

TEXAS WATER DEVELOPMENT BOARD

REPORT 77

EVAPORATION FROM BRINE
SOLUTIONS UNDER CONTROLLED
LABORATORY CONDITIONS

By

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FOREWORD

This report contains descriptions and results of studies and analyses of data prepared by Mr. Jaroy Moore, Graduate Student, and Dr. J. R. Runkles, Professor of Soil Physics, in the Soil and Crop Sciences Department of the College of Agriculture, Texas A&M University, College Station, Texas in performance of research into salt water-fresh water evaporation relationships at various air and water temperatures, relative humidity, and wind movement under Inter-Agency Cooperation Contract Number 4413-95A with the Texas Water Commission beginning July 1, 1964.

The report provides results important to the investigation of means of disposal of salt water through evaporation. Surface disposal areas which will not endanger underground usable water through leakage need to be properly sized. This sizing is dependent upon the rate of evaporation. Control measures being considered for naturally occurring mineralized water in the Red, Brazos, Colorado, and Rio Grande river basins may use large evaporation reservoirs as one alternative means to prevent contamination of better quality water in those basins. Results of this report have already been used in considering these alternatives.

The research and control parameters for this study were selected and proposed to Dr. Morris E. Bloodworth, Head of the Soil and Crop Sciences Department, by Louis L. McDaniels, Coordinator of the Commission's Applied Research Programs (now Chief Hydrologist, Texas Water Rights Commission), for the purpose of exploring and defining the stability of the effect of salinity on evaporation under various climatic conditions to extend the data reported by G. Earl Harbeck, Jr. in the U.S. Geological Survey Professional Paper 272-A, "The Effect of Salinity on Evaporation," 1955. Dr. Harbeck recommended additional research to supplement his report on which procedures for the design of lined brine disposal ponds were being

studied by the Commission. The complexities and instabilities of salt water-fresh water evaporation relationships as reported support Dr. Harbeck's recommendations.

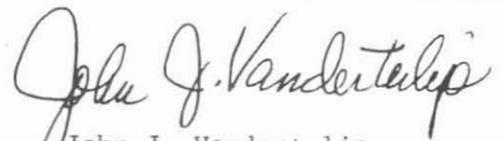
Some of the functions of the Texas Water Commission were assigned to the Texas Water Development Board by the Legislature, with this action effective September 1, 1965. The Texas Water Commission was renamed the Texas Water Rights Commission. Research in progress at that date was continued to the completion of the report. The preliminary draft manuscript was reviewed by Louis L. McDaniels for the Water Rights Commission and John J. Vandertulip for the Water Development Board. Comments and suggestions made by these reviewers were incorporated into the final report.

In addition to information available on oil-field brine production mentioned in the Introduction, data are also available for 1961 and are being obtained for 1967. However the research purposes are related to mineralized water regardless of source.

Results described in this report are with sodium chloride solutions. As time and funds permit similar research studies using variable concentration solutions of other constituents, and mixtures approximating brines which occur naturally, need to be made.

In publishing this report to make the results available it is recognized the laboratory results and report discussion may not be representative of conditions existing at a reservoir.

TEXAS WATER DEVELOPMENT BOARD


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ACKNOWLEDGMENTS

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C H A P T E R I

INTRODUCTION

Clean fresh water is no longer considered to be inexhaustable and concern is rapidly arising relative to the proper utilization and conservation of this important resource. The demands for water are increasing as industries expand and population grows and man faces many problems in the preservation of water to meet these needs. One such problem is that of pollution of waters by contaminants which arise from many sources.

Saline or mineral water is one source of contamination which is found naturally occurring in both surface and underground deposits as well as by-products resulting from industrial plant operations. The large amount of oil production in Texas also accounts for an even larger production of brine water. Information is available for the production of oil but data on brine production is lacking except for information on specific fields and counties.

Reports such as one from the Powell-Wood brine field in Navarro County, Texas, (16) give some idea as to the oil and salt water production resulting in this industry. It related the production of 33,856,381 barrels of oil and 35,724,000 barrels of brine in 1924 - or a ratio of essentially one.

In nearby Limestone County, Edmonson (6) reported 1955 figures for oil and brine, respectively, as being 291,413 and 5½ million barrels. Garza County (5) in the Southern High Plains of Texas produces about 5,638,000 barrels of oil while salt water production

was listed as 14,296,709 barrels for 1961.

The only figures available for statewide production of oil and brine were those given by Kennedy (11), in 1936, where he estimated that 2.2 barrels of salt water were produced for each barrel of crude oil. Regardless of the exact brine to oil ratio, it can be seen that large quantities of salt water are produced each year. This brine production combined with that from industry presents serious problems relating to the proper disposal of saline waters.

Disposal of salt water is generally accomplished by either re-injection into existing or abandoned oil wells, or by pumping into surface pits to evaporate. The literature on this subject is limited but it appears that both methods have been used extensively in the past.

*Salt Sulphur Co
Madagascar
Country*

Many legal disputes have erupted between oil companies and landowners over the improper disposal and the subsequent contamination of soils, ground water, surface waters, and streams. Industries are faced with these same problems of disposal and often find themselves at odds with the public because of pollution of rivers and streams.

Evaporation of these saline waters is one means of disposal; however, information is lacking about the rates of evaporation which would be expected to occur. Also with oil occurring in almost all parts of Texas there exists a wide variety of climatic conditions under which evaporation may take place. A knowledge of the effects of the climatic variables, and also of salt concentration, would provide valuable information relating to the expected rates of evaporation. Information of this type will aid in pit design for

disposal of saline water by evaporation.

The Texas Water Development Board is one of several state and federal agencies which are concerned with the production and subsequent disposal of salt water. It was through their interest in the problem that an inter-agency contract was established with the Texas Agricultural Experiment Station to finance this study. The principal objectives of the study were:

1. To establish the effect of sodium chloride concentration on the evaporation of water under controlled climatic conditions.
2. To determine the influence of air temperature, relative humidity and wind velocity on the evaporation of water from salt solutions.
3. To develop an empirical equation which will express the evaporation of water from brines in terms of such parameters as salt concentration, air temperature, wind speed, and relative humidity.

C H A P T E R I I
REVIEW OF LITERATURE

Studies of evaporation and the factors influencing it were begun in the early 1800's. As is the case with much of the research being conducted in relation to the processes of nature, many things are not fully understood and theory advanced in the laboratory is often difficult to convert to natural conditions. The basic parameters which affect evaporation have been known for some time. The work of Dalton (6, 7) laid the basic foundation from which the current theories of evaporation have evolved. His generalized formula of evaporation,

$$E = C (P_w - P_a)$$

was proposed in 1834. In his formula

E = rate of evaporation;

P_w = vapor pressure in the film of air next to the water surface;

P_a = vapor pressure in the air above the film;

C = coefficient that is dependent upon barometric pressure, wind velocity, and other variables.

From the above formula have come many related equations to depict evaporation as a mass transport process. Numerous investigators have contributed to the theory of evaporation since the early work of Dalton. It will be the purpose of this review to look only at those contributions in which saline waters were employed as the source for evaporation.

Some of the early work in evaporation of salt solutions was conducted by Harris and Robinson (9) in 1916. They examined the factors affecting evaporation from soils including the influence of

salt. The effects of dissolved salts were known to reduce vapor pressure and consequently reduce evaporation. Solutions of sodium chloride were placed in glass tumblers, two tumblers per treatment, and set in the open laboratory where evaporation losses were determined by weighings. Distilled water and solutions of 10, 20, and 30 percent sodium chloride were used. Results showed evaporation to be about 79, 68, and 52 percent for the 10, 20, and 30 percent sodium chloride solutions, respectively, as compared to the rate obtained with distilled water. From these results they concluded as salt concentration increased, evaporation decreased.

Lee (12) in 1927 undertook the problem of determining the effect of specific gravity of solutions on the rate of evaporation.^{1/} Methods employed were as follows: Two samples of water were used, one distilled and one a brine from Owens Lake, California with a specific gravity of 1.11. The samples were placed in circular, flat-bottomed pans, $4\frac{1}{4}$ inches deep and 12 inches in diameter, and filled to the same depth. The pans then were placed in a bath in a room free from drafts. The successive depths of water in the pans were calculated from the observed weight and specific gravity of the samples and the known dimensions of the pans. It was found the rate of evaporation from Owens Lake brine decreased with increasing salt concentrations. At a specific gravity of 1.275, crusting of salt began and the evaporation of water was 27 percent less than from distilled water. The

^{1/} Some of the earlier workers used the term specific gravity as an expression of salt concentration. This term is not generally used today as specific gravity may be influenced by things other than salt concentration.

rate of evaporation continually decreased with increasing specific gravity.

As a practical check to experimental data obtained, Lee had data available from Owens Lake where evaporation rates had been calculated for a period of seven years. The average specific gravity of the water was 1.11 and the existing data indicated an annual evaporation of 60.8 inches. Data from nearby Owens River gave an annual evaporation of 67 inches from fresh water for a three-year period. Reducing this by the 10 percent as indicated by his experimental data gave a value of 60.3 inches for the annual loss as compared with 60.8 inches determined from the hydrographic data.

The process of evaporation is defined by Lee in his paper as consisting mainly of the gradual "bombardment" into the adjacent atmosphere of the rapidly moving molecules which compose the liquid. The most important factors controlling evaporation are the relative temperatures of the liquid surface and of the adjacent atmosphere, the vapor and barometric pressures immediately above the liquid surface, and the concentration of salt in the waters.

Ball (1) estimated the probable rate of evaporation that would occur from a lake formed in the Qattara Depression of the Libyan Desert. These estimates made in 1933 were based on previous investigations performed in areas of similar climates and waters of various salinities.

He assumed an average value for salinity of sea water to be approximately 37.7 grams of dissolved solids per liter of solution.

Ball's estimates suggested a decrease of near 2.7 millimeters average daily evaporation as concentration of salt changed from fresh water conditions to a saturated brine.

In 1933 at Fort Collins, Colorado, Rhower (17) compared evaporation of water from sodium chloride solutions with that of distilled water. His experiment was conducted out of doors and the variables wind speed, and temperature of air and solutions were recorded. Solutions were placed in tanks containing 36 square inches of surface area and 18 inches deep with solution levels being maintained very near the surface. Observations of evaporation were made using hook gauges to determine the water level. Ratios of daily evaporation of the salt solutions to that of distilled water were as follows: [2 percent (NaCl solution) - 0.97; 5 percent (NaCl solution) - 0.98; 10 percent (NaCl solution) - 0.93; and 20 percent (NaCl solution) - 0.79.] Air temperatures during the course of study varied from 75° Fahrenheit (F) to 49.9°F, water temperatures ranged from 75.3°F to 52.2°F, mean differences in vapor pressure were from 0.425 to 0.138 millimeters Hg, and mean wind velocity in miles per hour (mph) varied from 1.18 to 0.84. Rhower developed an equation for estimating evaporation, from Weather Bureau pans.

The formula was as follows:

$$E = (1.465 - 0.0186B) (0.44 + .0118W) (e_s - e_d)$$

where E = evaporation in inches per day

B = barometric pressure in inches of Hg at 32°F

W = wind speed in mph

e_s = saturated vapor pressure in inches of Hg at temperature of water surface

e_d = saturated vapor pressure in inches of Hg of air at dew point temperature

Using this formula it was determined that ratios of evaporation for the salt solution would have been 0.989 for the 2 percent NaCl solution, 0.972 for the 5 percent NaCl solution, 0.948 for the 10 percent NaCl solution, and 0.880 for the 20 percent NaCl solution.

Young (18) was interested in the effect of salinity on evaporation from lakes in the western states such as the Salton Sea in California, the Great Salt Lake in Utah, and lesser bodies of saline waters in the Great Basin. The saline conditions had developed from the absence of outlets from the lakes leaving evaporation as the only means of disposal of water. He conducted an evaporation study using concentrations of sodium chloride ranging from 5 to 25 percent. Salt solutions were placed in pans which were exposed to out-of-doors climatic conditions. The study was conducted in Orange County, California; however, the environmental conditions existing during the period of the study were not given.

Information obtained from the study indicated that the average rate of decrease in evaporation from sodium chloride solutions was essentially one percent for each one percent increase in salt concentration. Results of the 25 percent salt solutions were not conclusive because salt crystals began to form due to high salt concentration.

In a 1955 U. S. Geological Survey paper, Harbeck (8) pointed out that the effect of dissolved solids was to reduce the saturation vapor

pressure of solutions. Also he stated that in almost all equations based on mass transfer or turbulent transport of energy and in nearly all empirical equations, evaporation was directly proportional to the vapor pressure differences. Therefore, when the other variables such as wind movement are held constant, evaporation was directly proportional to the difference between the vapor pressure of air in contact with the water (i.e. saturation vapor pressure of air at the temperature of the water surface) and the vapor pressure of air at some height above the water surface.

One of the latest papers dealing with the effects of salinity on evaporation is reported by Janson (10). A laboratory study was conducted using temperatures and relative humidities corresponding closely to those of arid regions. Temperatures ranged between 27° Centigrade (C) and 30°C while the relative humidity varied between 6 and 17 percent. No wind movement of any significance was imposed on the test water surfaces. Glass pans having an inner diameter of 20 centimeters and a depth of 7 centimeters were used as containers. Evaporation was determined using hook point gauges. Solutions were made using a mixture of several salts, predominantly sodium chloride, with smaller quantities of magnesium chloride, sodium sulfate and calcium chloride. Tap water and solutions containing 30,000, 60,000, 100,000 and 250,000 parts per million (ppm) of mixed salts were used. Based on tap water as 100 percent, the evaporation losses were 92, 82, 79, 62 percent for the 30,000, 60,000, 100,000 and 250,000 ppm salt solutions, respectively. Since some salt crystallization had occurred in the highest

concentration, another test carried out using only sodium chloride at the level of 250,000 ppm. Evaporation from this solution expressed in percent of the evaporation from tap water was 67 percent.

The effect of salinity on evaporation is well established in the literature where it has been shown that evaporation decreases as salinity is increased. The reported evaporation decreases are not in complete agreement but are apparent as to the effect exhibited by salts in solution. The previous investigations may be considered in two categories - one where the effect of salt concentration was measured under constant environmental conditions, and the other being studies of the effects of salinity in a naturally-occurring environment at a certain locality. No attempts have been made to investigate the effects of salinity on evaporation under a wide variety of wind speeds, air temperatures, and relative humidities, as well as salt concentrations in any one study. It is the purpose of this study to include a wide range of climatic variables with various salt concentrations to determine the effects of salinity on evaporation.

C H A P T E R I I I

MATERIALS AND METHODS

The data presented are the results of a controlled environmental experiment conducted during 1965 and part of 1966. The main objective of the study was to determine the effects of air temperature, relative humidity, wind speed, and salt concentration on evaporation from a free-water surface.

A. Treatments

Due to the wide variety of climatic conditions existing in Texas, treatments listed below were selected as a basis for obtaining data on rates of evaporation.

The following treatments were used:

1. Sodium Chloride (NaCl) was used in the following concentrations.
 - a. 0 (Distilled water as check)
 - b. 50,000 parts per million (ppm)
 - c. 150,000 parts per million
 - d. 300,000 parts per million
2. Relative Humidity
 - a. 40 percent
 - b. 60 percent
 - c. 80 percent
3. Air Temperature
 - a. 40° Fahrenheit (F)
 - b. 76° Fahrenheit
 - c. 90° Fahrenheit
4. Fluid Air Movement
 - a. 2 miles per hour (mph)
 - b. 6 miles per hour
 - c. 10 miles per hour
 - d. 16 miles per hour

Sodium chloride was selected as the common salt for the study. The use of sodium chloride was considered to be a practical approach because many natural brine waters are composed largely of this compound.

Restrictions due to limitations of space and time prevented a completely randomized design from being employed in the study. Due to the size of the solution containers and the environment chamber, only four containers could be used during one run. Information from preliminary data indicated evaporation was not equal from the containers; however, after beginning the study, little difference could be noted between rates of evaporation from the four containers. The above factors, plus the time factor that would have been required in changing solutions, rinsing and cleaning containers after each evaporation determination, directed that only one salt concentration be studied at a time.

The order of the four salt concentrations was randomly chosen, and the thirty-six climatic variables were imposed on each concentration. The climatic variables imposed on the solutions were randomly selected. A total of 144 combinations of concentration and climatic factors were studied.

B. Experimental Systems

The basic design of the experiment was similar to that reported by Meinke and Bloodworth (14).

1. Controlled environmental system. The controlled environmental system has been used in previous studies of evaporation from

soil, water, and plant surfaces. The controlled environment chamber is 4 x 4 x 10 feet in size, constructed of 5/16-inch plexiglass, and housed in a constant temperature room. A detailed description of the controlled environmental system has been presented by Bloodworth (2, 3, 4). The experimental apparatus and environment chamber are shown in Figure 1.

Instrumentation in the chamber provided control of air temperature and relative humidity. Air temperatures were controlled at $90^{\circ}\text{F} \pm 2^{\circ}\text{F}$ and $76^{\circ}\text{F} \pm 2^{\circ}\text{F}$. Temperature at the 40°F level, however, could not be maintained for long periods of time and a gradual increase in temperature was noted as a determination progressed. Relative humidity was controlled automatically at 40, 60 and 80 percent for all conditions except those at the 40°F air temperature level. In order to evaluate evaporation rates at the low temperature levels, air temperatures and relative humidities were recorded each time an observation was made of elapsed time and water loss from the burettes. Shown in Figures 1 and 2 is the psychrometer with wet and dry bulb thermometers which was used to determine air temperatures and relative humidities during the study.

