DESIGN CHARACTERISTICS FOR

EVAPORATION PONDS IN WYOMING

L. Pochop	December, 1984
J. Borrelli	August, 1985 (Rev)
V. Hasfurther	WWRC-84-08

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by

Larry Pochop
Agricultural Engineering

John Borrelli
Agricultural Engineering

and

Victor Hasfurther
Wyoming Water Research Center

University of Wyoming

ABSTRACT

Information for the design of evaporation ponds in Wyoming has been developed. The suitability of various models for estimating evaporation and its variability was investigated while the spatial and temporal variabilities of net evaporation at seven locations were described. A routing procedure was developed to analyze the effects of uncertainty in net evaporation estimates on the probability of pond failure.

Comparison of equations which estimate evaporation using climatological data showed that the equations vary greatly in their ability to define the variability of evaporation. The Kohler-Nordenson-Fox equation provided monthly and annual evaporation estimates having statistics resembling those of measured pan data closer than any of seven other equations tested. The equation requires temperature, radiation, wind, and humidity data as inputs. The Kohler-Nordenson-Fox equation using climatic data extrapolated from nearby stations provided better definition of the variability of evaporation than did equations requiring only on-site temperature data. However, results indicate that extreme care must be taken in selecting the stations from which data will be extrapolated.

Monthly and annual means, standard deviations, and highest and lowest evaporation and net evaporation values have been calculated for seven Wyoming stations. The year-to-year and spatial variation of evaporation and/or net evaporation in Wyoming was shown to be great enough to cause serious problems in defining rates for evaporation pond designs. Several factors were shown to exist which might produce uncertainties in any estimate of evaporation. The routing procedure was applied to analyze the effects of these uncertainties and variations. Results indicate that the liquid depth of an evaporation pond depends greatly on evaporation rates and maintenance of minimum liquid depths without pond overflow is very difficult.

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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.

The design of an evaporation pond depends critically upon knowledge of the spatial and temporal distribution of net evaporation rates and of the evaporative characteristics of the wastewater. The purpose of this project was to consider the former. However, analysis of the effects of decreased evaporation rates, as compared to free water surface evaporation, is included.

Precipitation data for many locations in Wyoming are readily available. NOAA (1973) publishes monthly and annual precipitation normals for approximately 75 locations in Wyoming. Precipitation probabilities are also available for several locations (Becker and Alyea, 1964; Alyea and Pochop, 1976-1977). Evaporation data have been summarized (Smith, 1974; Lewis, 1978; SCS), but only monthly and annual normals are given. 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.

State Guidelines and/or Regulations, in most cases, do not seem to provide definite criteria for the design of evaporation ponds. A survey of Wyoming's neighboring states indicates that Montana is one of the few states providing design criteria for evaporation ponds. Montana's Wastewater Treatment Pond Guidelines (1981) state that "net evaporation rate shall be calculated by using mean annual lake evaporation rate and the 10-year frequency precipitation rate." This guideline is for retention ponds in which wastewater disposal occurs by evaporation and/or seepage but discharge to surface water is not permitted.

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.

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 are the most common means for defining free water evaporation. However, the density of evaporation pan stations is much less than that of weather stations. Thus, the question persists as to the validity of evaporation estimates and especially with respect to the degree of variation in evaporation rates.

The evaporation rate of a solution will decrease as the solids and chemical composition increase. Depending upon its origin, evaporation pond influent may contain contaminants of various amounts and composition. Decreases in evaporation rates as 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 project. An analysis of the effects of the problem has been included without any attempt to define the amount of the decrease in evaporation.

The purpose of this report is to provide an analysis of information for the design of evaporation ponds in Wyoming. The report reviews evaporation data and the models for estimating net evaporation. The suitability of various models for estimating evaporation and its variability are defined. An analysis of the spatial and temporal variability of net evaporation is provided. Based on the results of this analysis, the effects of uncertainty in net evaporation estimates on the probability of failure of ponds are given.

PROJECT OBJECTIVES

This report is the final report for the project entitled "Design Characteristics for Evaporation Ponds in Wyoming". The main objective of the study was to develop design information for disposal of wastewater by evaporation in Wyoming. Specific objectives were:

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.

2. Statistically describe monthly, seasonal and/or yearly variations in evaporation through frequency distributions as well as predict expected average annual evaporation losses.

Three major sections follow. The first section entitled "Evaporation Measurements and Estimates" considers the methodology and results for objective #1. The second section entitled "Variability of Net Evaporation" considers the methodology and results for objective #2. The third section provides an analysis of design considerations for evaporation ponds based on the effects of the factors presented in the first two sections. Finally, these three sections are followed by a report summary.

EVAPORATION MEASUREMENTS AND ESTIMATES

Many methods exist for either measuring or estimating evaporative losses from free water surfaces. Measuring devices such as the Piche evaporimeter, Wild evaporimeter, and Livingston atmometer have been used but data from these instruments are difficult to relate to natural evaporation. Other methods for estimating evaporation are the eddy correlation and water budget approaches. The eddy correlation method requires relatively expensive and sensitive instrumentation while the water budget method is subject to inaccuracies, mainly due to hard to define seepage inflows and/or outflows. Long term records using any of the aforementioned methods do not exist in Wyoming.

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.

In order to define the variability of evaporation in Wyoming, data upon which to base the statistical analysis are required. Obviously the choices are to use existing evaporation pan data or to use climatological data in equations for estimating evaporation. Use of pan data is the more direct and easier approach. However, adequate pan data, in terms of spatial coverage and length of records, may not exist. If not, the only alternative are the equations based on climatological data. The analyses which follow consider the suitability of each approach for defining evaporation rates in Wyoming.

Analysis of Pan Data

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 in 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 has 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, 1984). 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 or spatial 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. In this manner, the climatological model which gives estimates best replicating actual evaporation rates could be identified. Once identified, the model could be used to provide evaporation estimates during the entire year as well as at additional locations.

Use of pan data for predicting free water evaporation from ponds requires that the pan readings be multiplied by a coefficient. Class A pan coefficients vary with the size, depth, and exposure of the water body for which evaporation estimates are being made as well as seasonally and geographically. An average annual value of 0.7 is commonly assumed for lake evaporation. The coefficient increases for smaller water bodies, with summer values as high as 0.94 reported for stock-water ponds in Wyoming (Cueller, 1961). Smith (1974) has used an average annual coefficient of 0.93 for stock-water ponds in Wyoming.

Comparison of Class A pan coefficients across the United States show annual coefficients ranging from 0.6 to 0.8 for lake evaporation (Hounam, 1973; Nordenson, 1963; Gangopadhyaya,1966). The annual coefficient is usually taken as 0.70 for climatic conditions where pan water temperature and ambient air temperature are approximately equal. Lower annual coefficients are normally applied in arid regions while higher coefficients are applied in humid regions. Selection of a pan coefficient for application to evaporation ponds requires consideration of the contradictory effects of Wyoming's semi-arid conditions, which call for a low pan coefficient, and the size of evaporation ponds, which require a larger coefficient as compared to lakes. Reasonable values would seem to lie in the range of approximately 0.7 to 0.95, depending on pond size. The exposures of both the pan and water body also affect the magnitude of the coefficient.

The seasonal variation of pan coefficients must also be considered. For lakes, monthly coefficients vary greatly (Nordenson, 1963; Garrett and Hoy, 1978) with short term pan coefficients depending on the thermal inertia of the water body and, thus, mainly on depth. However, the shallow depths of evaporation ponds create little temperature lag. Garrett and Hoy (1978), using a numerical lake model to compare depths of 16.5 ft, 65 ft, and 260 ft, have shown least seasonal variation for lakes with depths of 16.5 feet.

Comparison of pan data at Whalen and Pathfinder shows that mean monthly values are not greatly different at the two stations (Table 1). The greatest difference is in September, with Whalen having evaporation about 18% lower than Pathfinder. The five month totals are about 7% lower at Whalen. The standard deviations were similar at the two locations. The values indicate that the variability of monthly evaporation was slightly greater at Whalen during four of the five months. The coefficients of variation show the standard deviations range from nearly 7% to 17% of the monthly means.

Equations for Estimating Evaporation

In 1955 Kohler et.al. (1955) performed an extensive analysis of procedures for estimating lake evaporation. Their model consisted of an adaptation of Penman's combination equation (1948) which they essentially calibrated for lake evaporation. Since 1955 many modifications to the methods of Kohler et.al. have been suggested. A recent review of some of these modifications is given by Brutsaert (1982).

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.

