reasonably be neglected in calculating annual evaporation. A more important consideration is the evaporation which occurs during winter from ponds which may remain unfrozen due to the introduction of warm wastewater. In these cases, water temperature will influence the evaporation rates. However, the low value of the saturation vapor pressure of the air above any water body will limit evaporation. Annual estimates of evaporation herein have been made by applying the Kohler-Nordenson-Fox equation throughout the year. Such estimates should provide near maximum possible evaporation estimates.

For lined ponds, evaporation will be confined mainly to the water surface area. Evaporation from the soil and vegetation on the banks surrounding the pond should be minimal. However, for ponds which have appreciable seepage to the surrounding area, evaporation from this area will be dependent upon the type and amount of vegetation and the moisture content of the upper soil layers. Methods for calculating evaporation and/or evapotranspiration in these instances are readily available. Reports on evaluations of equations for calculating evapotranspiration (Jensen, 1973; Hill et al. 1983) indicate that the questions concerning selection of the appropriate equations are similar to those discussed previously for free-water evaporation.

If water losses from the surrounding area are a major component of the total evaporative losses of the pond, then soil moisture conditions will be expected to be high. Under non-limiting soil moisture conditions, vegetative moisture losses are often defined as "potential" losses. Evaporative losses in this case would not be expected to differ greatly from free water evaporation. As stated by Jensen (1973), "lake evaporation is frequently used as a measure of potential evapotranspiration." This statement is supported by an ongoing study in the Green River Basin of Wyoming for which preliminary results indicate that the magnitudes of pan evaporation and evapotranspiration from well-watered mountain meadow vegetation are very similar (Burman et al. 1984). Thus, for high soil moisture conditions, evaporation rates calculated for the water surface should be applicable to the surrounding area.

The influence upon evaporation of vegetative growth within a pond is uncertain. Idso (1981) has presented a review of literature on the relative rates of evaporative losses from open and vegetation covered water bodies. The review is inconclusive as to whether vegetation will increase or decrease evaporation compared to an open surface. It appears that the effect may be somewhat dependent upon the size of the water body. Idso concludes that evidence indicates vegetation will decrease evaporation for extensive surfaces with the effect being less for smaller surface areas. He states that "it is very possible, however, that the introduction of vegetation upon the surface of a water body of more limited extent may increase its evaporative water loss, but only while the vegetation remains in a healthy, robust condition." Thus, the effect of the presence of vegetation appears to range from being a water conservation mechanism to that of increasing evaporation. In either case, the potential effects appear to be quite large with reported ratios of vegetative covered to open water evaporation under extreme conditions ranging from 0.38 to 4.5. In most instances, this ratio would be expected to be much closer to unity.

SUMMARY

Information for the design of evaporation ponds in Wyoming is presented. Analyses include determination of the suitability of models for estimating evaporation and its variability in Wyoming and statistical description of the spatial and temporal variability of net evaporation.

The Kohler-Mordenson-Fox equation appears to be the best of the climatological equations for defining the amount and variability of evaporation in Wyoming. The equation is a combination method and requires temperature, wind, humidity, and radiation data as input. Since only temperature data are available at most locations in Wyoming, the single parameter equations requiring only temperature are often considered for calculating evaporation. With calibration, single parameter equations may be capable of predicting mean evaporation values nearly as well as the more complex equations. However, the single parameter equations do not properly describe the variability of evaporation. Since wind, radiation, and humidity data are readily available at only four locations in Wyoming, application of the Kohler-Nordenson-Fox equation can be accomplished only if climatic data is spatially extrapolated. Evaporation estimates using extrapolated data have variability characteristics similar to those of measured pan data and estimates using on-site climatic data. However, the means of evaporation estimates using extrapolated data may differ greatly depending upon the similarity of the climate at the two locations. This indicates that extreme care must be taken in selection of stations for data extrapolation and also the need for additional climatic measurements throughout the State.

Monthly and annual means, standard deviations, and highest and lowest evaporation and net evaporation values have been calculated for seven Wyoming stations. The standard deviations and ranges between highest and lowest annual values for net evaporation are nearly twice those for evaporation. The lowest monthly values for net evaporation are often negative, especially during winter months, indicating an excess of precipitation over evaporation. The spatial variation of annual mean net evaporation for the seven stations ranged from 23.7 inches per year at Sheridan to 37.7 inches per year at Rock Springs. The overall spatial variation throughout Wyoming can be expected to be greater when locations having more extreme climatic conditions are considered. Pond designs at sites not included herein need an evaluation of the net evaporation for that location. This evaluation may consist of simply confirming the similarity of conditions between the site of interest and one of the locations for which evaporation values have been calculated and/or using the Kohler-Nordenson-Fox equation along with the necessary climatic data to calculate net evaporation estimates for the desired location.

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