Wind movement across the solution surfaces was obtained using an auxiliary, air duct and fan placed in the chamber. Wind speeds were controlled by regulating fan speed with a rheostat. The air duct and fan are shown in Figure 1. A closer view of the air duct is shown in Figure 2 where it will be noted that wind was pulled across the surface of the containers from left to right. Also shown is an aluminum

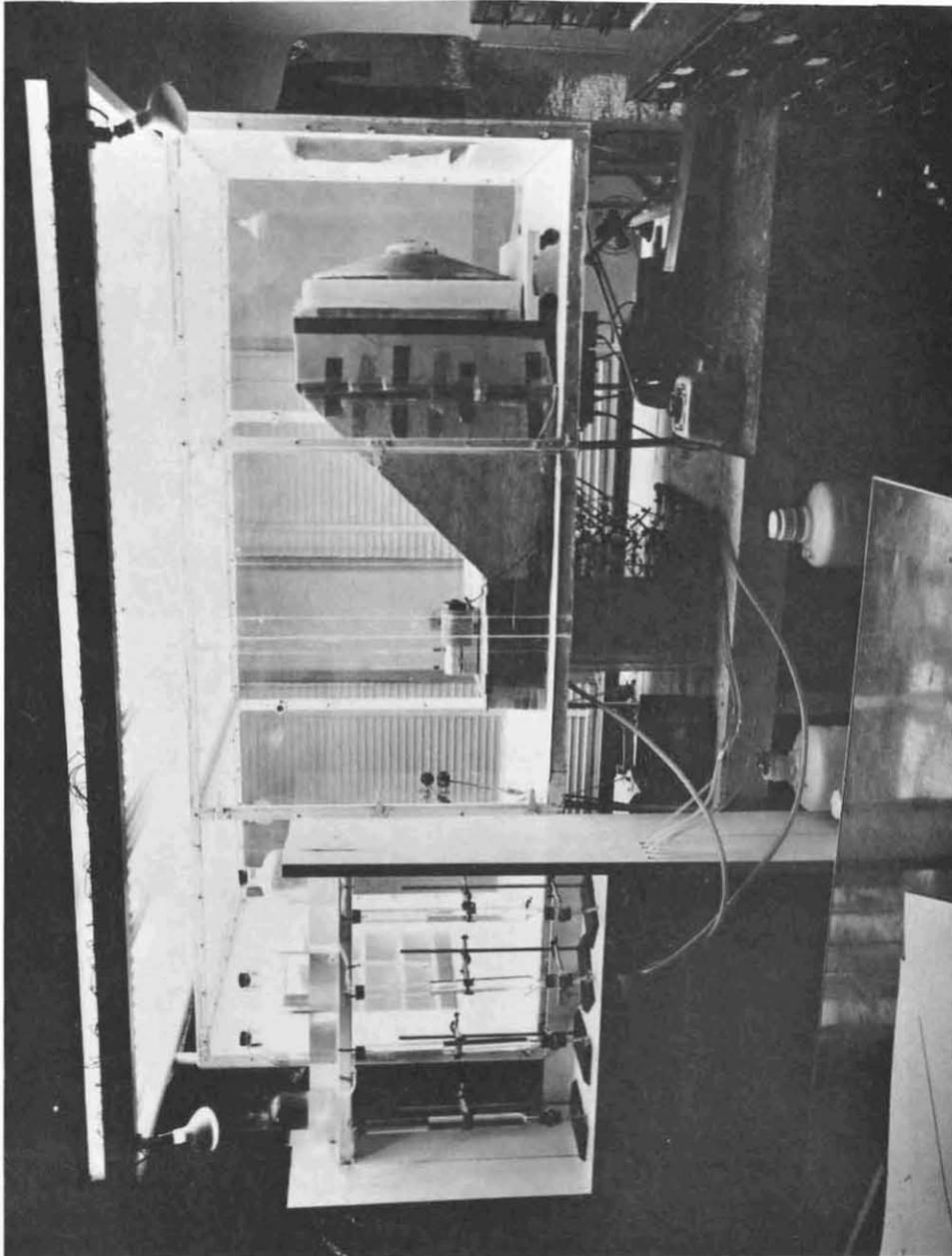


Figure 1. Experimental set-up used in the study.

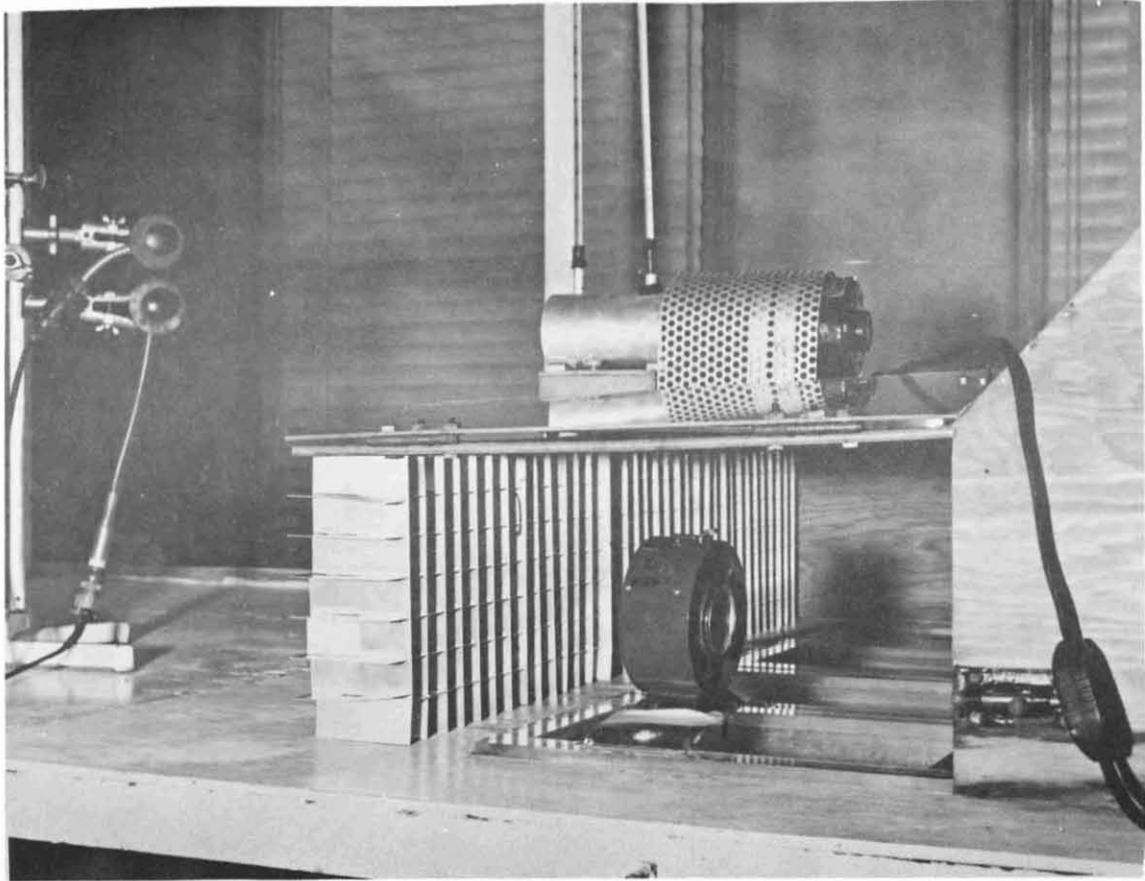


Figure 2. Shown here are temperature sensing device and controls, anemometer in position for wind speed measurement, and the psychrometer.

grill network which was placed in front of the containers to obtain laminar movement of air although no independent check was performed to insure such movement. An anemometer, shown in Figure 2, was used to determine the wind speed in the air ducts.

2. Evaporation containers. The four containers used to hold the solutions being evaporated are shown in Figures 3 and 4. They were constructed with double walls to allow water from a constant temperature bath to circulate around the solutions in order to provide control of solution temperature. Plexiglass was used in construction of the containers to avoid corrosion due to the salt solutions. The outer walls were constructed of 3/8-inch plexiglass and the inner walls were 1/2-inch plexiglass. Dimensions of the solution wells were 6.5 inches wide by 10.5 inches long by 21.5 inches deep giving a surface area of 68.25 square inches.

A close-up view of one container is shown in Figure 4. The double-wall construction can be seen as well as the location of sampling tubes and thermocouples through the wall of the container.

3. Profile studies. Information on depth distribution of salt concentrations and solution temperatures was obtained by sampling at the depths of 1.75, 3.75, 5.75, 9.75, 13.75 and 17.75 inches below the solution surfaces.

Solution temperature in the profile of each container was recorded at the start and end of each evaporation rate determination. Those readings were made using copper-constantan thermocouple attached to a 24-point Leeds and Northrup temperature recorder.

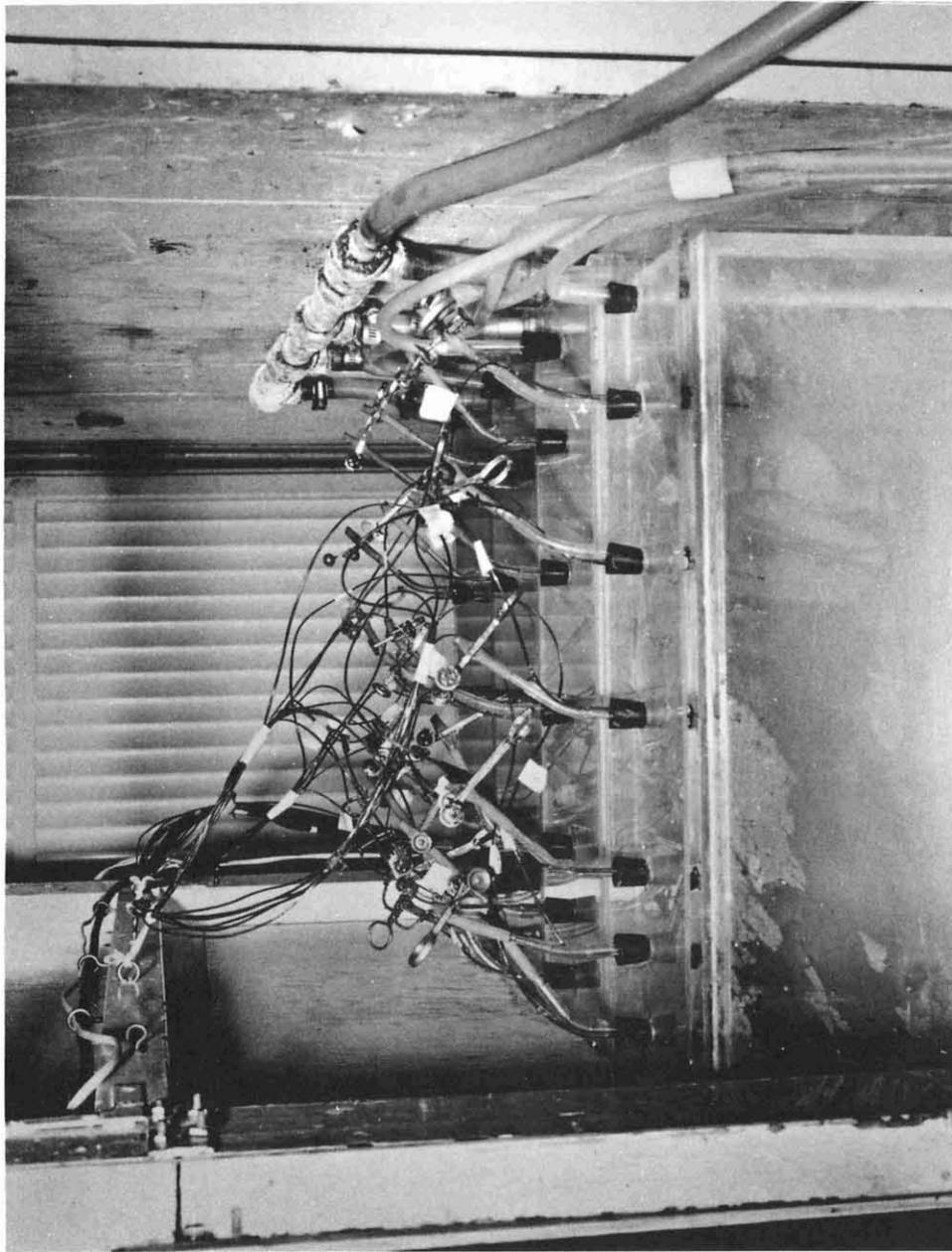


Figure 3. The four containers with sampling tubes and thermocouples inserted.

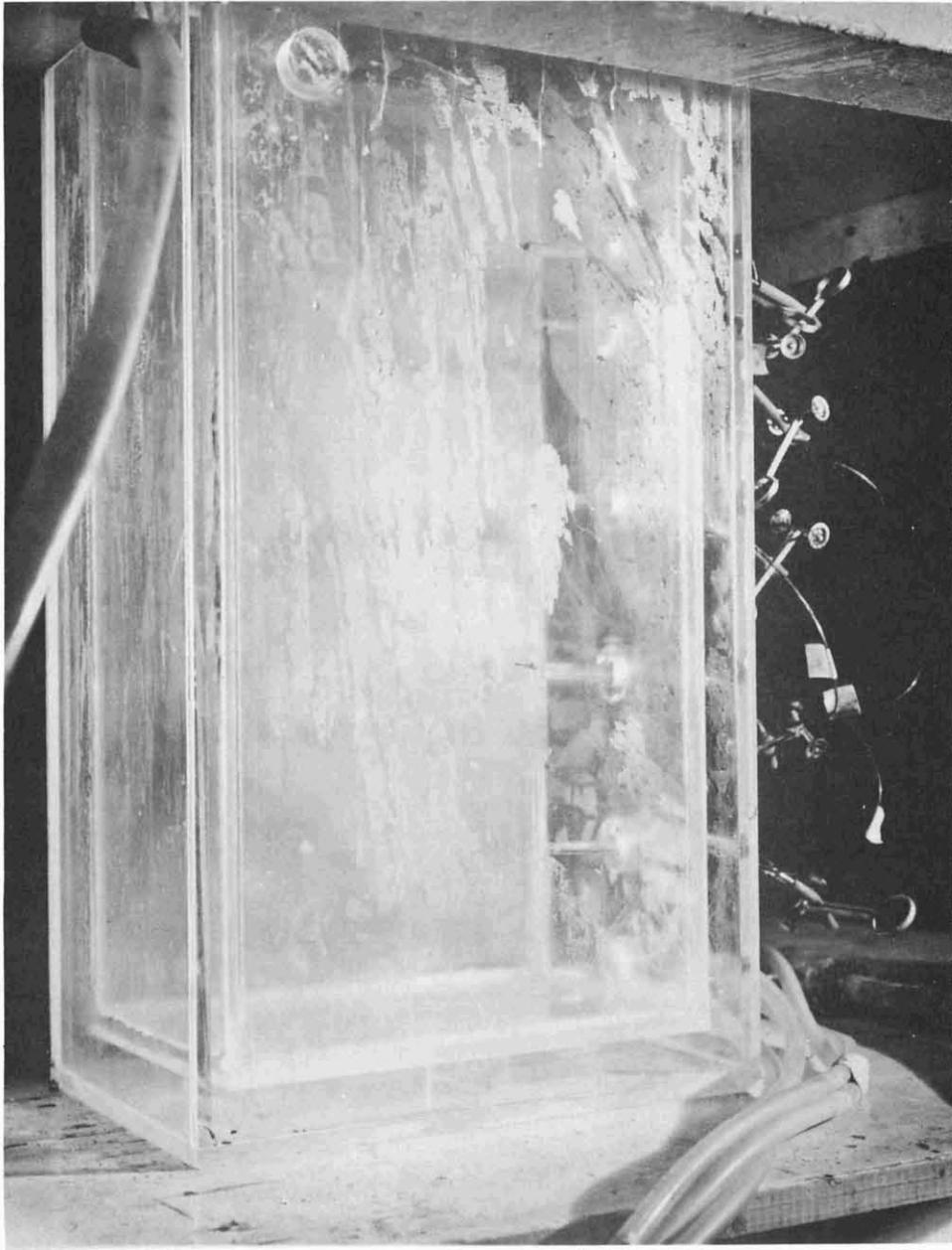
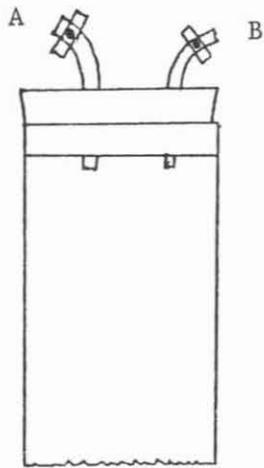


Figure 4. Close-up view of one container showing double walls and position of sampling depths.

Determinations of salt concentration were made periodically to obtain information regarding "layering" which can occur in salty waters that are static. Samples of five-milliliter volume were drawn from access tubes seen in Figures 3 and 4, at the previously indicated depths, and then conductance and temperature of the samples were determined and values reported as electrical conductivity at 25°C. Conductivity readings were made with an Industrial Instruments conductivity bridge Model RC-12C-1 with a 100 K pipette cell attached.

4. Water metering system. Evaporation from each of the containers was determined by readings taken from 500-milliliter burettes which functioned as constant-head devices similar to a mariotte bottle. A diagram of the water metering system is presented in Figure 5. When burettes were filled, tubes A and B were opened and tubes C and D closed. During evaporation determinations, tubes A and B were closed and C and D opened. Solution levels in the containers were determined by the height of the water level in the chamber attached below the burettes. Solutions in the containers were maintained at a constant level of 0.25 inches from the tops of the containers. As water evaporated from the containers, water flowed from the chamber to replace that evaporated. When the water level in the chamber receded below the tip of the burette, air could then enter the burette and water moved down into the chamber bringing the water level up to the tip of the burette. The response of the system was checked by pipetting solution from the containers, and it was found that bubbling would occur in the burettes when from five to fifteen milliliters of solution was removed.