Of the criteria considered above, a relatively small amount of information exists on the ability of various equations to define the variation of evaporative losses. Most comparisons of methods have considered average annual evaporative losses [e.g., Anderson and Jobson, 1982] rather than the statistics describing the variation of these losses. Allen and Wright [1983] have compared estimates of evapotranspiration using a modified combination equation and the Blaney-Criddle formula. Standard deviations of long-term daily and monthly estimates compared much more closely with measured alfalfa water use when using the combination equation than when using the single parameter Blaney-Criddle. Kohler, et.al., [1959] have published the standard deviations of annual Class A pan evaporation, but they did not compare the predictive capability of various equations. There have been a number of sensitivity analysis of evaporation and/or evapotranspiration formulas [e.g., Camillo and Gurney, 1984], but these generally have been concerned with the interactions of the various components for purposes such as analyses of the effect of meteorological measurement errors. In summary, equations using fewer parameters may, with calibration, predict mean evaporation values as well as the more complex equations but are usually thought not to describe the variation in evaporation as well.

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 locations 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.

Selection of a method suitable to Wyoming for estimating evaporation requires a reference against which the estimates may be compared. In Wyoming, the only available data base is the evaporation pan records. Assuming that the pan data provide the best available estimates of actual free water evaporation, then these may be used as a basis for comparing evaporation models. Thus, the most suitable evaporation model is the one providing estimates nearest the means and standard deviations of existing pan data. As discussed in the previous section, an uncertainty exists with respect to the proper magnitude of the pan coefficient.

Statistics of Evaporation Estimates

Eight climatological methods have been 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 2. 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. Further details of each formula will not be given here since such details may be found in the references cited in Table 2. In addition, an excellent summary is given by Warnaka (1985). Only the method which is selected for use in estimating evaporation will be outlined in detail later in this section.

Table 1. Statistics of Monthly Pan Evaporation*

Month	Means (in/mo)		Standard Deviations (in/mo)		Coeff Var (%)	
	Whalen	Pathfinder	Whalen	Pathfinder	Whalen	Pathfinder
May	5.3	5.2	0.87	0.79	16.4	15.2
Jun	6.4	6.4	1.06	0.94	16.6	14.7
Jul	7.4	7.9	0.79	0.71	10.7	9.0
Aug	6.5	7.3	0.67	0.55	10.3	7.5
Sep	4.5	5.5	0.67	0.75	14.9	13.6

*A coefficient of 0.7 has been applied to the pan data.

Table 2. Data Requirements of Evaporation Equations.

Method	Data Required				Reference
	Temp	Hum	Wind	Rad	
Blaney-Criddle	X				SCS, 1967
Linacre	X				Linacre, 1977
Stewart-Rouse	X			X	Stewart and Rouse, 1976
Priestley-Taylor	X			X	Priestley and 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

Analysis of the equations involved using Whalen Dam and Pathfinder Dam pan data as a standard against which estimates from the various equations were compared. Monthly estimates were made for all years having data at each station. Monthly means and standard deviations of the pan evaporation and estimated values were compared for each equation. The only climatological data at the pan stations was air temperature. The standard Class A evaporation pan station does include wind measurements, but these are near pan level and records appear inconsistent. Measurements of radiation, humidity, and wind are required as input to the various equations. These data were taken from nearby first-order stations, Casper for Whalen Dam and Lander for Pathfinder Dam.

Tests of normality were made for estimated and measured evaporation for each month and location. Pan data at both Whalen Dam and Pathfinder Dam were normally distributed for all months at a 0.05 level of significance. Estimated monthly evaporation was normally distributed at a 0.05 level of significance for all equations at both locations except for estimates using the Priestley-Taylor and Kohler-Parmele at Pathfinder Dam. In general, the assumption of normal distributions for monthly totals was accepted.

Selection of an equation for use in estimating pond evaporation rates requires that the equation predict both the mean (Table 3) and the variability of actual evaporation. Examination of the standard deviations (Table 4) and the coefficients of variation (Table 5) indicate three equations--Linacre, Penman, and Kohler-Nordenson-Fox--with variability similar to pan evaporation. The Blaney-Criddle, Priestley--Taylor, deBruin, and Stewart-Rouse methods gave a narrower range of variability at both locations as did the Kohler-Parmele equation at Pathfinder. Of the three equations predicting the variability of evaporation, the Kohler-Nordenson-Fox had means closest to the pan standard. Both the Penman and Linacre equations predicted monthly means higher than the measured pan evaporation. An additional advantage of the Kohler-Nordenson-Fox method is that it is the only equation of those tested that includes the pan coefficient as a variable in the equation. Thus, regardless of the magnitude of the coefficient applied to the pan data, the means calculated using the Kohler-Nordenson-Fox equation will reflect the same adjustment. The Kohler-Nordenson-Fox equation means ranged from 119% to 85% of the 0.7* pan standard, with all months at both locations averaging 102% of the 0.7*pan standard. Using a pan coefficient of 0.7, the Linacre mean ranged from 202% to 147% of the 0.7*pan standard while the Penman means ranged from 201% to 137%.

The Kohler-Nordenson-Fox equation provided the best estimates of the means and variability of pan evaporation at Whalen and Pathfinder. 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.

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

$$E = \frac{\Delta}{\Delta + \gamma} Rn + \frac{\gamma}{\Delta + \gamma} Ea$$

Table 3. Mean Monthly Estimates of Evaporation (inches/mo).

Location	Month	B-C	LIN	S-R	P-T	deB	PEN	KNF	K-P	PAN*0.7
Whalen	May	3.2	7.8	6.6	5.5	7.9	8.3	5.1	3.1	5.3
	Jun	5.1	10.4	8.0	7.3	9.5	10.5	6.8	4.9	6.4
	Jul	6.6	13.3	8.9	8.4	10.9	12.2	7.9	6.0	7.4
	Aug	5.7	12.8	7.4	7.1	11.0	11.6	7.2	5.2	6.5
	Sept	3.3	7.6	5.7	4.6	9.3	9.8	5.4	3.2	4.5
Pathfinder	May	2.8	7.8	6.3	6.6	5.5	7.4	5.2	3.3	5.2
	Jun	4.3	9.8	8.2	8.2	6.7	9.3	6.7	4.8	6.4
	Jul	6.0	12.9	8.8	9.1	8.4	10.9	7.7	5.9	7.9
	Aug	5.2	12.5	7.8	7.8	8.1	10.0	6.9	5.1	7.3
	Sept	3.0	9.6	5.8	5.8	6.5	7.8	4.7	3.1	5.6

Table 4. Standard Deviations of Evaporation Estimates (inches/mo).

Location	Month	B-C	LIN	S-R	P-T	deB	PEN	KNF	K-P	PAN*0.7
Whalen	May	0.39	0.99	0.20	0.44	1.42	1.20	0.68	0.37	0.86
	Jun	0.60	1.52	0.23	0.71	2.19	1.70	1.08	0.78	1.08
	Jul	0.53	1.22	0.16	0.54	1.59	1.29	0.71	0.63	0.78
	Aug	0.45	1.00	0.15	0.52	1.41	1.13	0.68	0.51	0.67
	Sep	0.49	1.42	0.22	0.45	1.55	1.19	0.73	0.43	0.66
Pathfinder	May	0.42	1.13	0.23	0.65	1.03	1.10	0.89	0.47	0.78
	Jun	0.52	1.35	0.24	0.74	1.39	1.20	0.91	0.65	0.93
	Jul	0.50	1.02	0.17	0.58	0.80	0.66	0.56	0.57	0.72
	Aug	0.40	0.96	0.14	0.53	0.91	0.83	0.65	0.51	0.53
	Sep	0.44	1.16	0.22	0.53	0.79	0.90	0.66	0.40	0.76

Table 5. Coefficients of Variation of Estimates (%).

Location	Month	B-C	LIN	S-R	P-T	deB	PEN	KNF	K-P	PAN*0.7
Whalen	May	12.2	12.7	3.1	8.0	18.0	14.4	13.3	11.9	16.2
	Jun	11.8	14.6	2.9	9.7	23.1	16.2	15.9	15.9	16.9
	Jul	8.0	9.2	1.8	6.4	14.6	10.6	9.0	10.6	10.5
	Aug	7.9	7.8	2.0	7.3	12.8	9.7	9.4	9.8	10.3
	Sep	14.8	14.8	3.9	9.8	16.7	13.1	13.7	13.4	14.7
Pathfinder	May	15.0	14.5	3.7	9.8	18.7	14.9	17.1	14.2	15.0
	Jun	12.1	13.8	2.9	9.0	20.7	12.9	13.6	13.5	14.5
	Jul	8.3	7.9	1.9	6.4	9.5	6.1	7.3	9.7	9.1
	Aug	7.7	7.7	1.8	6.8	11.2	8.3	9.4	10.0	7.3
	Sep	14.7	12.1	3.8	9.1	12.2	11.5	14.0	12.9	13.6

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, Rn is the net radiation exchange expressed in equivalent inches of water evaporated, and Ea is an empirically derived bulk transfer term of the form

$$Ea = f(u)\ (es - ed)$$

where f (u) is a wind function and (es - ed) is the vapor pressure deficit.

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

$$Ea = (0.37 + 0.0041\ Up)\ (es - ea)^{0.88}$$

where Ea is in inches of water per day, Up is the wind speed 2 feet above the ground expressed in miles per day, and es and ea 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-Nordenson-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).

Evaporation from Ice and Vegetation

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.

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 reasonable 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. During months when ponds are frozen, evaporation rates near zero may be assumed. Confirmation of these values is difficult, since measurements of pan evaporation in Wyoming seldom extend beyond the months of May through September. For most locations in Wyoming, mean monthly air temperatures are below freezing during at least the months December through February (Becker and Alyea, 1964). This period may be two months longer for many of the colder locations in Wyoming. As will be shown later, the estimated evaporation during the three coldest months (December through February) averaged about 10% of the annual evaporation for seven Wyoming locations. Net evaporation during the same three months and locations was lower, averaging about 7.5% of the annual net evaporation.

Free vs Contaminated Water Evaporation

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. As shown later in this report, small percentage over estimates of the evaporation rates from waste ponds can lead to designs that greatly increase the potential of pond overflows.

A series of laboratory and 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. It was not the intent of this project to define the effect of contaminants on the evaporation rates of various wastewaters.

Laboratory tests were conducted during a 60 day period from January 19 through March 20, 1984. Small plastic cups having a diameter of about 3.5 inches and a height of 5 inches were used with a liquid depth of 4 inches. Daily measurements were taken of the relative evaporation rates of tap water, municipal wastewater, high salinity water, and water with oil films created using about 0.06, 0.31 and 0.61 cubic inches of oil added to cups containing tap water. The oil films were defined as light, medium, and heavy treatments. Six cups were used for each of the 6 treatments, for a total of 36 cups. The relative evaporation rates, as compared to tap water, are shown in Figure 1. Results show that oil films can definitely decrease evaporation rates, at least in a laboratory environment. The effect might be considerably less in an outdoor pond due to the effects of wind in breaking up the oil film. The average losses from the municipal wastewater and high salinity water were similar to the rates from tap water.

Field tests were conducted during the period from June 20 through October 28, 1984. Plastic buckets with a diameter of 1 ft 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 6. Results of approximately weekly evaporation measurements are shown in Table 7 in terms of depth of evaporation per measurement period. A comparison of evaporation for each treatment vs the evaporation for tap water is shown in Table 8. 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.

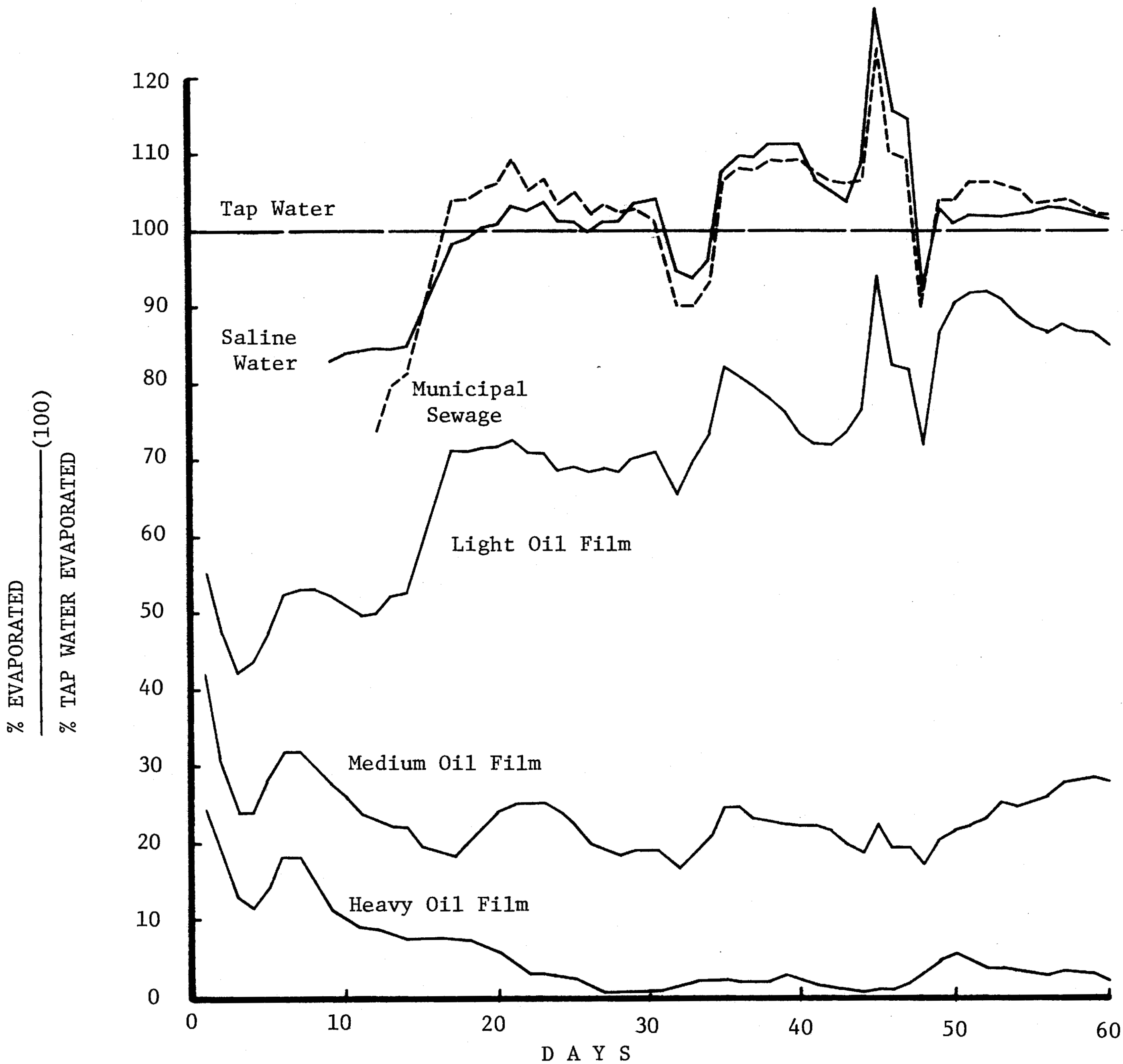

Figure 1. Comparisons of Relative Evaporation Rates of Tap Water vs Various Treatments

Table 6. 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 7. Depths of Evaporation (Inches) From Various Types of Wastewater.

Period	Tap Water	Source of Wastewater: Municipal	Coal	Oil Shale	Uranium	Trona
Jun20-Jun26	1.34	1.46	1.76			
Jun27-Jul 4	3.10	3.26	3.35			
Jul 5-Jul10	1.49	1.76	1.74			
Jul11-Jul17	2.27	2.71	2.71	2.07		
Jul18-Jul22	0.74	0.71	0.66	0.73		
Jul23-Jul29	1.42	1.45	1.73	1.81		
Jul30-Aug 5	1.48	1.49	1.56	1.71		
Aug 6-Aug12	2.02	2.36	2.09	2.35	1.31	
Aug13-Aug19	1.55	1.63	1.60	1.60	1.79	1.75
Aug20-Aug26	1.35	1.53	1.58	1.56	1.35	0.53
Aug27-Sep 3	2.06	1.98	2.07	2.39	2.00	1.47
Sep 4-Sep 9	2.17	2.20	2.19	2.44	2.18	1.76
Sep10-Sep16	0.95	0.92	1.04	1.02	0.97	0.77
Sep17-Sep23	1.35	1.43	1.46	1.55	1.53	1.11
Sep24-Sep30	0.96	0.96	0.84	1.15	0.89	0.82
Oct 1-Oct 7	0.47	0.49	0.45	0.55	0.46	0.41
Oct 8-Oct21	1.34	1.34	1.32	1.53	1.41	1.16
Oct22-Oct28	0.56	0.57	0.59	0.69	0.50	0.59

Table 8. 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

VARIABILITY OF NET EVAPORATION

Previous summaries of evaporation data for Wyoming have been prepared (Smith, 1974; Lewis, 1978; SCS). These summaries present annual normals of evaporation but do not provide monthly normals nor probabilities of occurrence of evaporation events.