A - Filler tube (closed during evaporation)

B - Air vent (" " ")

C - Air vent (open during evaporation)

D - Outlet to tank (" " ")

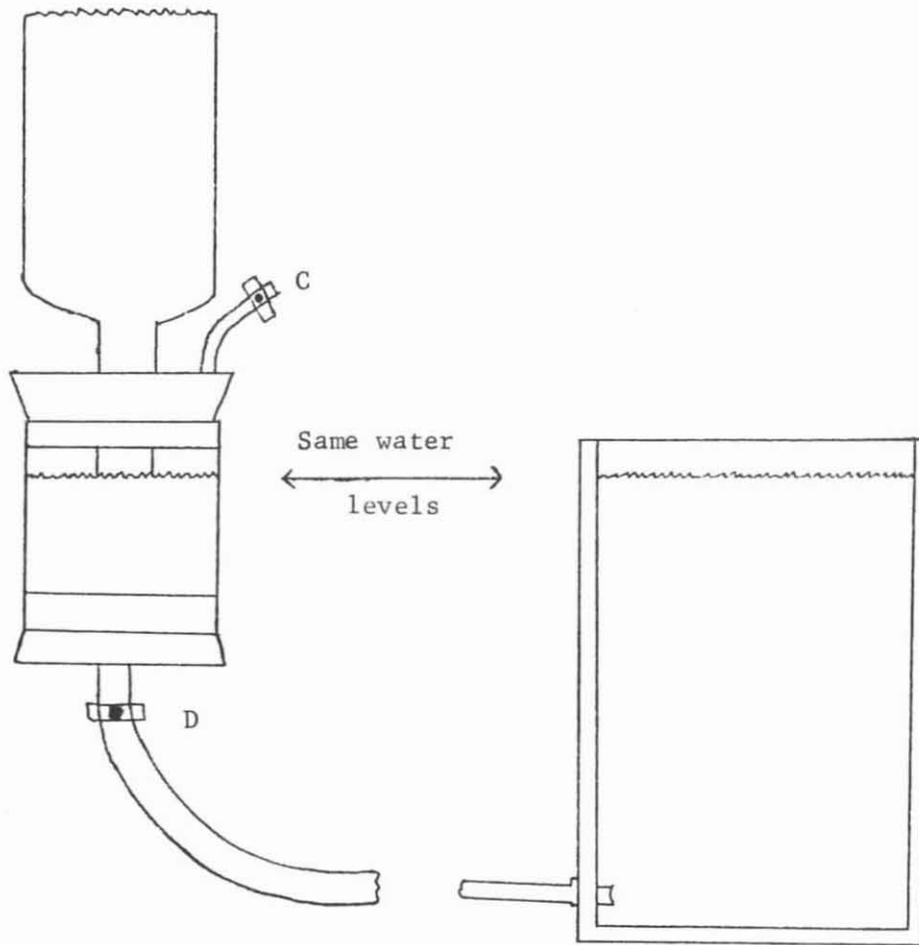


Figure 5. Diagram of water metering system.

Figure 6 shows the burettes and reservoir jugs which were used to fill the burettes. In all cases distilled water was used to replace water evaporated from the containers in order that constant levels of salinity could be maintained.

C. Sampling Period for Evaporation Rate Determinations

The following procedure was used during each evaporation rate determination: First, the selected climatic condition to be imposed on the treatment was obtained by adjusting temperature controls to the desired temperature reading and then the relative humidity setting was made. An anemometer was placed across each of the containers and the fan speed was adjusted with a rheostat until the selected wind speed was reached.

Total time required for completion of a rate determination was variable; depending primarily on the rate at which evaporation occurred. Time periods varied from about seven hours to as many as 60 hours. In all cases, except those where little or no evaporation took place, determinations were continued until water levels in the burettes were near the 500-milliliter mark.

Evaporation rates were calculated by dividing elapsed time into water lost from the burettes. In most cases the first one to two hours' data were not included to allow time for evaporation to become constant from each of the containers.

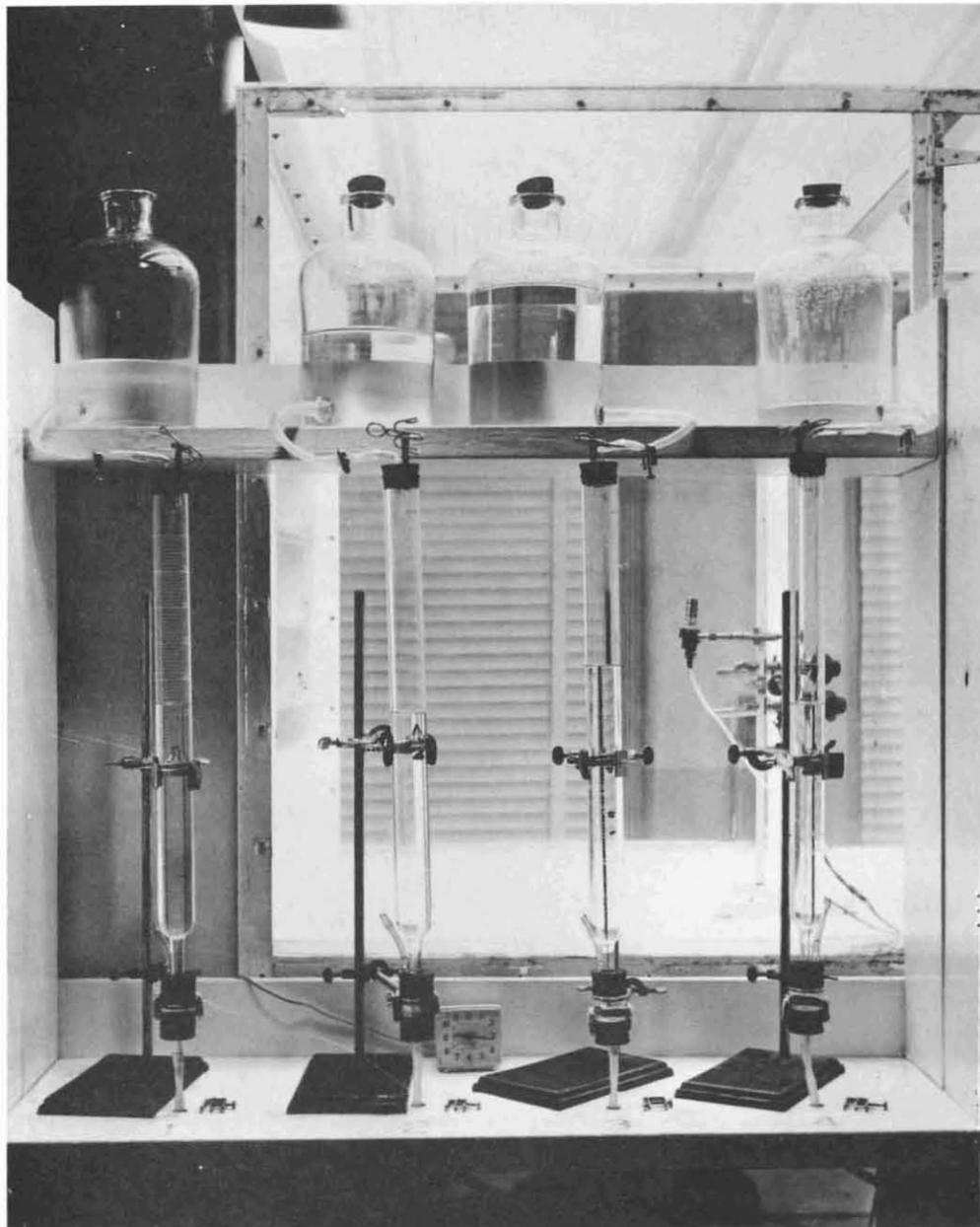


Figure 6. Reservoir jugs and burettes used to supply water to evaporation containers.

C H A P T E R I V
RESULTS OF EXPERIMENTS

A. Evaporation Investigations

All possible combinations of variables included in the study yielded 144 evaporation rate determinations. During the study it was found that the cooling capacity of the environmental control chamber was not adequate for these conditions which included the low air temperature levels (i.e. 40°F). Therefore, data were collected for only 25 determinations instead of the originally-planned 36 determinations for the low air temperature levels. Thus, it will be noted that 125 determinations are reported.

It was planned to maintain the temperature of solutions at 76°F throughout the study; however, temperature was not effectively controlled and considerable fluctuation occurred between determinations. The resulting temperature was a function of conditions imposed and the resulting evaporation rate. Temperature control within the profile was achieved and no significant differences could be noted between the depths sampled in the profiles.

Given in Table 1 are the evaporation rates determined for all combinations of variables at the 76° and 90°F air temperature levels. The first three columns in the table give the climatic conditions which were imposed on the salt concentrations. Next, the four concentrations of sodium chloride are given with evaporation rates and solution temperatures recorded at the 1.75-inch depth. For

Table 1. Evaporation from distilled water and salt solutions in relation to air temperature, air humidity, wind speed and salt concentration.

Air			H2O		50,000 PPM		150,000 PPM		300,000 PPM	
Temp. °F	Wind speed mph	R.H. %	Evap. in/day	Temp °F	Evap. in/day	Temp. °F	Evap. in/day	Temp. °F	Evap. in/day	Temp. in/day
90	2	40	0.303	80.42	0.382	80.96	0.264	85.64	0.323	90.14
		60	.319	80.6	.118	82.76	.157	88.7	.043	89.24
		80	.00	80.78	.00	84.74	.00	88.88	.020	88.16
	6	40	.496	80.06	.594	80.42	.445	82.94	.464	87.44
		60	.260	80.42	.264	82.4	.350	86.54	.205	88.34
		80	.074	76.64	.051	85.45	.047	89.06	.031	91.04
	10	40	.768	78.62	.736	80.24	.476	82.4	.551	87.08
		60	.338	80.06	.315	82.94	.437	87.08	.264	88.34
		80	.236	85.82	.087	84.56	.457	91.22	.024	92.3
	16	40	.909	78.98	1.032	80.6	.716	81.5	.713	78.98
		60	.417	78.98	.378	81.5	.650	86.72	.299	88.7
		80	.311	86.0	.217	84.2	.070	87.44	.091	82.22
76	2	40	.264	78.44	.283	78.44	.406	82.76	.488	80.42
		60	.303	78.26	.220	78.26	.394	80.42	.157	82.4
		80	.130	80.06	.157	80.06	.04	80.6	.012	82.4
	6	40	.563	78.44	.610	78.44	.772	83.48	.488	81.14
		60	.480	77.9	.338	77.9	.315	82.04	.252	83.66
		80	.260	78.08	.224	78.08	.201	84.2	.043	84.56
	10	40	.791	76.46	.842	76.46	.835	79.52	.480	78.08
		60	.492	76.28	.634	76.28	.524	81.14	.311	81.32
		80	.456	77.72	.413	77.72	.224	80.96	.098	84.02
	16	40	1.087	74.66	.953	74.48	.929	76.28	.964	82.04
		60	.854	75.02	.748	75.02	.815	81.32	.354	80.78
		80	.685	77.0	.303	77.0	.232	80.78	.193	82.94

? 00 °F

each concentration, evaporation rates and solution temperatures reported are mean values of the four containers.

The corresponding mean values of evaporation rates and solution temperatures for the low air-temperature level are given in Table 2. Results were separated into Tables 1 and 2 because of variable air temperatures and relative humidities present in the low air-temperature level.

The data presented in Tables 1 and 2 do not readily allow direct comparisons of evaporation rates as solution temperatures were not constant; however, certain trends can be noted. The influence of relative humidity is evident. Evaporation rates decreased as humidity was increased, especially at the higher air temperatures. The effect of wind speed is also apparent. Evaporation rates increased as wind speed increased. In general, decreasing air temperature resulted in an increase in the rate of evaporation.

The effect of salt concentration is not clearly evident and appears erratic. In some cases as salt concentration increased, evaporation decreased; yet in other cases the saline solutions had greater evaporation than did distilled water. One would expect evaporation to decrease as salt concentration increased, and in some cases this was the result; yet diversity is noted. When consideration is given to the solution temperature differences between salt concentrations, the reason for this diversity becomes more evident.

As was noted in the preceding discussion, some effects of the variables imposed were apparent, but definite comparisons of conditions were not practical because solution temperatures were not held

Table 2. Evaporation from distilled water and salt solutions at low air temperature in relation to air humidity, wind speed and sodium chloride concentration.

Temp. °F	Air		H ₂ O		50,000 PPM		150,000 PPM		300,000 PPM	
	Wind Speed mph	R.H. %	Evap. in/day	Temp. °F	Evap. in/day	Temp. °F	Evap. in/day	Temp. °F	Evap. in/day	Temp. °F
39.92	2	60			0.524	75.74				
38.84	6	75			.748	74.66				
41.00	6	76			.705	74.66				
41.00	6	80			.661	75.56				
41.90	10	75			.850	73.58				
39.92	16	68			.842	72.68				
41.00	16	69			1.177	72.68				
39.92	16	80			1.161	72.68				
39.92	2	68							0.315	78.44
39.92	16	60							.331	78.44
38.84	2	67							.378	78.44
35.96	6	73							.520	78.62
35.96	6	82							.480	78.62
43.88	10	71							.827	75.56
45.86	10	72							.823	75.56
39.92	16	76							1.032	73.40
39.92	2	80	0.563	74.66			0.464	77.00		
36.86	2	74	.516	75.38						
39.92	6	68	.756	73.58						
41.90	6	62	.780	73.58						
39.92	10	76	1.094	73.04						
39.92	10	80	1.00	72.14						
42.98	16	70	1.402	68.54						
43.88	16	86	1.209	69.80						
37.94	6	67					.701	75.20		
39.92	10	71					.831	73.58		
39.92	10	75					.835	73.58		
43.88	16	71					.984	78.80		

constant. In order to compare the various conditions and specific effects of the included variable, two types of models - physical and statistical - which would account for solution temperature along with other variables were selected.

B. Physical Model for Evaporation

Evaporation is a physical process and physical models have been employed to define evaporation since Dalton (7) advanced his theory. His theory and those since have related evaporation to the vapor pressure difference existing between a water's surface and the air directly above the water.

The following model was selected to express evaporation:

$$E = K_w (VP_o - VP_a) \quad [1]$$

in which

E = evaporation rate (inches per day)

K_w = constant for wind speed (miles per hour)

VP_o = vapor pressure of water (millibars)

VP_a = vapor pressure of air (millibars)

Data given in Tables 1 and 2 were used to determine the values for the terms of equation [1]. Explanation and procedures used are given in the following:

1. Evaporation rates. These are the mean values given in Tables 1 and 2.
2. Vapor pressure of the solutions. Vapor pressure is a temperature-dependent function, and mean temperatures of the solutions at the 4.45-centimeter depth were used to determine vapor pressures.

Ideally temperatures should have been measured at the solution surfaces; but due to salt crystallization which occurred on thermocouple leads, this procedure was not followed. However, for a short period during the study thermocouples were placed just beneath the surface and no temperature differences could be noted between surface and 1.75-inch depth.

The Smithsonian Meteorological Tables (13) were used to convert temperature data to vapor pressure values. A correction was necessary for those treatments which contained sodium chloride. It will be recalled from the literature that salts reduce the vapor pressure of solutions, and therefore the following corrections were used for 50,000 parts per million (ppm) NaCl - $0.971 VP_0$; for 150,000 ppm NaCl - $0.91 VP_0$; and for 300,000 ppm - $0.80 VP_0$. Data from the International Critical Tables (15) were used to determine these reductions.

3. Vapor pressure of the air. Values for this term were determined using the air temperature imposed, converting to the vapor pressure given by the Smithsonian Meteorological Tables (13), and reducing the vapor pressure by the corresponding relative humidity present during the evaporation determination.

4. Constant for wind speed. Data from Tables 1 and 2 were separated into four parts, one for each wind speed, in order that constants (K_w) could be determined. The resulting constants corresponded to the slopes of the regression lines determined for each wind speed.

After the data were converted to vapor pressures to fit equation [1], a regression analysis was made on the data for each wind speed.

The analysis was a linear regression where evaporation (E) was considered the dependent variable Y and vapor pressure difference ($VP_o - VP_a$) the independent variable X. Results of the analyses are shown in Figures 7, 8, 9 and 10.

Theoretically the regression lines should have passed through the origin instead of having a positive or negative Y intercept. A student's t test was performed and showed no significant differences between slopes calculated with the corrected and uncorrected sums of square indicating that the Y intercept is not significantly different from zero.

The physical model appears satisfactory for each of the four wind speeds as the higher wind speeds had coefficients of determination of about 96 and the 2 miles per hour (mph) wind speed in Figure 7 had a value of 93. This is evident from the greater spread of points about the regression line. The increased scattering resulted from fluctuations in wind speed as control was not as effective at the low level.

The influence of wind speed is shown by the increased slope of the regression lines from 2 mph to 16 mph of air movement. Although the slope increased with increasing wind speed, the rate of increase is greater at the lower levels giving a curvilinear effect due to wind.

Effects of the other variables are not evident from the figures; however, the components that determine the vapor pressure differences must be considered. From the relationships determined in Figures 7, 8, 9 and 10 and use of equation [1], calculations of evaporation rates using adjusted solution temperatures were possible.