Review of reports shows a large variation in estimates (Table 9). These range from the 12 inches per year estimate taken from a world-wide map by Brutsaert (1982) to the 45 inches per year estimate at Casper from a state map developed by Lewis (1978) using pan data. Others include the 23 inches per year estimate at Casper from a state map of potential evapotranspiration prepared by the SCS using the Thorntwaite formula, which is a single parameter equation employing only air temperature; the 34 inches per year average state-wide estimate by Meyers and Nordenson (1962) based on pan data supplemented by estimates using the Kohler-Nordenson-Fox equation; and the 43 inches per year estimate at Casper adjusted from a state map of stock-water pond evaporation by Smith (1974), which is essentially a representation of evaporation given by Kohler et.al. (1959). The above estimates, except for the SCS estimate, are for lake evaporation but some are for shallow and others for deep lakes. Further confirmation of mean annual values is obviously desirable.

Summaries giving mean monthly evaporation values and/or defining the variability of evaporation for Wyoming apparently do not exist. The question of the variability of evaporation was addressed by Kohler et.al. (1959). Plate 5 of their evaporation maps for the United States included the standard deviations of annual Class A pan evaporation. The map, however, does not include any Wyoming stations. Numerous summaries for other types of climatic information have been prepared for Wyoming. Those considering the probabilities of occurrence include summaries for precipitation (Becker and Alyea, 1964; Heermann et.al., 1972), temperature (Becker and Alyea, 1964; Becker et.al., 1977), and heating and cooling degree days (Pochop et.al., 1978). As compared to evaporation, definition of the spatial variability of precipitation and temperature is easier since a large number of recording stations exist for precipitation and temperature.

Monthly and Annual Variability

Monthly evaporation estimates have been made at several locations using the Kohler-Nordenson-Fox equation with a pan coefficient of 0.7. 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 10). High, low, and mean values for pan coefficients other than 0.7 can easily be obtained from the data of Table 10 by dividing the values by 0.7

Table 9. Summary of Evaporation Estimates for Wyoming.

Location	Evaporation (Inches/Yr)	Reference
Wyoming	12	Brutsaert (1982)
Casper	23	SCS
Wyoming	34	Meyers and Nordenson (1962)
Casper	43	Smith (1974)
Casper	45	Lewis (1978)

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.

During periods of high precipitation, evaporation rates generally are expected to decrease leading to the lowest net water losses by evaporation. As an example, Figure 2 shows the relationships between evaporation and precipitation for each of the months May through September for Whalen Dam. Monthly evaporation decreases with increasing precipitation except for the month of June. No explanation exists for the exception in June. The correlation coefficient for June, however, was only 0.26 and, although not high for the other months, the correlation coefficient ranged from a low in August of 0.44 to a high in September of 0.69. With high values of evaporation most often associated with low precipitation and low evaporation with high precipitation, the variability of net evaporation will be greater than that of evaporation.

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 11). Again, a pan coefficient of 0.7 was used. The greater variability of net evaporation as compared to evaporation is shown by the values of Tables 10 and 11. The range of annual net evaporation values average 34% above and 42% below the mean annual values (Table 11). These are over twice the magnitude of the percentages for evaporation (Table 10). The standard deviations of the annual values are also near twice the magnitude for net evaporation than for evaporation.

Table 10. 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

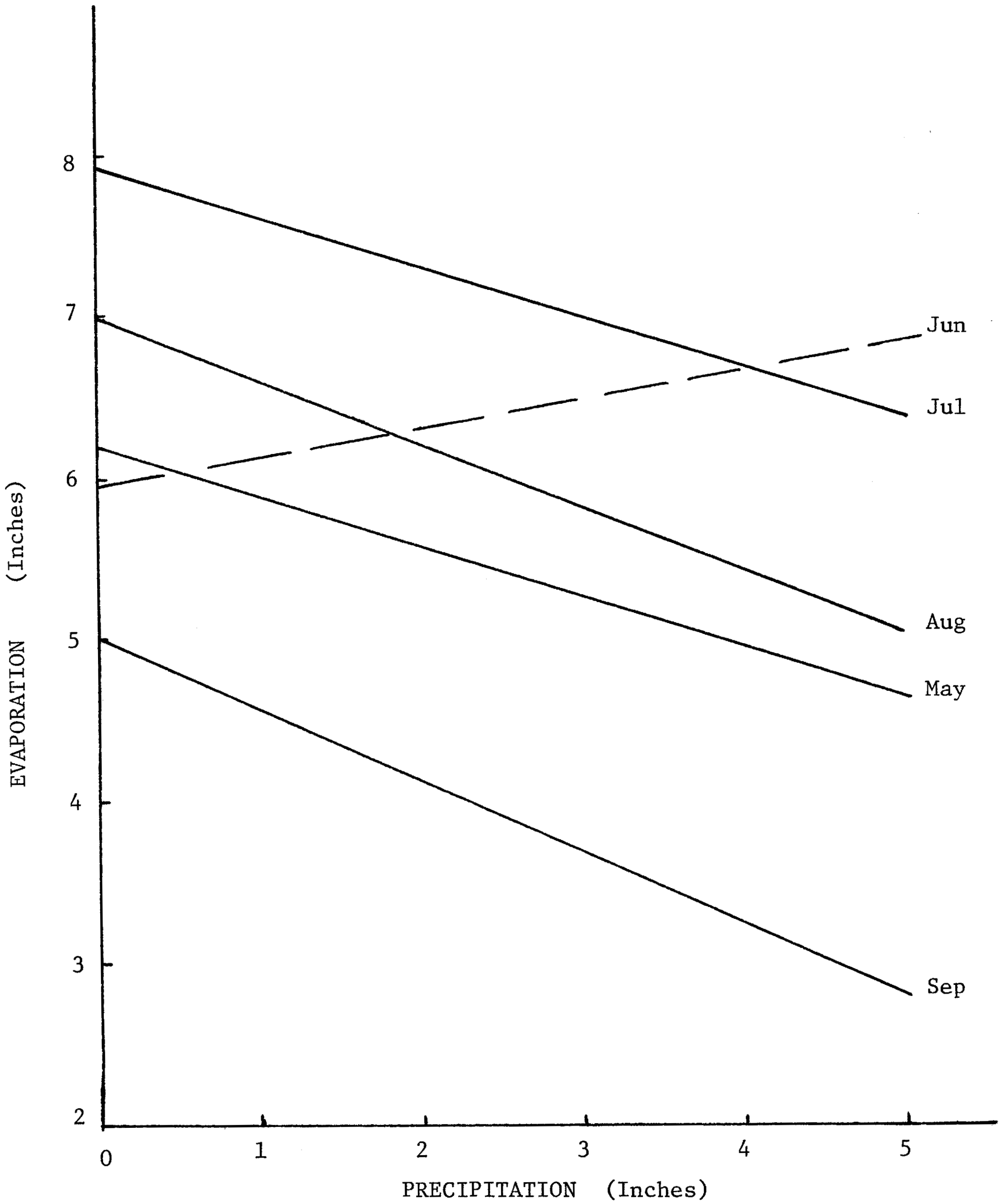

Figure 2. Evaporation vs Precipitation for Each of Five Months at Whalen. (Evaporation = Pan Data * 0.7).

Table 11. 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

Spatial Variation

Estimated values at Whalen and Pathfinder can be compared with measured values for the months May through September (Table 12). The five month totals of the estimated evaporation values are about 2% higher and 7% lower than the measured totals at Whalen and Pathfinder, respectively. This indicates that even though some climatic data are extrapolated from nearby stations, the Kohler-Nordenson-Fox equation provides close estimates of evaporation.

The stations from which climatic data are to be extrapolated for use in the Kohler-Nordenson-Fox equation must be selected with care. An example of the differences that may be obtained using various first order stations as the source of climatic data is given in Table 13. Estimated evaporation for Cody show a range of mean annual values ranging from 40.1 inches per year using humidity, wind, and radiation data from Sheridan to 55.0 inches per year when using data for the same parameters from Casper. The estimate is about 27% lower when using Sheridan data than when using Casper data. However, based on several factors, the most reasonable station for extrapolation of data would be Lander. Using Lander data gave a mean annual estimate of 45.0 inches per year. The estimated standard deviations are similar for the three cases.

The spatial variations of estimated evaporation and net evaporation are indicated by the values of Table 10. 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).

Table 12. Comparison of Measured Pan Data and Estimated Evaporation* at Whalen and Pathfinder.

Month	Whalen Means (Inches) Meas	Whalen Means (Inches) Estm	Pathfinder Means (Inches) Meas	Pathfinder Means (Inches) Estm	Whalen StDv (Inches) Meas	Whalen StDv (Inches) Estm	Pathfinder StDv (Inches) Meas	Pathfinder StDv (Inches) Estm
May	5.3	4.7	5.2	5.0	0.9	0.6	0.8	0.8
	6.4	6.3	6.4	6.5	1.1	0.9	0.9	0.9
	7.4	7.6	7.9	7.5	0.8	0.6	0.7	0.6
	6.5	6.9	7.3	6.6	0.7	0.7	0.6	0.6
	4.5	5.1	5.5	4.5	0.7	0.7	0.8	0.7
Season	30.1	30.6	32.3	30.1				

* A pan coefficient of 0.7 has been applied.

Table 13. Evaporation Estimates for Cody Using the Kohler-Nordenson-Fox Equation* with Humidity, Radiation and Wind Data Taken From Three Different First Order Stations.

Means (Inches)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Casper	1.7	1.9	2.6	3.5	7.0	8.1	9.1	8.1	5.7	3.5	2.0	1.8	55.0
Lander	1.1	1.5	2.5	3.8	5.4	6.6	7.7	6.7	4.4	2.8	1.4	1.1	45.0
Sheridan	1.1	1.3	2.1	3.3	4.7	5.5	7.1	6.1	3.9	2.6	1.3	1.1	40.1

Standard Deviations (Inches)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Casper	0.5	0.5	0.6	0.6	0.5	0.8	0.6	0.4	0.6	0.7	0.4	0.4	2.9
Lander	0.3	0.3	0.5	0.6	0.7	0.8	0.5	0.7	0.7	0.6	0.3	0.2	2.8
Sheridan	0.3	0.3	0.4	0.7	0.7	0.9	0.6	0.7	0.6	0.6	0.4	0.3	2.6

* A coefficient of 0.7 has been applied.

DESIGN CONSIDERATIONS

Analyses and comparison of current and previous estimates of pond evaporation show that uncertainties exist in any estimate. These uncertainties arise because of several factors, including: possible inaccuracies in historical pan measurements, questions concerning the magnitude of pan coefficients, the inability of climatological equations to model evaporation perfectly, nonavailability of data required as input to models for predicting evaporation and the unknown effect of contaminants in evaporation suppression. Pond designs can only recognize the fact that uncertainties exist and analyses of the effects of these uncertainties should be considered.

Another uncertainty which exists is the natural variation of evaporation rates. The previous section provides the empirical probabilities for net evaporation, but these probabilities do not define the chances of failure for an evaporation pond. However, the previous sections do provide information which allows analysis of probabilities of failure for evaporation ponds as related to the annual variation of net evaporation and the effects of uncertainty in evaporation estimates. Using the selected models, long term monthly net evaporation estimates can be calculated for any location having the necessary weather data. These estimates can be used in a routing procedure to develop the probabilities of success of a specific pond design for given conditions and locations.

Routing Procedure

A routing procedure was developed to analyze the water balance of an evaporation pond. The routing procedure for an evaporation pond is relatively simple because outflow is not a function of inflow. Outflow is simply the net evaporation (assuming no leakage from the pond) while the inflow is the design discharge rate specified by the user of the evaporation pond. The pond surface area was assumed to be a constant, even though most ponds will have sloping sides. This assumption could be considered a small safety factor, providing surface area is specified conservatively. The surface area, although considered a constant for a specific design, is however, a design variable.

Using an end of period convention, the routing algorithm is

$$Si = Si\text{-}i + Ii - EiA + PiA - SPi$$

where Si is the storage at the end of the period i in acre-ft, Si-i is the storage in the pond at the end of the period i - 1 in acre-ft, Ii is the inflow during period i in acre-ft, Ei is the depth of evaporation during period i in ft, A is the surface area of the pond in acres, Pi is the depth of precipitation during period i in ft, and SPi is the volume of spillage during the period i in acre-ft. To prevent failure, the storage volume Si must be maintained between minimum and maximum design values. Generally, a minimum allowable liquid depth is specified--often near 2 ft--to minimize weed growth in the pond, while a storage volume Si exceeding the maximum design volume will cause a spillage.

Numerous possibilities exist concerning pond designs that could be analyzed. For example, pond inflow rates vary depending upon the requirements of the user. For simplification, constant inflow rates were assumed in the following examples. Because of the ready availability of monthly climatic data, the length of the period i was specified as a month. Actual design depths may vary widely, but were limited herein to maximum values between 2 ft and 8 ft while two cases, zero ft and 2 ft, were considered for minimum liquid depth. Routing was begun by assuming a pond without water and then progressing through the years month-by-month. Thus, times at which both the minimum and maximum water depths were exceeded were identified.

The routing procedure was performed by estimating Ei using the Kohler-Nordenson-Fox equation for evaporation. A pan coefficient of 0.7 was used in all routing examples. Although a coefficient near 0.9 may be acceptable for fresh-water small pond evaporation in Wyoming, the use of a 0.7 value is conservative. A 0.7 value allows, in a very limited way, for some evaporation suppression due to contaminants in wastewater ponds. Monthly precipitation values were taken from the records of the nearest National Weather Service Station. Thirty-five or more years of monthly data were available at most stations.

Routing Analysis

Analyses were performed, using the routing procedure and conditions described in the previous section, to determine the frequencies of pond failure and the probable years of life of an evaporation pond before the first overflow. The analyses define the effects of uncertainty in estimates of design evaporation rates. All analyses were based on pond designs using estimated mean evaporation minus mean measured precipitation as the design criteria, Table 11. Constant inflow rates were used, as defined in terms of the estimated mean net evaporation. That is, annual inflow rates were calculated using the mean annual net evaporation on a per unit surface area basis for each location. Each monthly inflow was then taken as one-twelvth of the annual inflow. Due to uncertainties in the estimates, actual evaporation rates could be either greater or less than the estimated rates used in design. Most analyses were performed for Casper since it is the most centrally located of the four first order NWS stations in Wyoming.

Examples of the frequency of overflow occurrences for ponds of various depths and assumed errors in design evaporation rates are shown in Tables 14 through 21. The results show that, in most cases, once the first overflow occurs, then overflows can be expected on a rather regular basis thereafter. Thus, the number of years between the date of placing the pond in operation and the first overflow is very important. This period will be discussed in more detail later.

A 2 ft minimum depth is often recommended to reduce weed growth in wastewater ponds. As shown in Table 14, a liquid depth less than or equal to 2 ft is a common occurrence in ponds whenever the actual evaporation rate is equal to or greater than the design value. For actual rates slightly less than the design value the problem of a liquid depth of less than 2 ft disappears a few years after pond startup (Tables 15-21). Overall pond depth has little influence on minimum liquid depths.

Consideration of design requirements of both minimum and maximum liquid depths indicates the difficulty in meeting these requirements. Maintenance of minimum liquid depths requires design evaporation values slightly greater than actual rates. Except for the 2 ft depth, no overflows were found for the case when actual evaporation equalled the design value. However, actual rates of the magnitude of a few percent less than design rates will lead to frequent overflow problems. In general, pond designs which will maintain minimum liquid depths without exceeding pond holding capacities appear to be very difficult to achieve. Ideally, designs with design evaporation rates 5% greater than actual rates are desirable (Tables 15 and 19).