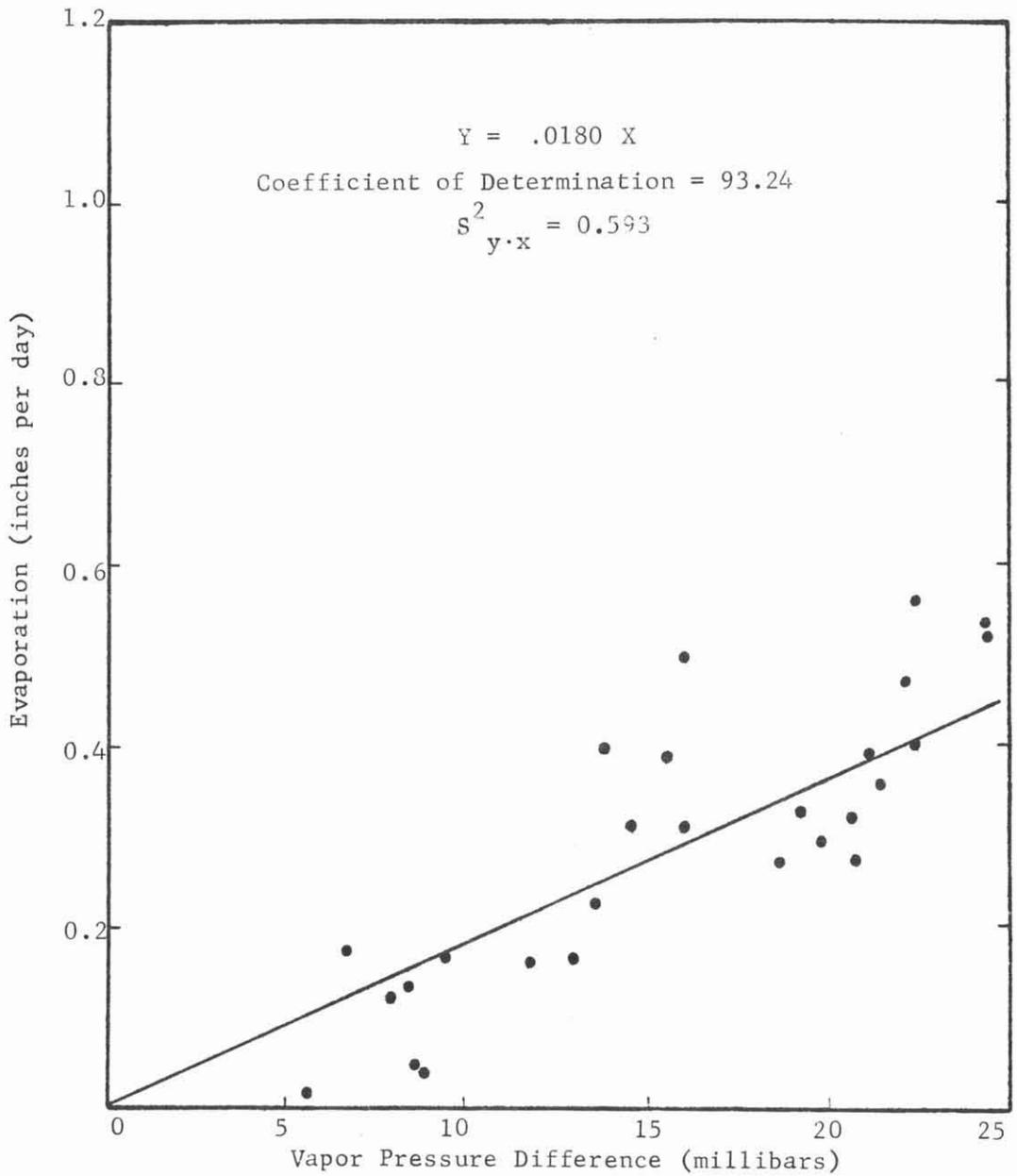


Figure 7. Evaporation in relation to vapor pressure difference between air and water surface at a wind speed of 2 miles per hour.

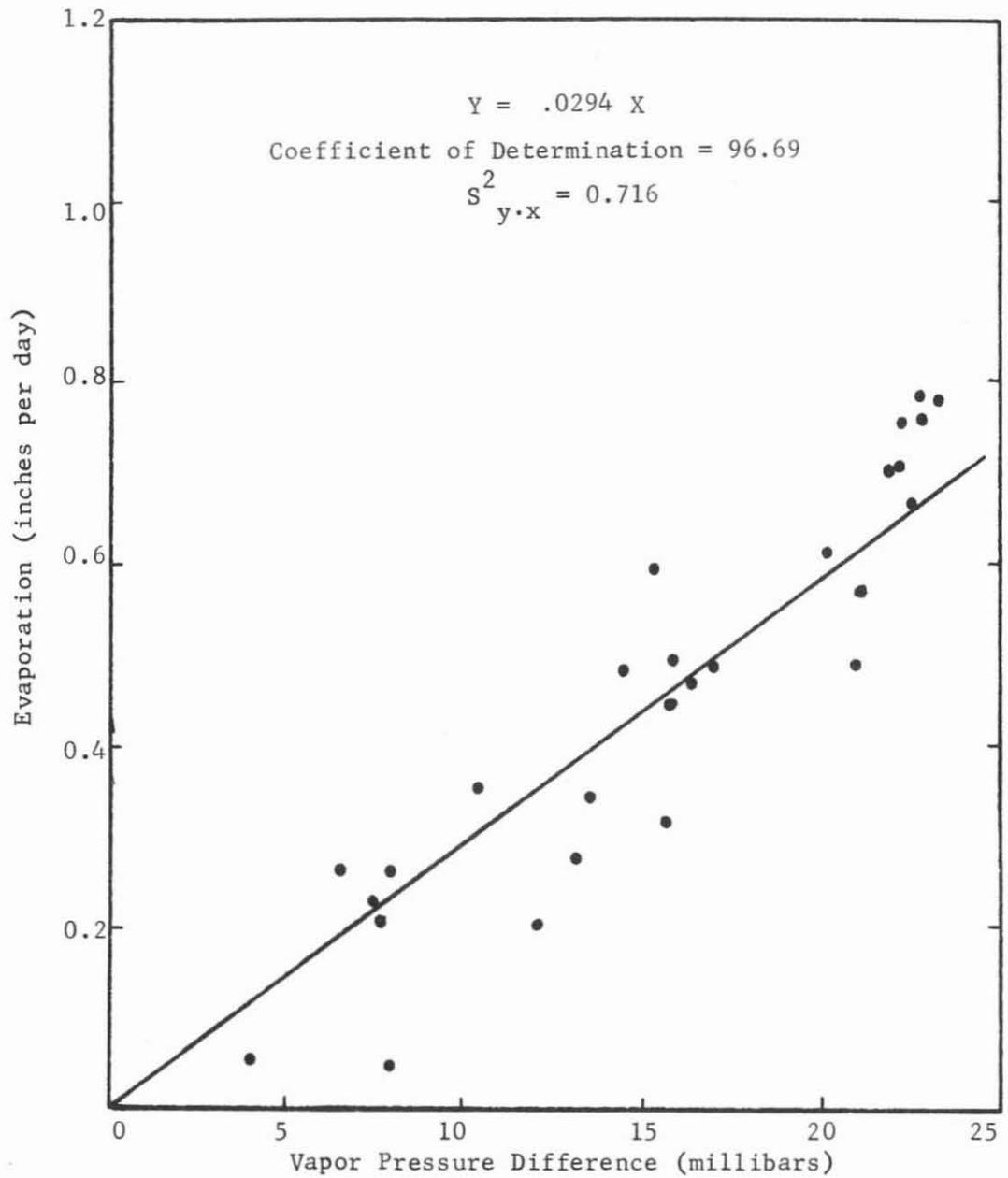


Figure 8. Evaporation in relation to vapor pressure difference between air and water surface at a wind speed of 6 miles per hour.

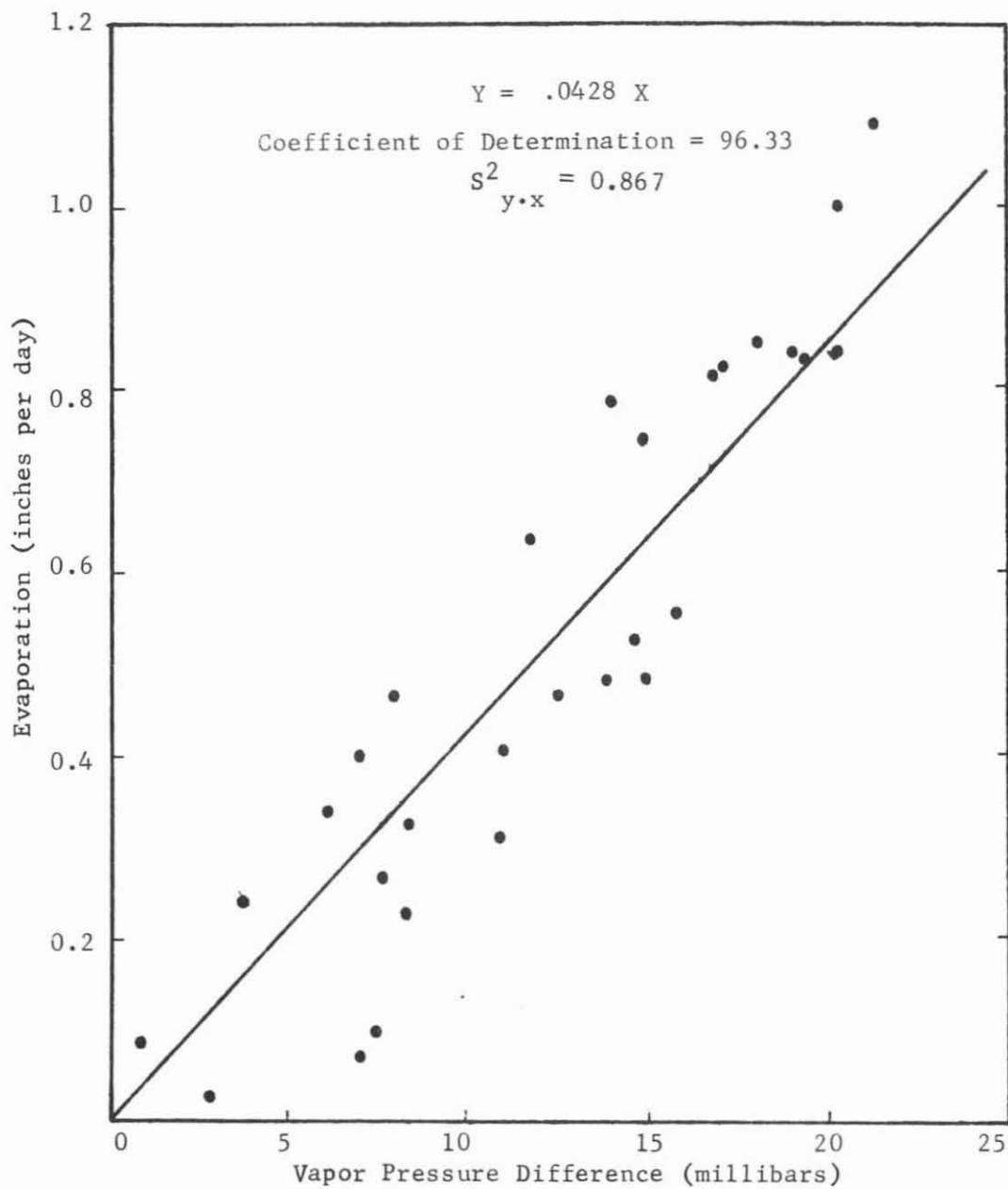


Figure 9. Evaporation in relation to vapor pressure difference between air and water surface at a wind speed of 10 miles per hour.

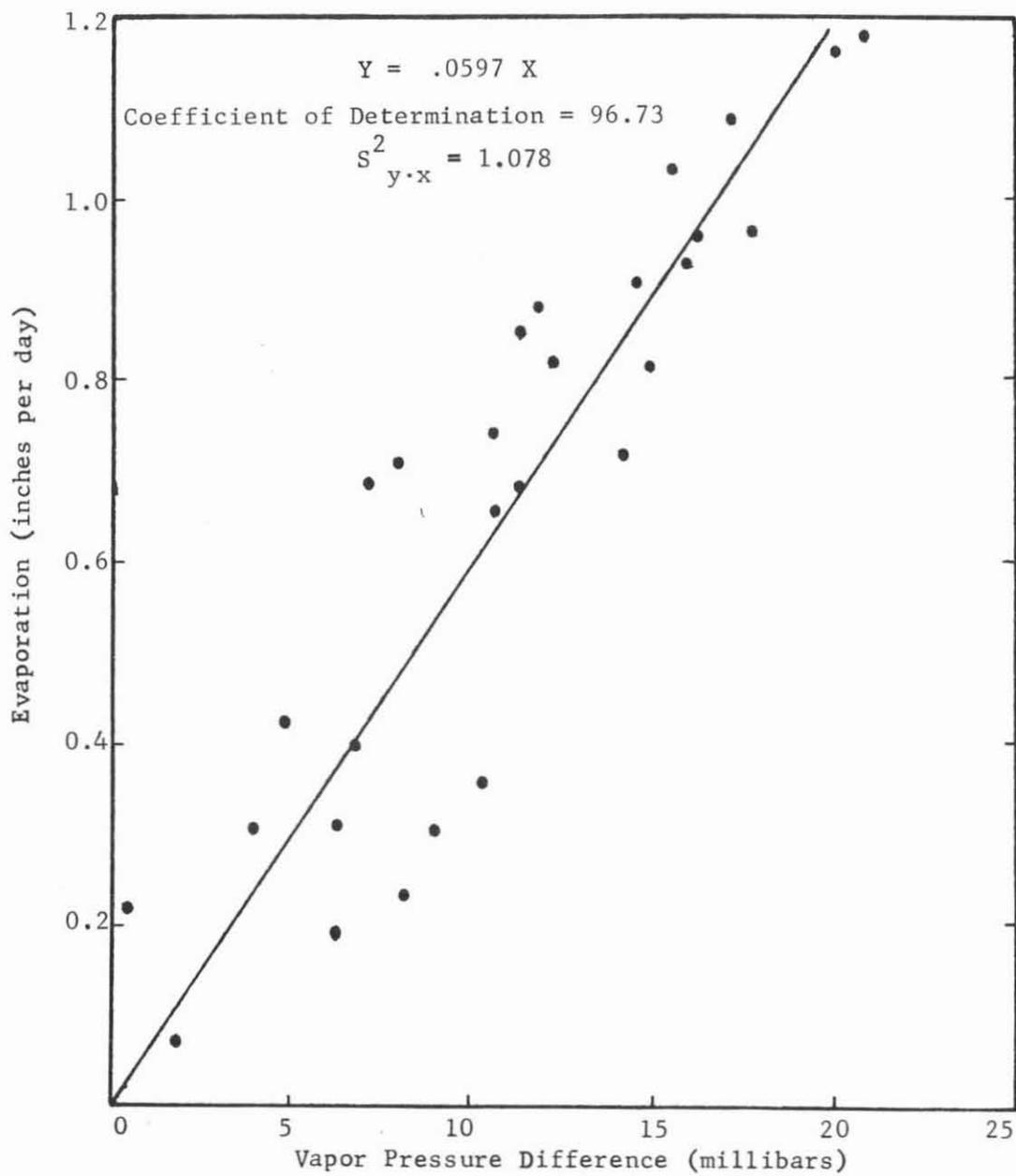


Figure 10. Evaporation in relation to vapor pressure difference between air and water surface at a wind speed of 16 miles per hour.

C. Statistical Model for Evaporation

Although evaporation is a physical process, a statistical model to define evaporation is often desirable. Due to the number of variables included in the study, a multiple regression analysis seemed the most effective approach. Programs adapted for use on an IBM 7094 computer were employed in making the analyses.

Data given in Tables 1 and 2 were used for all analyses. Several models were tried before a suitable one was found. First a quadratic regression model with linear and linear x linear product terms was fitted to the data. The resulting evaporation surface was allowed to intercept the Y-axis, i.e., not being restricted to pass through the origin. A coefficient of determination of 94 was obtained. The regression model was then altered where the evaporation surface was forced to pass through the origin. A higher value of 98 was obtained for the coefficient of multiple determination. This model appeared satisfactory; however, when the resulting equation derived from the analysis was used to calculate adjusted evaporation rates holding solution temperature constant, acceptable values were not obtained for all conditions.

Examination of the values indicated that the model was not giving the proper curvilinear response, so a square root transformation was used replacing the quadratic model. Again the deviations of the uncorrected sums of square were used, and the evaporation surface intercepted the origin. The coefficient of determination was not changed significantly, being 98.

Calculated evaporation rates using this model were satisfactory when solution temperature was held constant for all of the rates at 76 and 90°F air temperatures. On the basis of the calculated evaporation rates and the high coefficient of multiple determination the following statistical model was selected:

$$\begin{aligned}
 E = & B_1(AT) + B_2(W) + B_3(RH) + B_5(WT) + B_6(AT)^{\frac{1}{2}} + B_7(W)^{\frac{1}{2}} + B_8(RH)^{\frac{1}{2}} \\
 & + B_9(C)^{\frac{1}{2}} + B_{10}(WT)^{\frac{1}{2}} + B_{11}(AT)(W) + B_{12}(AT)(RH) + B_{13}(AT)(C) \\
 & + B_{14}(AT)(WT) + B_{15}(W)(RH) + B_{16}(W)(C) + B_{17}(W)(WT) \\
 & + B_{18}(RH)(C) + B_{19}(RH)(WT) + B_{20}(C)(WT)
 \end{aligned} \tag{2}$$

in which:

E^* = evaporation rate (centimeters per day)

AT = air temperature (° Fahrenheit)

W = wind speed (miles per hour)

RH = relative humidity (percent)

C = concentration of NaCl units of 50,000 per unit

WT = solution temperature (° Centigrade)

B_i = multiple regression coefficients (i = 1 to 20)

Given in Table 3 are the multiple regression coefficients corresponding to the variables given in equation [2]. A complete summary of the multiple regression analysis is given in the Appendix.

Examination of the variables and their coefficients given for equation [2] in Table 3 showed the overall effects of the variables on evaporation. All terms for air temperature give a gross negative

* To obtain evaporation rate in inches per day, divide E by 2.54.

Table 3. Multiple regression coefficients for the statistical model.

Variable	Variable Number	Coefficient Value
AT	B ₁	-0.22755707
W	B ₂	0.24255180
RH	B ₃	0.087365801
C	B ₄	0.21286694
WT	B ₅	-0.34244233
(AT) ^{1/2}	B ₆	1.8153194
W ^{1/2}	B ₇	0.20633426
(RH) ^{1/2}	B ₈	-0.68118977
C ^{1/2}	B ₉	-0.078121885
(WT) ^{1/2}	B ₁₀	0.95232571
AT x W	B ₁₁	-0.0014897699
AT x RH	B ₁₂	-0.00033214763
AT x C	B ₁₃	-0.0001964624
AT x WT	B ₁₄	0.0045861293
RH x W	B ₁₅	-0.0018604553
W x C	B ₁₆	-0.0068475297
W x WT	B ₁₇	0.0017291619
RH x C	B ₁₈	0.00013828061
RH x WT	B ₁₉	-0.0011228342
C x WT	B ₂₀	-0.0075581367

influence on evaporation if the air temperature x solution temperature cross product is not considered. Although wind speed has some negative cross product terms, it yields a positive effect. An overall negative effect results from relative humidity as is also the case with salt concentration. Solution temperature gives a positive effect on evaporation.