Table 14. Overflow and minimum depth occurrences for a 5 ft deep pond and actual evaporation equal to the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-		-		-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-	-	-	-	-	-
29	-	-	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-
31	-	-	-		-	-	-	-	-	-	-	-
32	-	-	-			-	-	-	-	-	-	-
33	-	-			-		-	-	-	-	-	-
34	-	-	-	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-
36	-	-	-	-			-	-	-	-	-	-
37									-			
38									-	-		

- Liquid depth less than 2 ft
+ Liquid depth greater than 5 ft

Table 15. Overflow and minimum depth occurrences for a 5 ft deep pond and actual evaporation 5% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-					-	-	-	-	-	-
7	-					-	-	-	-	-	-	-
8	-	-						-				
9												
10												
11												
12												
13												
14									-	-		
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28				+	+							
29				+	+							
30				+								
31	+	+	+	+								
32		+	+	+								
33				+	+							
34												
35												
36					+							
37	+	+	+	+	+							
38	+	+	+		+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 5 ft

Table 16. Overflow and minimum depth occurrences for a 5 ft deep pond and actual evaporation 10% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-						-	-		
6												
7												
8												
9												
10					+							
11					+							
12			+									
13												
14												
15				+	+	+					+	+
16	+	+	+	+								
17		+	+	+	+							
18		+	+	+								
19												
20			+	+	+							
21	+	+	+	+								
22				+	+							
23					+	+						
24	+	+	+	+								
25												
26	+	+	+	+	+							
27		+	+	+								
28		+	+	+	+							
29			+	+	+							
30			+	+								
31	+	+	+	+								
32	+	+	+	+								
33			+	+	+							
34					+							
35		+	+	+								
36		+	+	+	+							
37	+	+	+	+	+							
38	+	+	+		+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 5 ft

Table 17. Overflow and minimum depth occurrences for a 5 ft deep pond and actual evaporation 15% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-			-	-	-	-	-	
5												
6												
7												
8												
9		+	+	+	+	+					+	+
10	+	+	+		+							
11				+	+							
12			+									
13			+	+								
14			+	+	+							
15				+	+	+					+	+
16	+	+	+	+								
17	+	+	+	+	+							
18		+	+	+								
19												
20	+	+	+	+	+							
21	+	+	+	+								
22			+	+	+							
23			+	+	+	+						+
24	+	+	+	+								
25						+	+					+
26	+	+	+	+	+							
27	+	+	+	+		+						
28	+	+	+	+	+							
29		+	+	+	+							
30		+	+	+								+
31	+	+	+	+								+
32	+	+	+	+								
33		+	+	+	+							
34			+	+	+							
35	+	+	+	+	+							
36		+	+	+	+							+
37	+	+	+	+	+							+
38	+	+	+	+	+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 5 ft

Table 18. Overflow and minimum depth occurrences for a 5 ft deep pond and actual evaporation 25% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-				-				
4												
5												
6			+	+	+							+
7	+	+	+	+	+							
8	+	+	+	+	+				+	+	+	+
9	+	+	+	+	+	+	+			+	+	+
10	+	+	+		+							
11	+	+	+	+	+							
12	+	+	+		+							
13		+	+	+		+						
14	+	+	+	+	+							
15		+	+	+	+	+				+	+	+
16	+	+	+	+								+
17	+	+	+	+	+							
18	+	+	+	+								
19		+	+	+							+	+
20	+	+	+	+	+	+					+	+
21	+	+	+	+								
22	+	+	+	+	+							
23		+	+	+	+	+					+	+
24	+	+	+	+								
25		+	+	+	+	+					+	+
26	+	+	+	+	+	+						+
27	+	+	+	+		+						+
28	+	+	+	+	+							+
29	+	+	+	+	+							
30	+	+	+	+	+						+	+
31	+	+	+	+						+	+	+
32	+	+	+	+								
33	+	+	+	+	+							
34	+	+	+	+	+						+	+
35	+	+	+	+	+							
36	+	+	+	+	+						+	+
37	+	+	+	+	+			+			+	+
38	+	+	+	+	+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 5 ft

Table 19. Overflow and minimum depth occurrences for a 8 ft deep pond and actual evaporation 5% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-					-	-	-	-	-	-
7	-					-	-	-	-	-	-	-
8	-	-						-				
9												
10												
11												
12												
13												
14									-	-		
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												
32												
33												
34												
35												
36												
37					+							
38	+	+	+		+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 8 ft

Table 20. Overflow and minimum depth occurrences for a 8 ft deep pond and actual evaporation 15% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-			-	-	-	-	-	
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15											+	+
16	+	+	+	+								
17	+	+	+	+	+							
18		+	+	+								
19												
20	+	+	+	+	+							
21	+	+	+	+								
22			+	+	+							
23			+	+	+	+						+
24	+	+	+	+								
25					+	+						+
26	+	+	+	+	+							
27	+	+	+	+		+						
28	+	+	+	+	+							
29		+	+	+	+							
30		+	+	+								+
31	+	+	+	+								+
32	+	+	+	+								
33		+	+	+	+							
34			+	+	+							
35	+	+	+	+	+							
36		+	+	+	+							+
37	+	+	+	+	+							+
38	+	+	+	+	+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 8 ft

Table 21. Overflow and minimum depth occurrences for a 8 ft deep pond and actual evaporation 25% less than the design value - Casper, Wyoming.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-				-				
4												
5												
6												
7												
8												
9					+	+	+			+	+	+
10	+	+	+		+							
11	+	+	+	+	+							
12	+	+	+		+							
13		+	+	+		+						
14	+	+	+	+	+							
15		+	+	+	+	+				+	+	+
16	+	+	+	+								+
17	+	+	+	+	+							
18	+	+	+	+								
19		+	+	+							+	+
20	+	+	+	+	+	+					+	+
21	+	+	+	+								
22	+	+	+	+	+							
23		+	+	+	+	+					+	+
24	+	+	+	+								
25		+	+	+	+	+					+	+
26	+	+	+	+	+	+						+
27	+	+	+	+		+						+
28	+	+	+	+	+							+
29	+	+	+	+	+							
30	+	+	+	+	+						+	+
31	+	+	+	+						+	+	+
32	+	+	+	+								
33	+	+	+	+	+							
34	+	+	+	+	+						+	+
35	+	+	+	+	+							
36	+	+	+	+	+						+	+
37	+	+	+	+	+			+			+	+
38	+	+	+	+	+							

- Liquid depth less than 2 ft
+ Liquid depth greater than 8 ft

Factors influencing the years before the first overflow were analyzed in greater detail. Basically, the two factors which may be controlled are pond surface area and depth. The surface area is directly dependent upon the evaporation rate used in design and, thus, the factor which is actually controlled is the selection of the design evaporation rate. Current designs are usually based on estimated mean net evaporation rates. The uncertainty in estimating evaporation rates, therefore, affects pond life before overflow.

Routing was performed for pond depths from 2 ft to 8 ft and actual evaporation rates equal to and 5, 10, 15, 20, and 25 percent less than design rates. All available years of record were used for each station (Casper and Gillette are discussed as examples, where Gillette evaporation was calculated using wind, humidity, and radiation data from Sheridan). Routing for each case was repeated using each of the available years as the beginning year. When a year other than the first year of the actual record was used as the beginning year, all data prior to the beginning year were added to the end of the record. This permitted simulation of many different sequences of weather events and identification of the effects of climatic variation upon pond life before the first overflow. Thus, maximum and minimum calculated pond lives in particular, and means to a lesser extent, are dependent upon the available record. The range could be greater if longer records were available.

Results indicate that the number of years before the first overflow is greatly influenced by how closely the design evaporation rate matches the actual rate. Figures 3 and 4 for a 5 ft pond depth at Casper and Gillette, respectively, show that actual evaporation rates as much as 10 to 15 percent below design rates can limit the period before the first overflow to less than 10 years on the average. Results at Gillette show a greater range between minimum and maximum values. This indicates a greater year-to-year variability in the net evaporation rates at Gillette.

If the surface area of a pond remains unchanged but depth is allowed to decrease, as may occur due to sludge accumulation, the useful life of the pond decreases. Figures 5 and 6 show the effect of varying pond depths on pond life for the case when actual evaporation is 15 percent below the estimated value. The depth effect is approximately linear, and as the error in evaporation estimates increases the effect of varying pond depths also increases.