Recalling Dalton's formula for evaporation and the physical model given in equation [1], it will be noted that the gross effects for the variables are similar for both the physical and statistical models. Using equation [2] it is possible to select conditions within the limits of variables studied and obtain calculated evaporation rates.

D. Relation Between the Statistical and Physical Models

The two previously proposed models appeared satisfactory from individual analyses. To further test the two methods a correlation analysis was made of evaporation rates found by each method. Conditions used for comparison of evaporation rates were those given in Tables 1 and 2. Results of the correlation analysis are shown in Table 4 and indicate a close agreement between the evaporation rates calculated using the two models.

Calculation of evaporation rates occurring from solutions having a constant temperature appeared possible with the use of either of the proposed models. The physical model is much simpler in final form and calculation of evaporation rates is easier. However, it requires precise measurement of the variables which are included in the equation.

Table 4. A correlation analysis showing the relation between evaporation rates calculated by the statistical and physical models.

Treatment	Observations	r^2	r
Statistical	125	0.946	0.972
Physical	125		

Also it is difficult to demonstrate the effects of the variables when using the physical model.

The statistical model is much more involved and requires a computer for determining evaporation rates. The effects of the variables are much more easily demonstrated using the statistical model. Whereas, only the effects of vapor pressure difference and wind speed are evident when the physical model is used. Therefore, the statistical model was selected for calculations of evaporation rates. The physical model was used to support the original data, the statistical model, and to aid in explanation of the processes of evaporation.

E. Effects of the Variables Employed

It will be recalled that original data collected during the study and presented in Tables 1 and 2 could not readily be interpreted because of variations in solution temperatures. To overcome this difficulty solution temperatures were adjusted to a constant value so that the effects of other variables could be examined. Equation

[2] was used to accomplish this purpose.

The variables, originally selected and used for determination of evaporation rates, were used in various combinations to demonstrate these effects. The adjusted solution temperature was 76°F in all cases. Graphical results, showing the effects of the variables, were presented in Figures 11-17. Only one figure was presented depicting evaporation at the 40°F air temperature. This resulted because of limitations in the use of equation [2]. Recalling those conditions at the lower air temperatures, it will be noted that no data were collected at the 40 percent and very little at 60 percent relative humidities; thus, calculation of evaporation rates for these conditions exceeded the limits of the data.

The calculated evaporation rates presented in graphical form were interesting and informative for showing relationships among the factors affecting evaporation. Consideration of equation [1], the physical model was used in the discussion of the results.

1. Air temperature. Perhaps the most indirect influence of the variables is the effect exhibited by air temperature (best seen in Figures 11, 14 and 17). Evaporation rates decreased as air temperature increased when other variables were held constant. At first this appears contrary to the normal concept of evaporation, but evaporation is a physical process and is related to the vapor pressure difference between the water surface and the air above. In Figures 11-17 the solution and water temperatures were considered constant, giving a constant vapor pressure within each concentration for all graphs. Air temperature increased from 40°F to 90°F in Figure 11 to Figure 17,

giving a considerable increase in the vapor pressure of the air. At the high air temperatures a very small vapor pressure difference was found to exist. Theoretically, no evaporation should be possible with the combination of conditions given in Figure 17, because a negative value is obtained when vapor pressure difference is calculated. A small amount of evaporation is shown for some conditions and probably resulted from errors in temperature measurements and control settings.

2. Relative humidity. The effect of this factor on evaporation is more easily understood than is the effect of air temperature but should be considered with a specific air temperature. A comparison of Figures 12, 13 and 14 shows the effects of relative humidity as do Figures 15, 16 and 17. For each of the air temperature levels, increasing relative humidities caused decreases in the evaporation rates. Referring to equation [1], an increase in the vapor pressure of the air results as moisture in the air increases. A smaller vapor pressure difference is then present at the higher humidities, causing the reduction in evaporation. Evaluation of relative humidity alone without consideration of air temperature is not practical as is demonstrated in Figures 11 (40°F, 80 percent relative humidity) and 15 (90°F, 40 percent relative humidity). Greater evaporation occurs at the low temperature and high relative humidity, which is expected if vapor pressure difference is again considered. The vapor pressure of the air is determined by first obtaining the vapor pressure at the temperature of air, and then reducing it to the corresponding relative humidity. This is also true in relating climatic conditions to

evaporation where temperature measurements without a corresponding relative humidity do not give the needed information. Figures 15 and 17 emphasize this fact, as considerable evaporation is shown with 90°F air temperature and 40 percent relative humidity while very little evaporation occurred at the same air temperature with a relative humidity of 80 percent.

3. Wind speed. General statements can be made concerning the effect of wind on evaporation, but simultaneous knowledge of the other parameters is important. Examination of the figures shows that, generally, higher wind speeds result in greater evaporation. The increase in evaporation from wind is a result of movement of air above the water surface preventing the build-up of a diffusion barrier. One point regarding wind, which is well illustrated in Figure 17, is that no matter what speed the air is moving, if a difference in vapor pressure is not present, evaporation will not occur. The importance of the vapor pressure is also borne out by comparisons of Figures 11, 12, 13 and 15 with Figures 14 and 16. Vapor pressure is greater in the first sequence, and the evaporation surfaces approach a straight line relationship. In Figures 14 and 16 where vapor pressure differences become more limited, the evaporation surface has more curve, implying that wind is not as effective in the latter case.

4. Salt concentration. Figures 11-17 show that in all cases salt reduced evaporation. The effects of salts have been previously discussed in the literature review where it was noted that salts reduced the vapor pressure of solutions, and thus reduced evaporation.

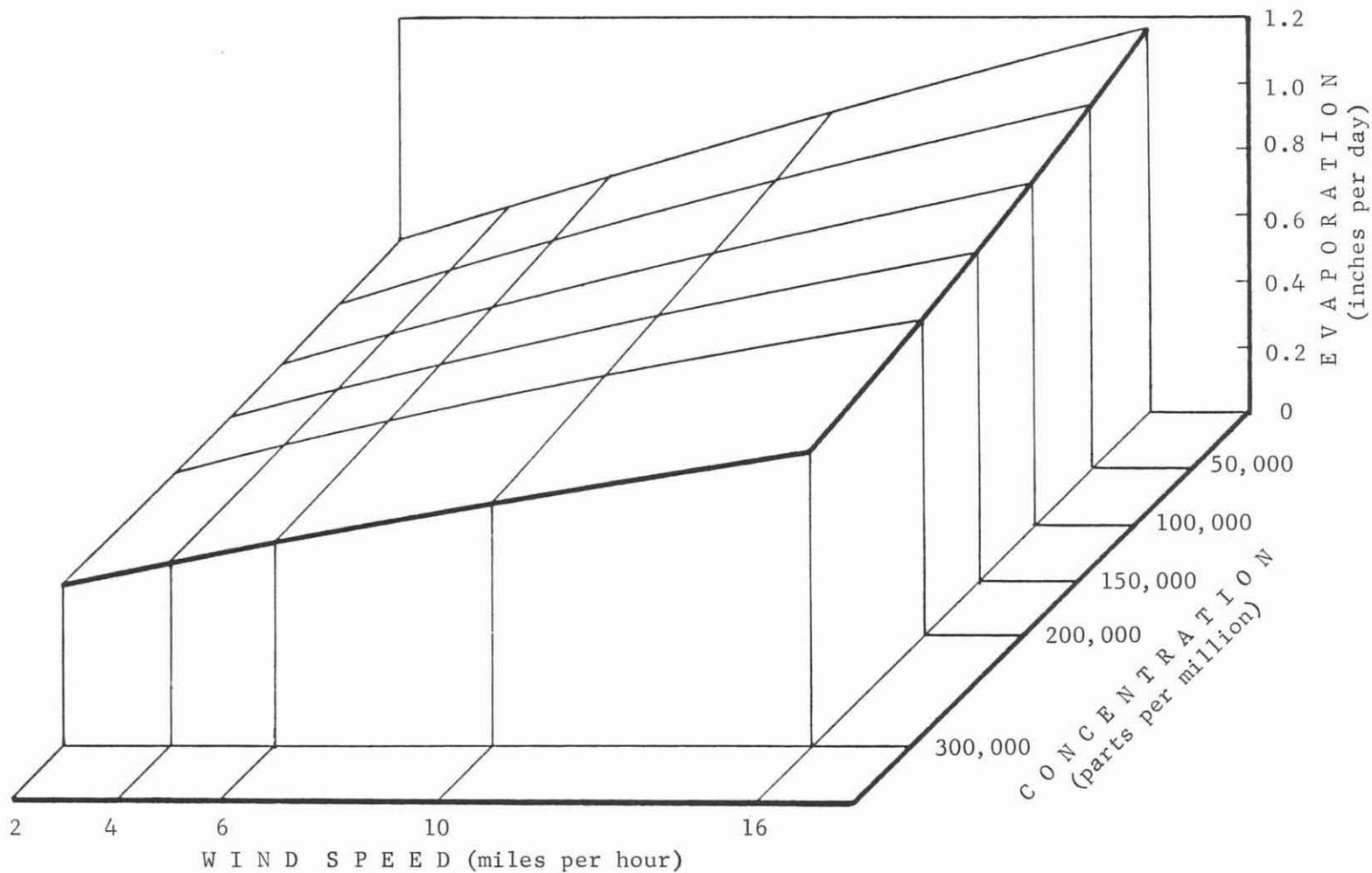


Figure 11. Evaporation in relation to wind speed and salt concentration at an air temperature of 40°F and 80 percent relative humidity.

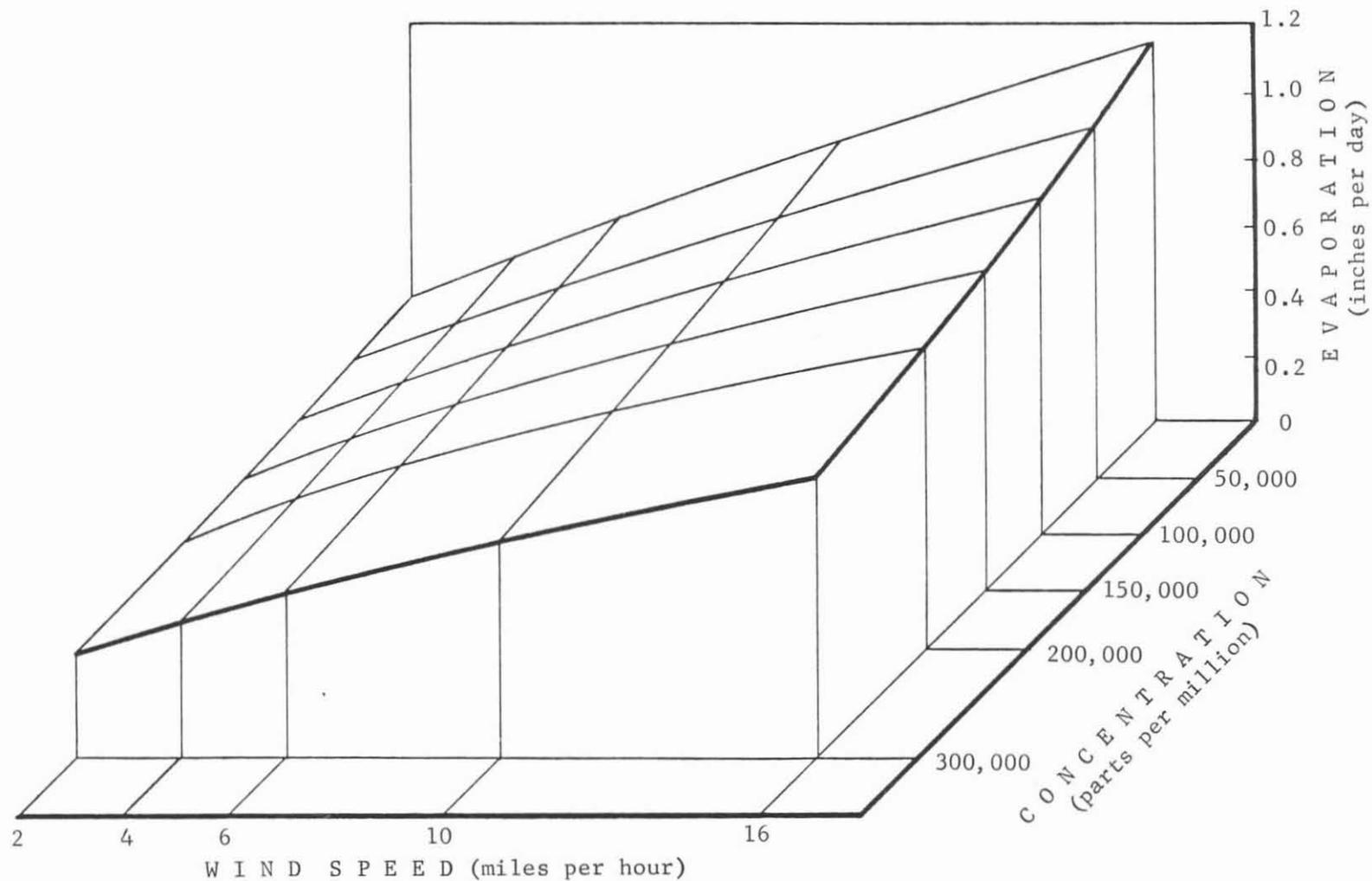


Figure 12. Evaporation in relation to wind speed and salt concentration at an air temperature of 76°F and 40 percent relative humidity.

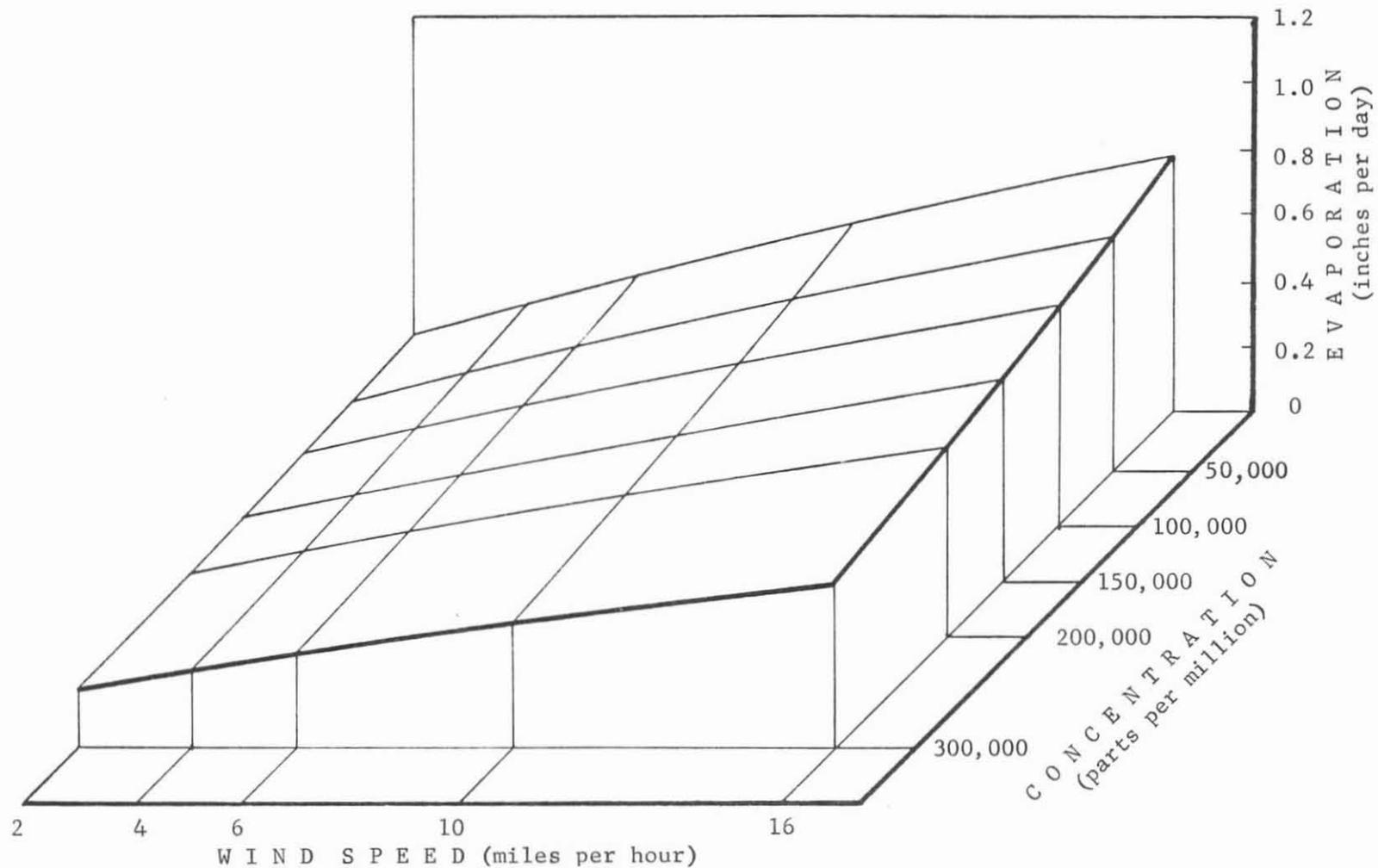


Figure 13. Evaporation in relation to wind speed and salt concentration at an air temperature of 76°F and 60 percent relative humidity.

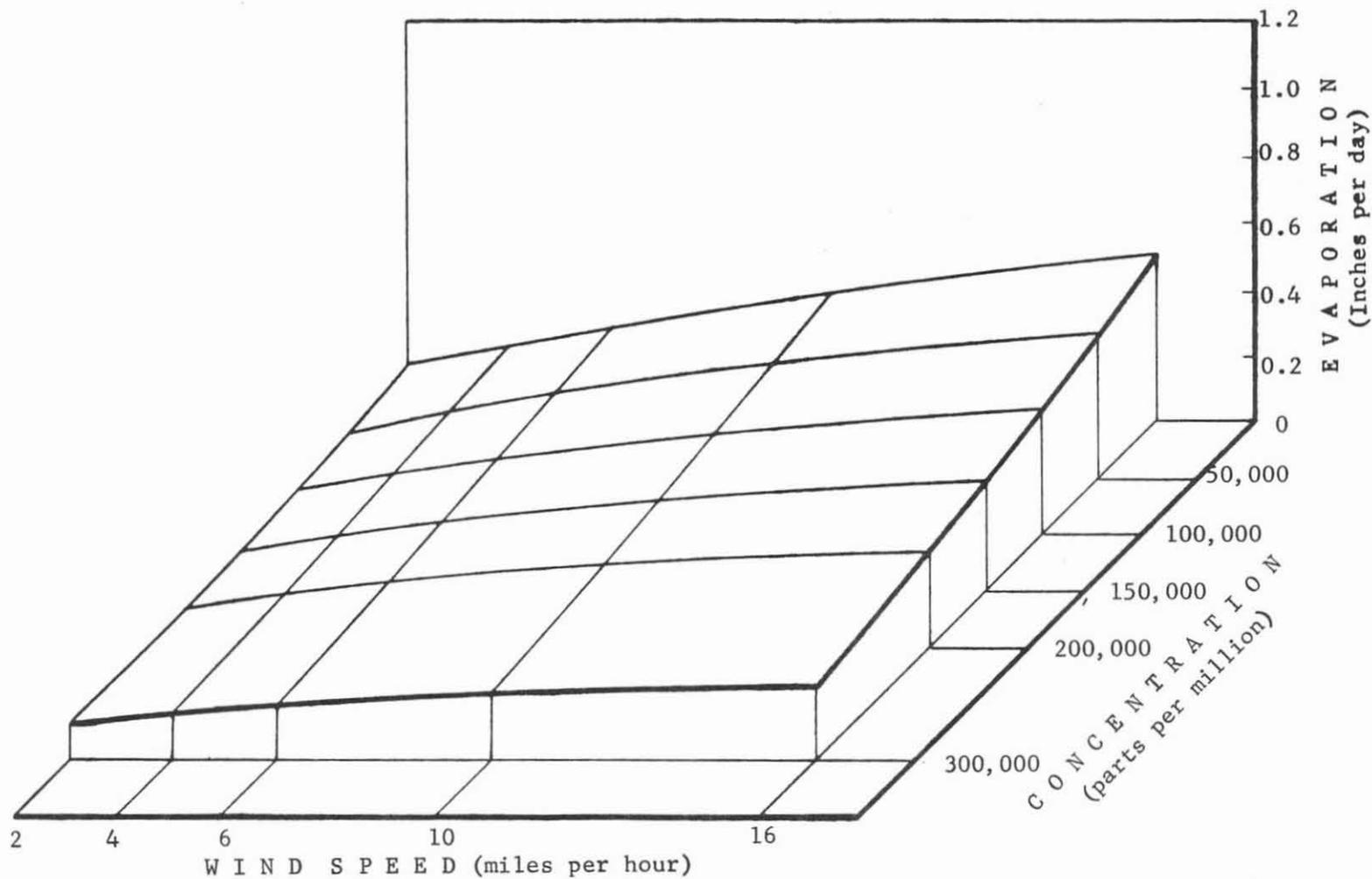


Figure 14. Evaporation in relation to wind speed and salt concentration at an air temperature of 76°F and 80 percent relative humidity.

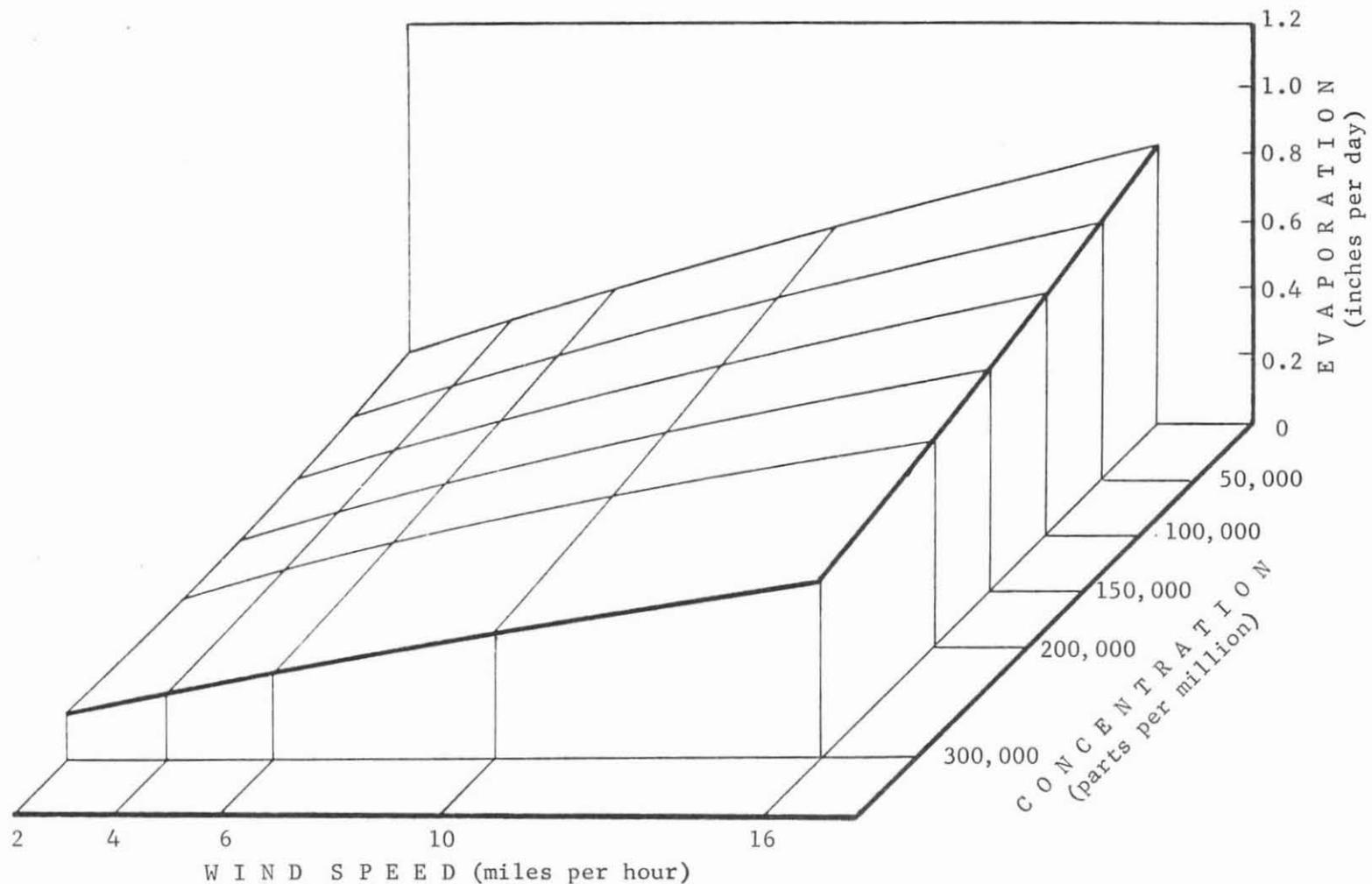


Figure 15. Evaporation in relation to wind speed and salt concentration at an air temperature of 90°F and 40 percent relative humidity.

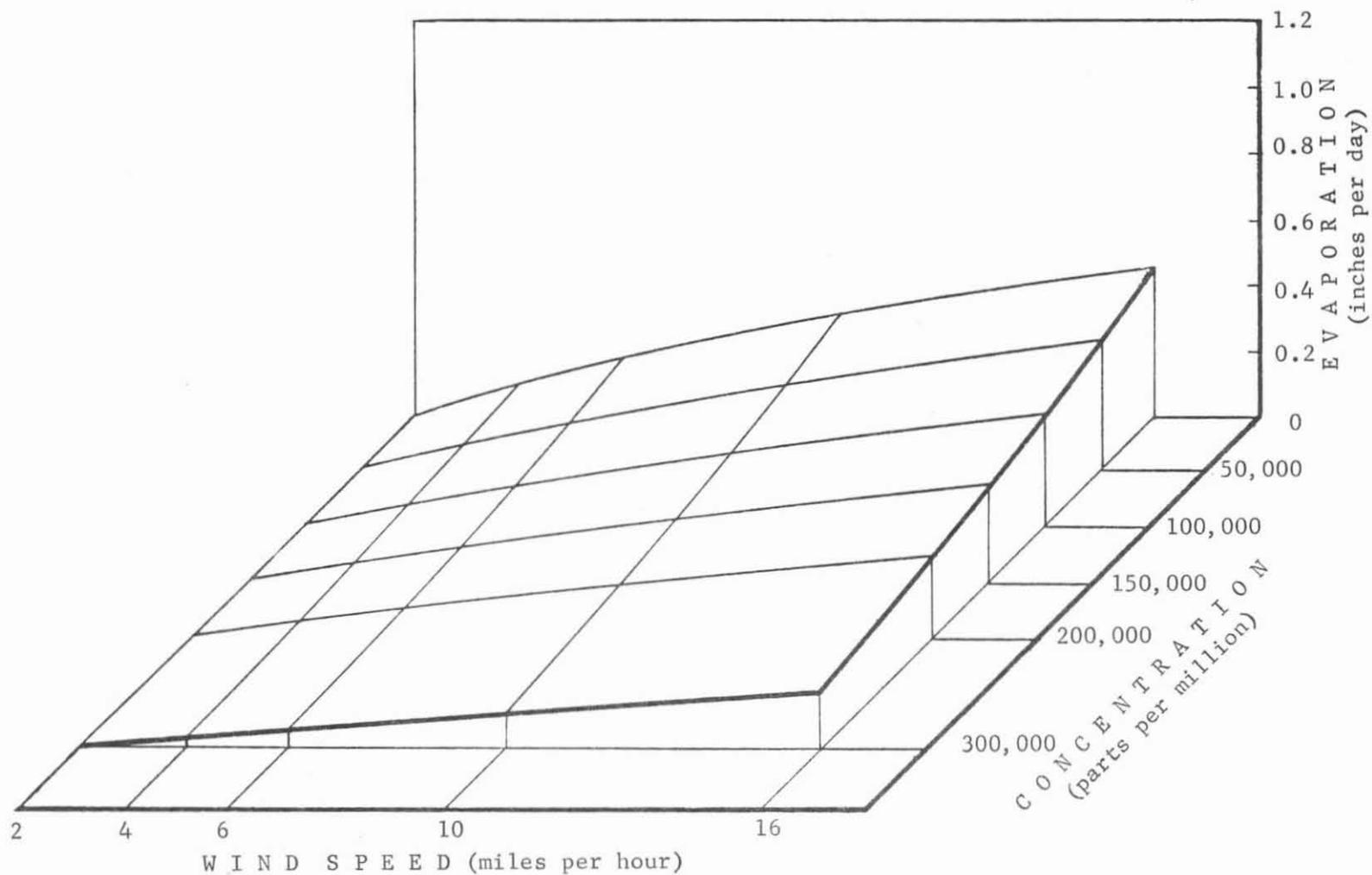


Figure 16. Evaporation in relation to wind speed and salt concentration at an air temperature of 90°F and 60 percent relative humidity.

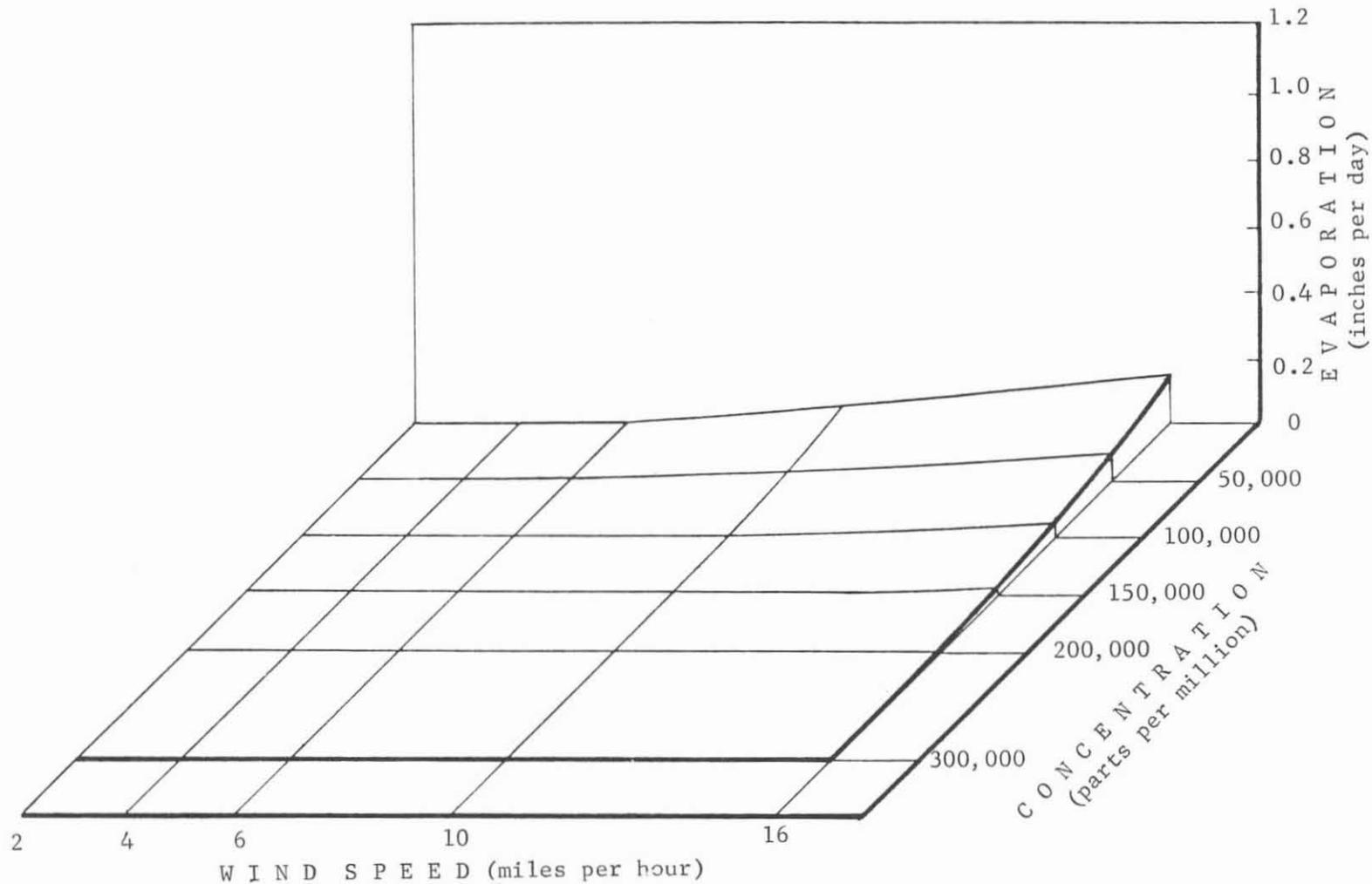


Figure 17. Evaporation in relation to wind speed and salt concentration at an air temperature of 90°F and 80 percent relative humidity.

An interesting relationship can be seen between wind speed and salt concentration in each of the figures depicting evaporation. The differences between evaporation rates of distilled water and saline solutions are more pronounced at the higher wind speeds. These greater differences are probably due to a diffusion barrier or film effect building up at the lower speeds. As wind speeds are increased the barriers are more effectively removed for those conditions having the higher vapor pressure differences, especially for distilled water. This would be similar to the effect noted in the figures where vapor pressures were limiting, such as is shown in Figures 14 and 16. Also, these differences between evaporation rates within each figure are more pronounced in those graphs where vapor pressure differences are the most limiting. This tends to support the idea of a diffusion barrier effect. The effects of salt concentration on evaporation is discussed more fully in the following section.

F. Reduction of Evaporation by Sodium Chloride Salts in Solution

In the previous discussion it was pointed out that salts had reduced evaporation for all climatic conditions as shown in Figures 11-17, however, the amount of reduction was not easily determined from these three-dimensional figures. In order that the specific reductions due to the sodium chloride salts might be shown, Figures 18-24 are given. These figures give comparisons of salt concentration and evaporation reduction ratios at five wind speeds for seven combinations of the climatic variables of temperature and relative humidity.