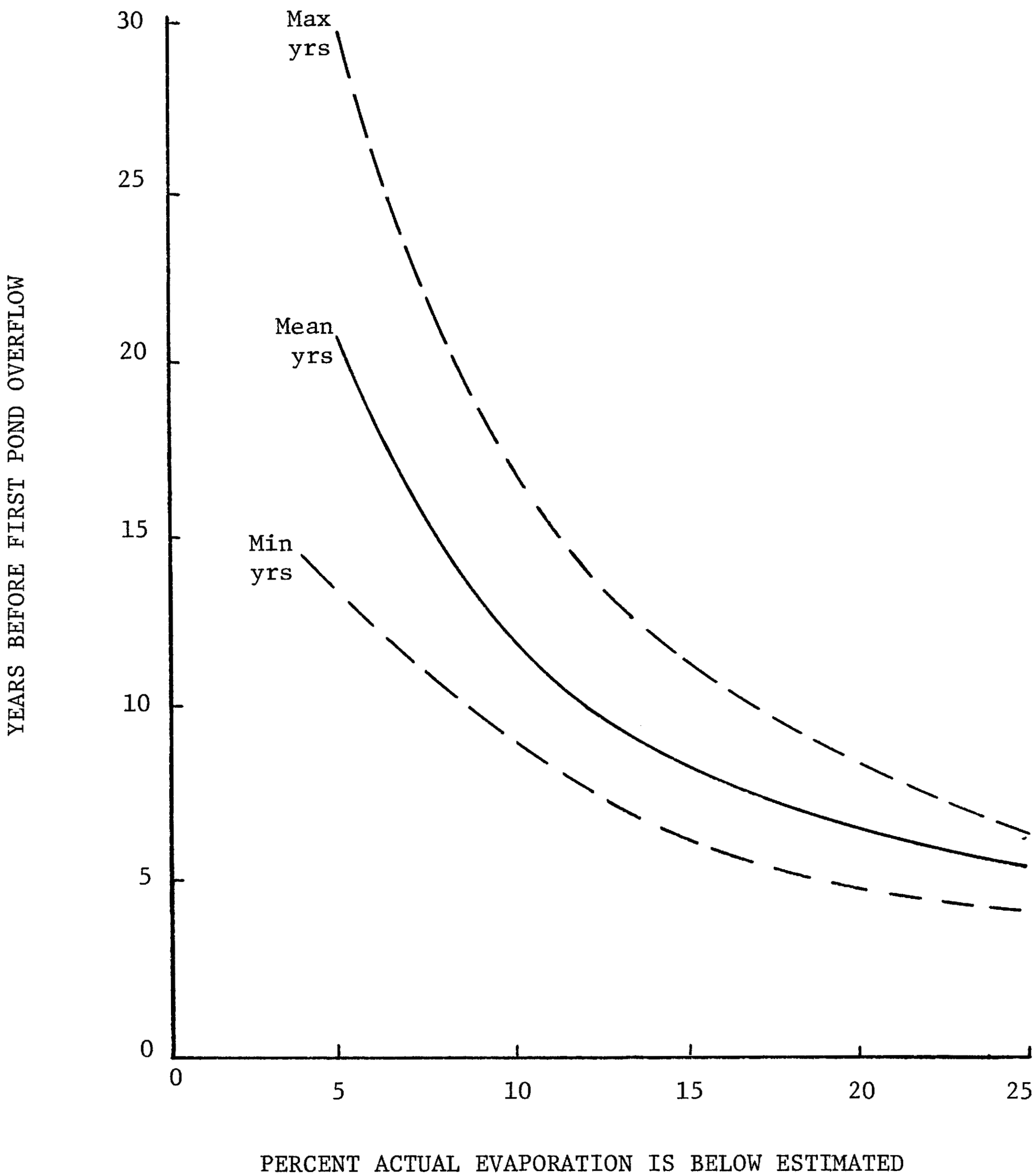

Figure 3. Years before first overflow if actual evaporation rates are below the estimated values - for Casper, Wy and a 5 ft pond depth.

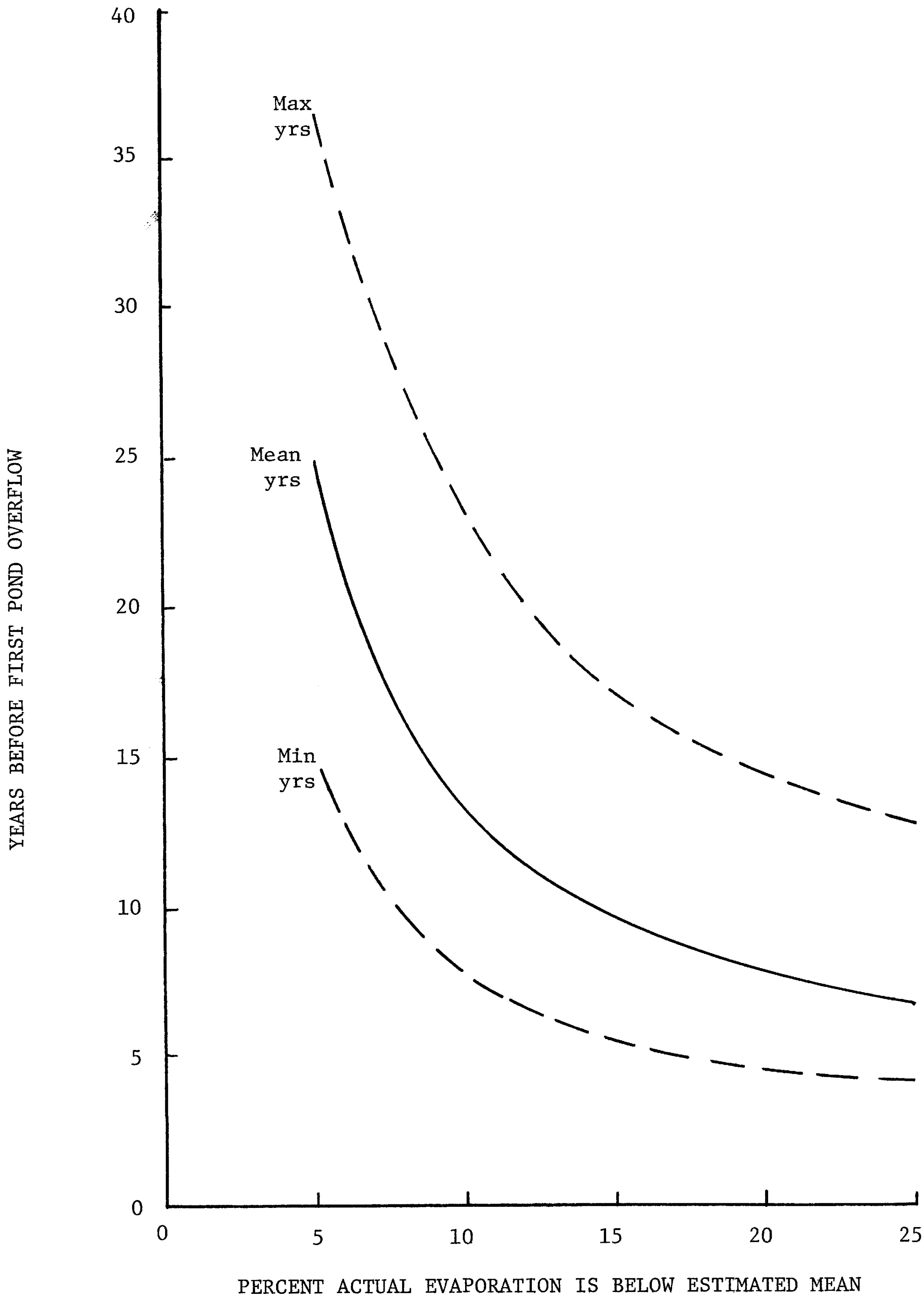

Figure 4. Years before first overflow if actual evaporation rates are below the estimated values - for Gillette, Wy and a 5 ft pond depth.