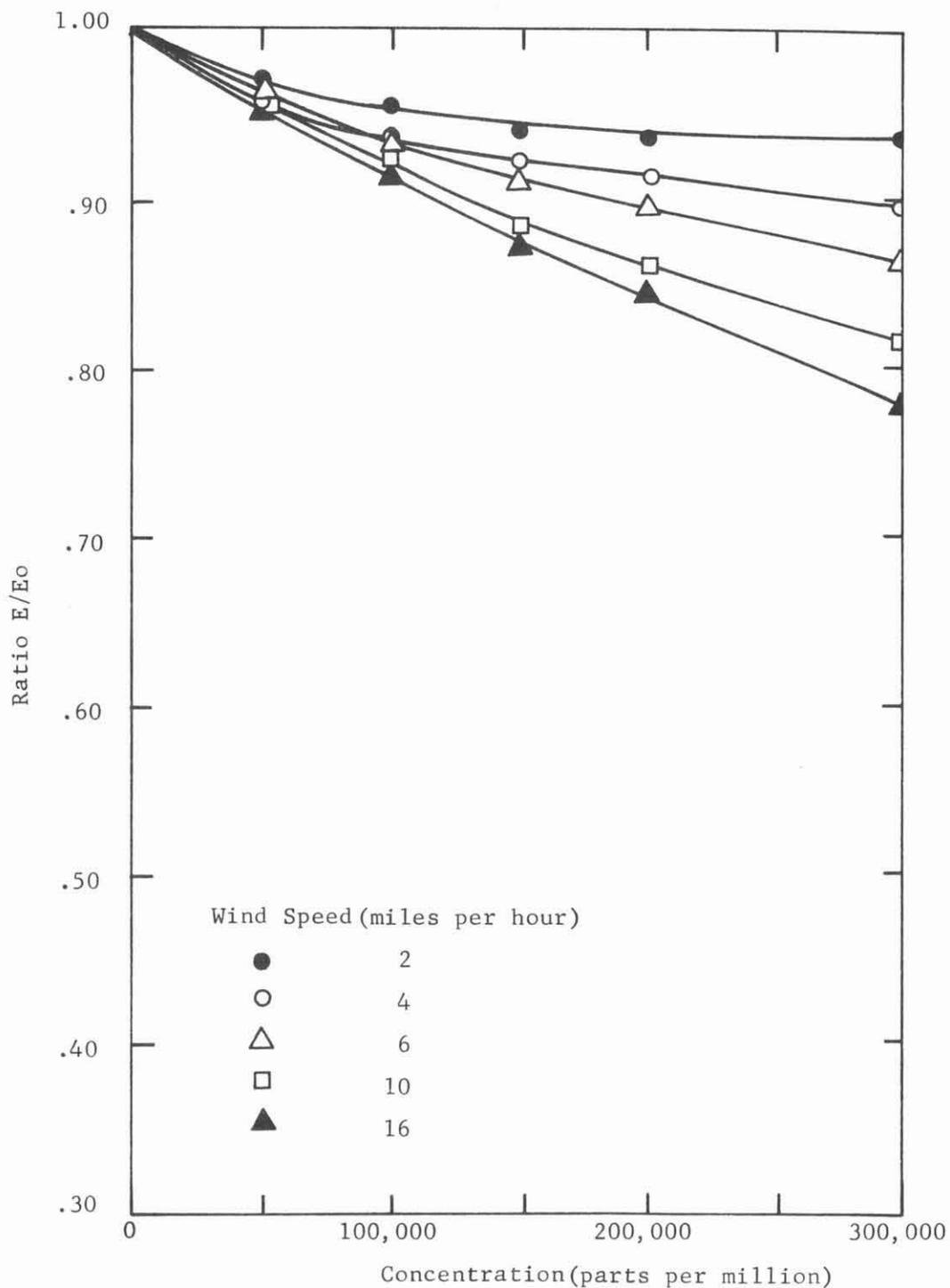


Figure 18. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 40°F and 80 percent relative humidity.

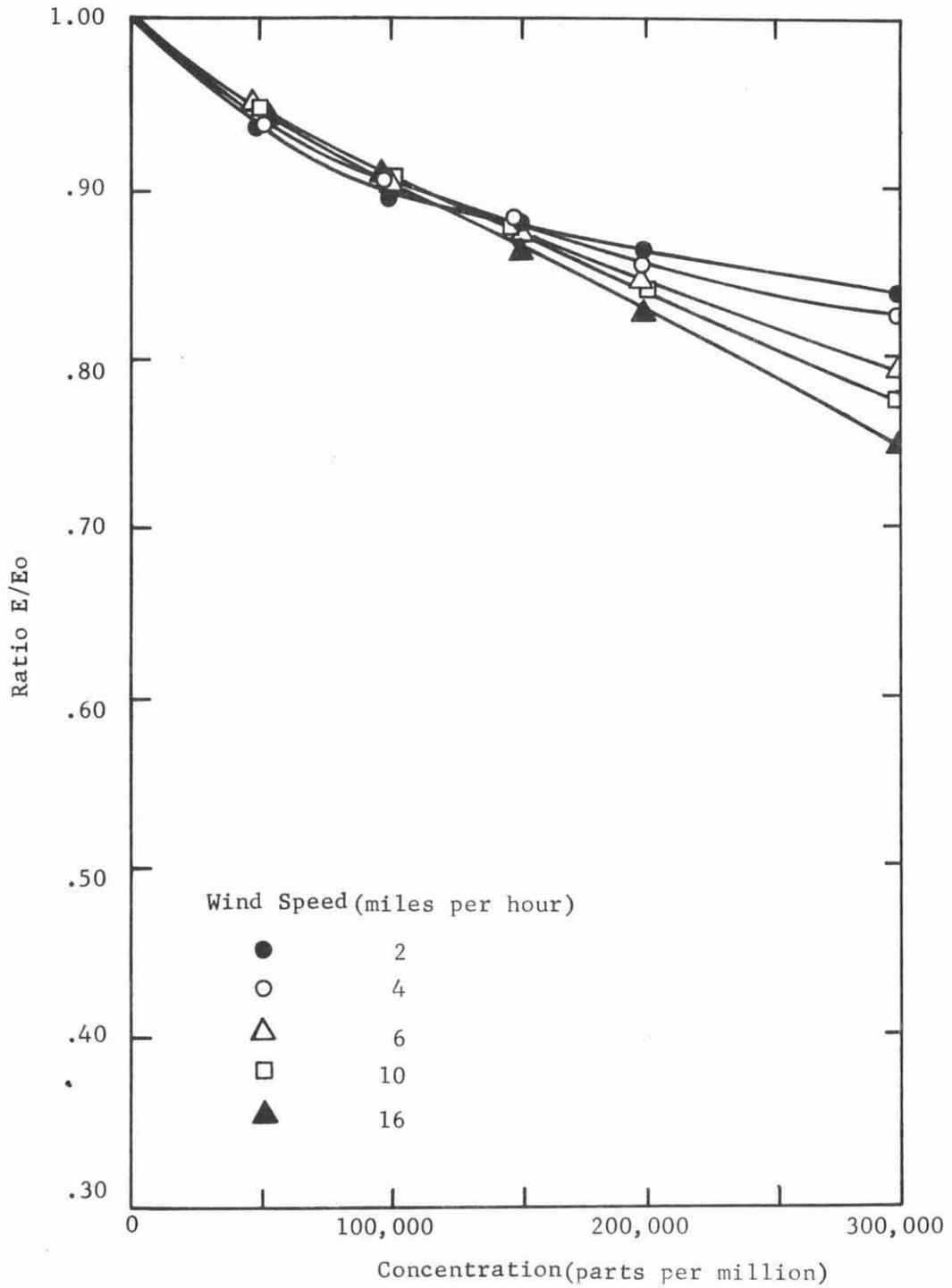


Figure 19. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 76°F and 40 percent relative humidity.

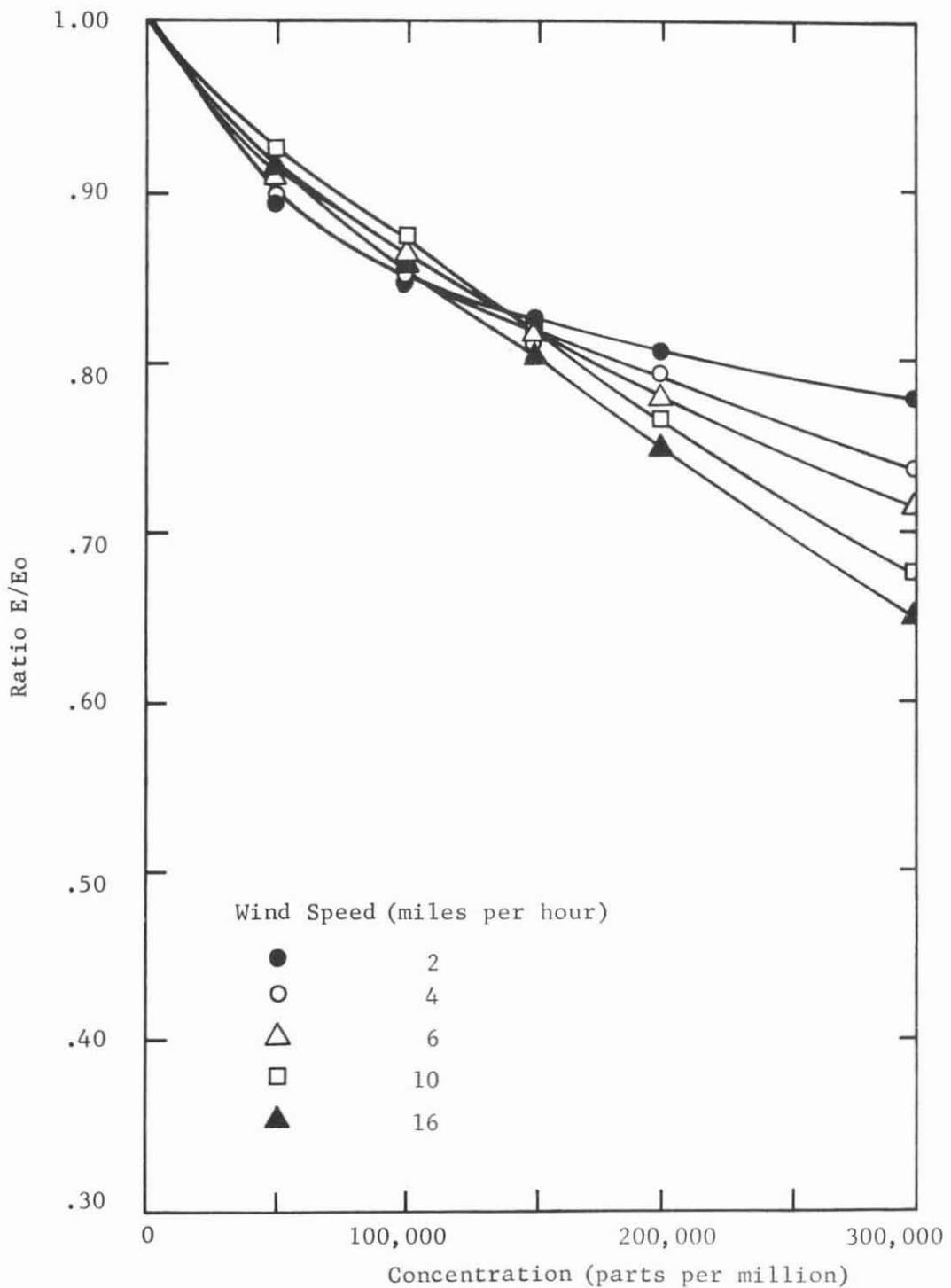


Figure 20. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 76°F and 60 percent relative humidity.

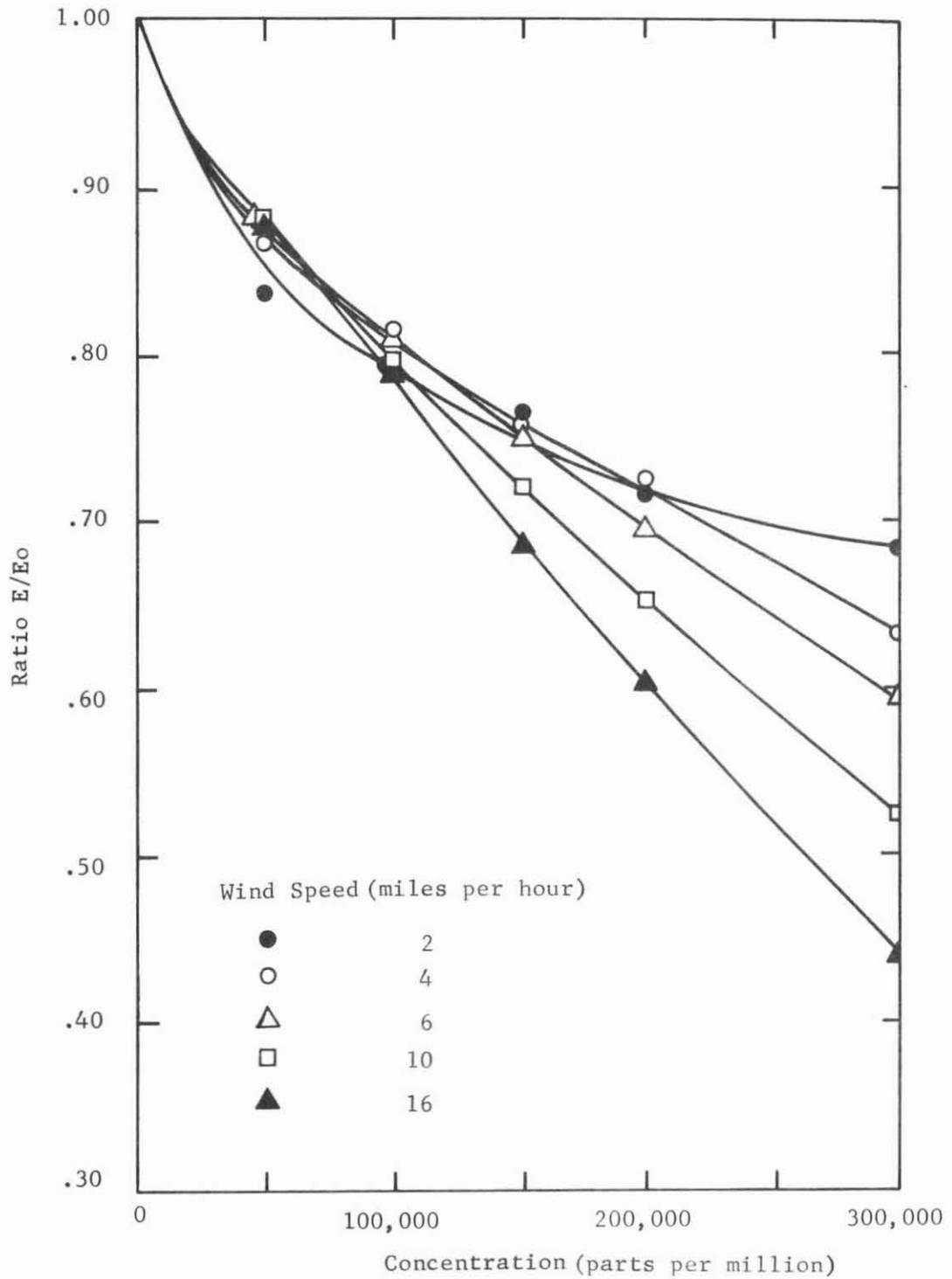


Figure 21. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 76°F and 80 percent relative humidity.

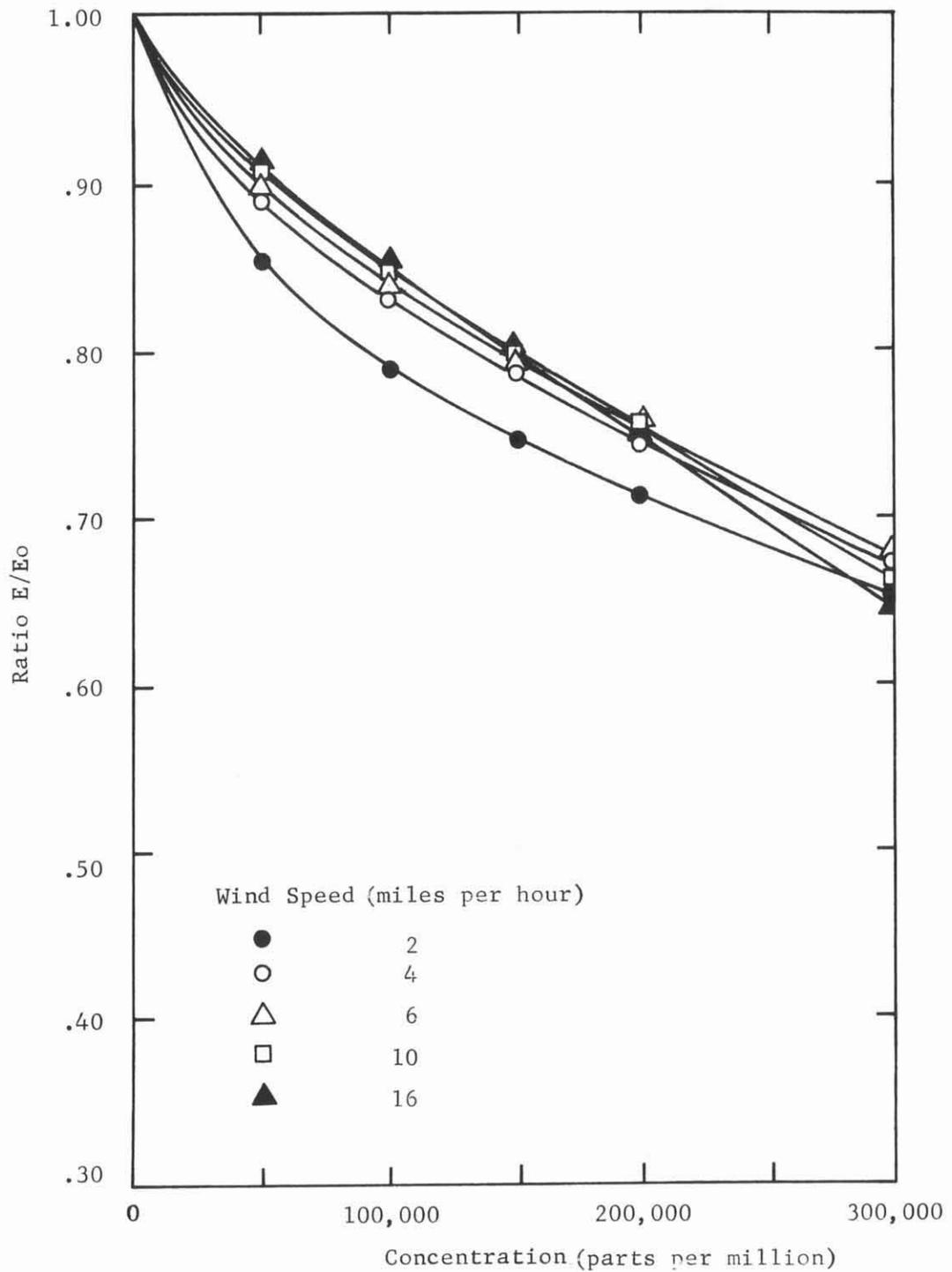


Figure 22. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 90°F and 40 percent relative humidity.