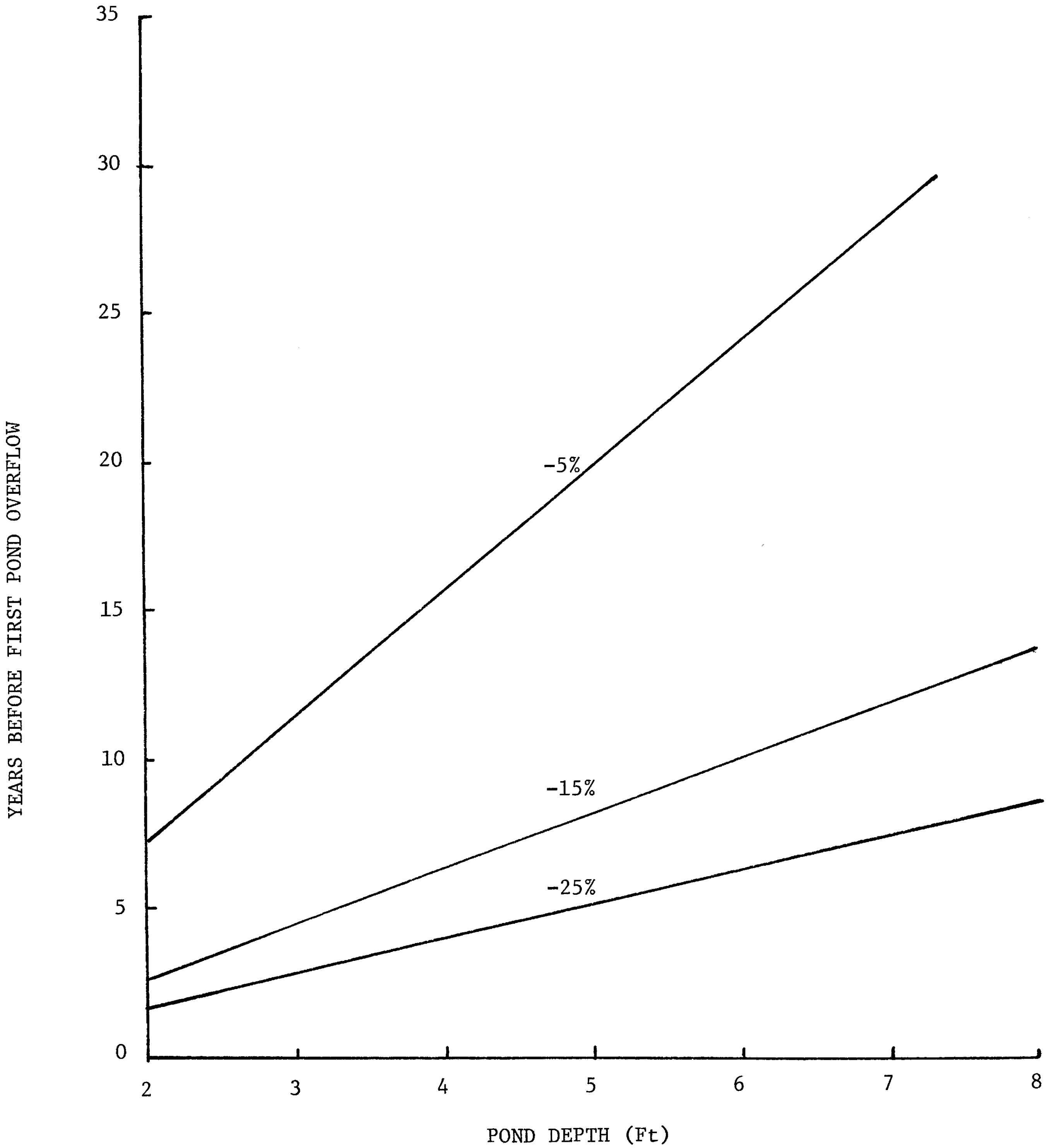

Figure 5. Years before first pond overflow versus pond depth for actual evaporation rates of 5%, 15%, and 25% below estimated free water rates - Casper, Wy.

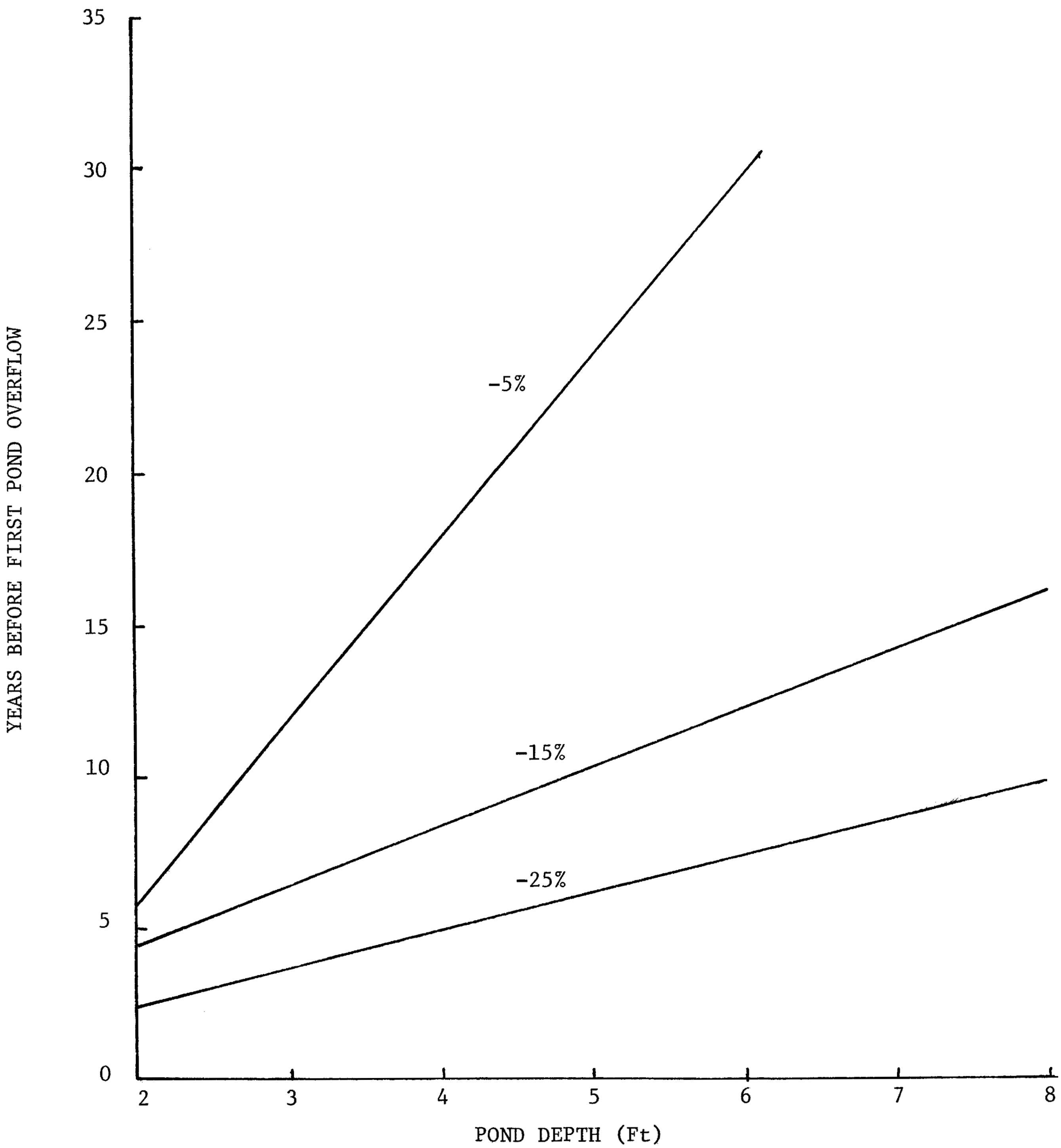

Figure 6. Years before first pond overflow versus pond depth for actual evaporation rates of 5%, 15%, and 25% below estimated free water rates - Gillette, Wy.

SUMMARY

Information for the design of evaporation ponds in Wyoming has been developed. Analyses have included determination of the suitability of models for estimating evaporation and its variability in Wyoming, statistically describing the spatial and temporal variability of net evaporation, and defining the effects of uncertainty in net evaporation estimates on the probability of pond failure.

The Kohler-Nordenson-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 inputs. 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 are spatially extrapolated. Evaporation estimates using extrapolated data have variability characteristics similar to those of measure 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.

Liquid depths in evaporation ponds are influenced greatly by net evaporation rates. A small overestimate of net evaporation used in design versus actual rates can lead to frequent overflows. In most cases, it has been shown that once an overflow occurs, then the probability of additional overflows in following years is very high. The expected number of years before the first overflow is dependent upon how closely the design evaporation rate matches the actual rate. Example calculations for Casper show that for ponds of 5 ft depth and constant inflow, actual evaporation rates as little as 10 percent below design rates can limit the period before the first overflow to less than 12 years on the average, with the year-to-year variability of net evaporation causing the range to vary between about 9 and 17 years.

Specific conclusions include:

1. The Kohler-Nordenson-Fox equation appears to be the best of the climatological equations for defining the amount and variability of evaporation in Wyoming.

2. The year-to-year variability of net evaporation is considerably greater than for evaporation, with the standard deviations of annual net evaporation being nearly twice those for annual evaporation.

3. The magnitude of the spatial variation of evaporation and net evaporation in Wyoming is great enough to cause serious problems in defining rates for evaporation pond designs, especially when considered with respect to the limited availability of pan and/or climatological data in the State.

4. The year-to-year variability of net evaporation can cause rather large ranges between the minimum and maximum number of years before overflow.

5. Liquid depth of an evaporation pond depends greatly on evaporation rate, thus, maintenance of minimum liquid depths without pond overflow is very difficult.

6. Routing analyses should be considered as one component of pond design procedures.

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PROJECT PERSONNEL AND COOPERATORS

Principal Investigators

Pochop, Larry	Agricultural Engineering
Borrelli, John	Agricultural Engineering
Hasfurther, Victor	Civil Engineering

Graduate Student

Warnaka, Karen

Student Assistants

Ferrall, Christopher
Hogan, Angela
Shenefelt, John

Secretarial Staff

Bonner, Ginny
Pliley, Connie

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