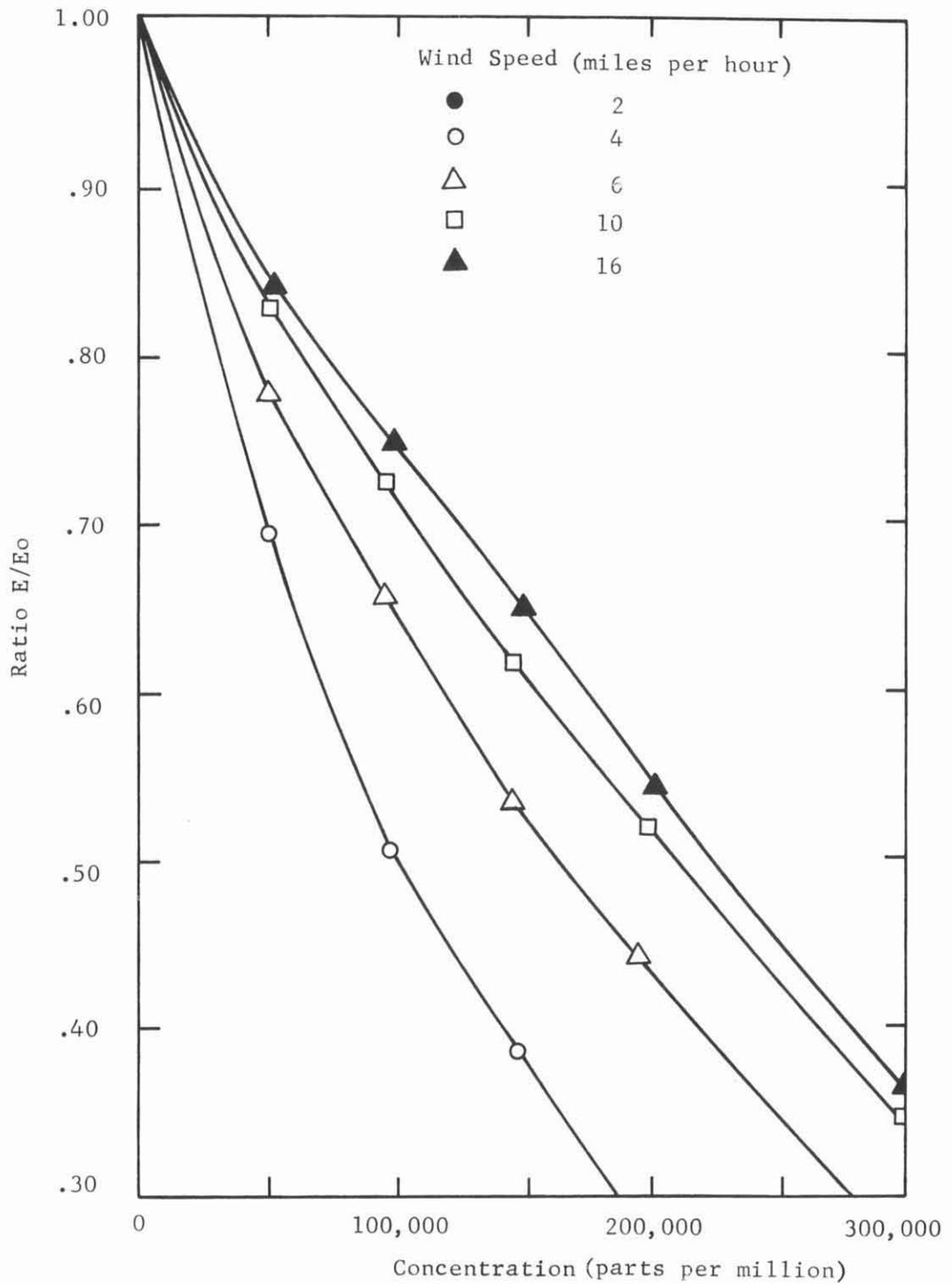


Figure 23. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 90°F and 60 percent relative humidity.

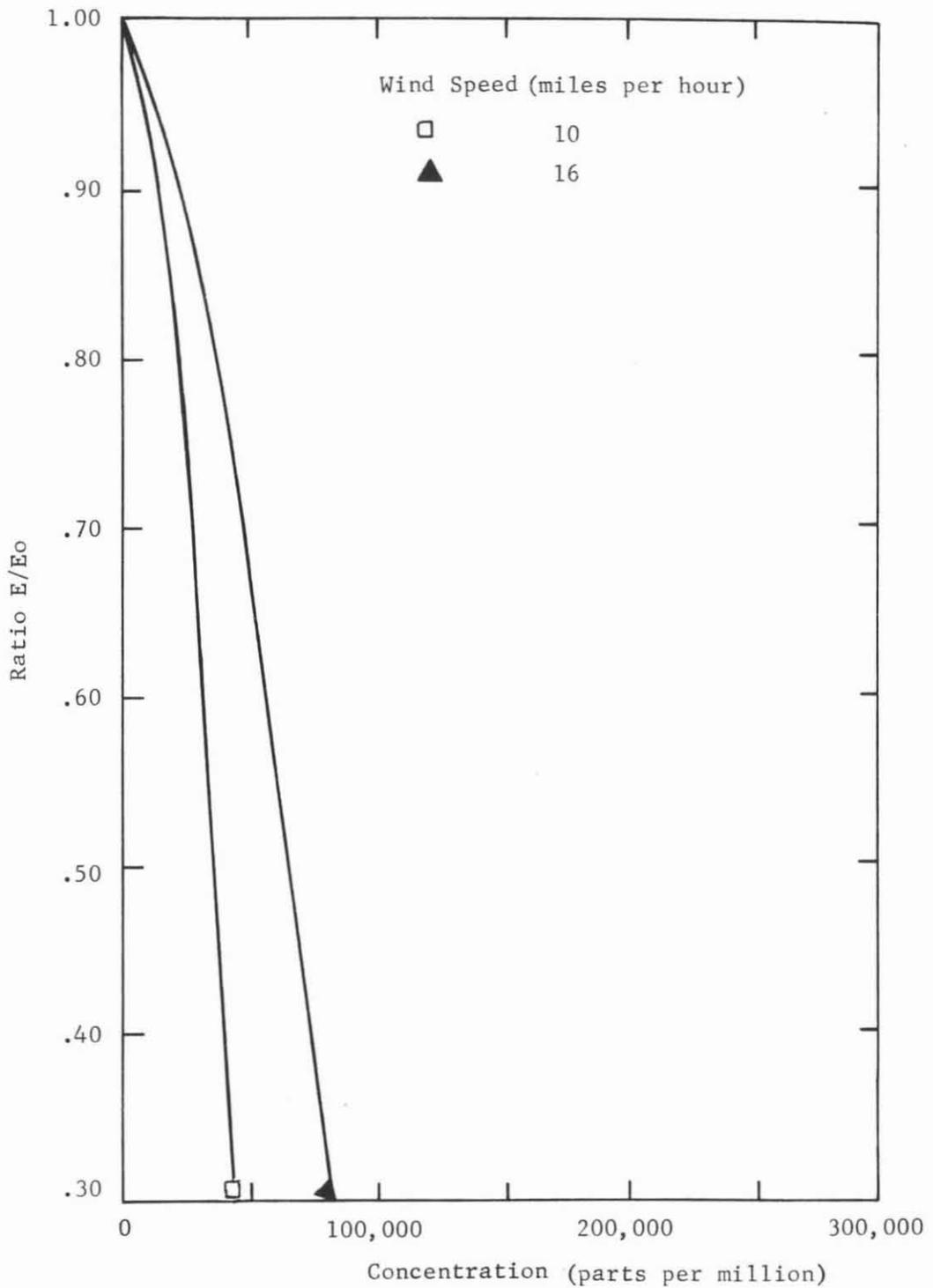


Figure 24. Relative evaporation rate (E/E_o) in relation to wind speed and salt concentration at an air temperature of 90°F and 80 percent relative humidity.

Data for these figures are the same data used in the previous section with results expressed to more effectively illustrate the influence of salinity.

Evaporation ratios are used in the literature to express the amount of reduction in evaporation due to salts in solution. They are computed as the ratio of evaporation from saline solutions (E) to that of evaporation from distilled water (E_0). Evaporation ratios are very useful but may often be misleading. For example, consider two conditions where the total amount of evaporation is quite different and yet the ratios could be the same. The evaporation ratio along with the total amount of evaporation is more meaningful.

Evaporation ratios are useful expressions because the reductions in evaporation due to salts can be shown in contrast to evaporation from fresh water. They can then provide estimations of the expected evaporation from saline water if data are available on evaporation from fresh water.

Examination of Figures 14-24 shows that evaporation ratios are not constant between the climatic conditions. In fact, under certain conditions, one set of evaporation ratios do not sufficiently show the reduction in evaporation for differing wind speeds. These differing evaporation ratios for differing conditions do not readily follow from the literature since almost all workers have reported only one set of climatic conditions was used. However, in discussions of results often comparisons were made with previous data from other workers which implied that ratios were expected to be comparable regardless of the climatic conditions existing between the experiments.

Harbeck's (8) paper emphasizes the effect of climatic conditions on evaporation ratios. He points out that as relative humidity is increased, evaporation ratios would be expected to decrease. Considering the three Figures (19-21) at 76°F and those (22-24) for 90°F, the effect of relative humidity on the evaporation ratios decreases as relative humidities increase from 40 percent to 80 percent.

Air temperatures are also seen to have a role in the determination of evaporation ratios. Beginning with Figure 18 and going through Figure 24, evaporation ratios decrease as the temperature is increased. Thus the increase in either or both temperature and relative humidity are shown to reduce the evaporation ratios.

Under certain conditions wind speed appears to be another factor that influences the amount of reduction in evaporation from saline water. A very noticeable difference between evaporation ratios for each of the wind speeds is seen in the figures having 80 percent relative humidity. At 40 percent relative humidities very little spread occurred between the ratios for different wind speeds. For the low humidities one set of evaporation ratios is sufficient regardless of the wind speed, while at the high humidities a considerable spread in the ratios for the different wind speeds was found.

The conditions which are responsible for the spread in evaporation ratios at the different wind speeds are high relative humidity, high air temperature and increased salt concentration. The differences between ratios for wind speeds are more apparent at the higher concentrations. Recalling the discussion of vapor pressure difference,

it should be remembered that each of the above conditions brings about a reduction in vapor pressure difference. Therefore, whether or not wind speed is an influential factor on the evaporation reduction appears to be a function of vapor pressure difference.

In Figures 23 and 24 the wind speed curves show a complete reversal in order of magnitude for the evaporation ratios. The reason for this reversal may be due to the fact that vapor pressure differences have become so limiting that any increase in air movement brings an increase in evaporation for all solutions. No evaporation was obtained at the lower wind speed for either set of conditions, and only the two highest gave evaporation in Figure 24 (90°F, 80 percent relative humidity).

Comparisons with data of previous studies are rather difficult. Oftentimes no mention was made regarding the specific climatic conditions used in the experiments. Many of the evaporation ratios reported were average values resulting from a variety of climatic conditions, thus, comparisons with data from this study aren't very meaningful.

Considering the findings of this study on the relations between salinity and the climatic variables, it is understandable why good agreement was not always found between the results of the previous studies. In order for close agreement to be shown between evaporation ratios, climatic conditions would need be very similar. Any change in one or more of the climatic variables which enter into the determination of vapor pressure difference will alter the resulting evaporation

ratio. This is, after all, the expected result. Any significant change in salt concentration will change the evaporation ratio. This change is brought about because of a change in the vapor pressure difference. The changes in the climatic variables must be just as important as any change in the salt concentration.

Given in Table 5 are evaporation ratios for various climatic conditions at several levels of salinity. The values given are the expected reductions in evaporation from the salinity levels when compared with distilled water under the same climatic conditions. All ratio data are the same water temperature (76°F).

This table shows the same effects as the graphs in Figures 18-24 but gives specific values. From this table interpolation between the given conditions will give some information for combinations of conditions not reported. It must be remembered that these ratios are only for conditions having a water temperature of 76°F.

For water temperatures other than the given temperatures the evaporation ratios will be different since water temperature influences the vapor pressure difference. It would only be speculation to try and give the amount of increase or decrease in the evaporation ratios because no very low or very high water temperatures were present in the study. However, if water temperature was increased, the evaporation ratios would be expected to increase for any given conditions. The reverse would also be true for a decrease in water temperature. It would also be expected that the evaporation ratios would continually decrease as water temperature decreases until the ratio was zero for a

Table 5. Evaporation ratios (E/E₀) for various climatic conditions at different levels of sodium chloride concentration.

Air Temp. °F	Salt Conc. ppm	RELATIVE HUMIDITY											
		40 percent				60 percent				80 percent			
		Wind Speed mph				Wind Speed mph				Wind Speed mph			
		2	6	10	16	2	6	10	16	2	6	10	16
40	50,000	0.95	0.96	0.96	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	100,000	.94	.94	.93	.93	.94	.90	.92	.92	.94	.93	.91	.91
	150,000	.93	.92	.90	.90	.93	.91	.90	.89	.94	.91	.89	.87
	200,000	.92	.90	.89	.88	.92	.80	.87	.86	.93	.89	.87	.84
	300,000	.91	.87	.85	.85	.92	.86	.83	.80	.93	.86	.82	.77
50	50,000	.95	.96	.96	.96	.96	.95	.95	.95	.95	.95	.94	.94
	100,000	.94	.93	.93	.93	.93	.92	.92	.91	.93	.92	.91	.89
	150,000	.93	.91	.91	.90	.92	.90	.89	.88	.93	.90	.88	.85
	200,000	.92	.90	.89	.87	.91	.88	.86	.84	.92	.88	.85	.82
	300,000	.91	.86	.84	.82	.91	.85	.81	.78	.92	.84	.79	.74
60	50,000	.95	.95	.95	.95	.94	.94	.94	.94	.93	.93	.93	.93
	100,000	.93	.93	.92	.92	.92	.91	.91	.90	.91	.90	.89	.87
	150,000	.92	.90	.90	.89	.90	.89	.87	.86	.90	.87	.85	.82
	200,000	.91	.88	.87	.86	.89	.86	.84	.82	.90	.85	.81	.77
	300,000	.89	.85	.82	.80	.88	.82	.78	.75	.89	.80	.74	.68
76	50,000	.92	.94	.94	.94	.88	.91	.91	.92	.83	.87	.87	.87
	100,000	.90	.90	.90	.90	.84	.86	.86	.86	.78	.80	.79	.78
	150,000	.87	.87	.86	.86	.82	.82	.81	.80	.75	.74	.72	.69
	200,000	.86	.87	.83	.82	.79	.78	.76	.74	.72	.69	.65	.61
	300,000	.83	.79	.77	.74	.76	.71	.67	.64	.69	.59	.52	.44
80	50,000	.91	.93	.93	.94	.85	.89	.90	.91	.71	.82	.83	.84
	100,000	.88	.89	.89	.89	.79	.83	.84	.84	.62	.72	.73	.72
	150,000	.85	.86	.84	.85	.75	.78	.78	.77	.56	.64	.63	.61
	200,000	.83	.82	.81	.80	.72	.73	.72	.71	.51	.56	.54	.50
	300,000	.80	.78	.74	.72	.68	.65	.62	.59	.44	.43	.37	.30
90	50,000	.85	.90	.91	.92	.00	.77	.83	.85	.00	.00	.16	.50
	100,000	.79	.84	.85	.86	.00	.64	.72	.75	.00	.00	.00	.14
	150,000	.75	.79	.80	.80	.00	.53	.61	.64	.00	.00	.00	.00
	200,000	.71	.75	.75	.75	.00	.43	.52	.55	.00	.00	.00	.00
	300,000	.65	.67	.66	.64	.00	.25	.34	.36	.00	.00	.00	.00

Note: Water temperature maintained at 76°F for all runs.

given condition. This "zero ratio" would be at the point at which the water temperature had become low enough that no vapor pressure difference exists. Such a condition as this is the case with 90°F and 80 percent relative humidity which was present in this study (Table 5).

C H A P T E R V
S U M M A R Y A N D C O N C L U S I O N S

Proper disposal of water contaminated with salt is one of the topics of concern with which man is faced today. Evaporation of the water, leaving salt as a residue, is one means which is used for disposal of high salt concentration water. However, the use of this method presents a problem in that the amount of evaporation expected is uncertain. The effects of salinity on evaporation have been studied previously with the conclusion being that salts in solution reduce evaporation. However, the actual reduction has not been well established for a wide range of variables in a given experiment. It was the objective of this study to (1) determine the effects on evaporation of a variety of climatic conditions in combination with various salt concentrations, and (2) find the reductions in evaporation that would occur under those conditions.

To accomplish these objectives evaporation of sodium chloride solutions, from concentration of zero to near saturation, were studied under a wide variety of climatic conditions. The climatic variables used were wind speed, air temperature, relative humidity and water temperature. The experiment was conducted in a controlled environmental chamber where control of the climatic variables could be maintained. Rates of evaporation were determined from containers of salt solutions in the chamber under the selected conditions.

The results of the study permit the following conclusions:

- (1) Evaporation can be expressed with a physical and a

statistical model. Both models fit the data of the study and close correlation was found between them. The much-used physical model is based on the resulting vapor pressure difference, times some constant for wind speed, which is dependent on climatic conditions and salinity of the water. The statistical model was a regression model with linear, linear x linear, and square roots terms included.

(2) Under conditions of constant water temperature, the effects exhibited by each of the variables were found to be related to vapor pressure. For each of the variables the following was noted:

- A. Air temperature - as air temperature increased, evaporation decreased.
- B. Relative humidity - as relative humidity increased, evaporation decreased.
- C. Salt concentration - as salt concentration increased, evaporation decreased.
- D. Wind speed - as wind speed increased, evaporation increased.

The three variables air temperature, relative humidity and salt concentration gave an increase in evaporation when decreased or a decrease in evaporation when increased. It will be noted that the same effect is seen when vapor pressure difference is replaced by evaporation.

Wind speed, when increased, increased evaporation where a vapor pressure difference was present. Also, increasing wind speed did not increase evaporation as much at the higher speeds if vapor pressure differences were more limiting.

(3) Under constant water temperature conditions, evaporation ratios were found to vary depending on the conditions present.

Ratios were a function of not only salt concentration but of relative humidity, air temperature and wind speed. Change in any one of the variables produced a change in the evaporation ratio.

(4) In the solution profiles both salt concentration and solution temperature remained essentially constant at all depths for any set of conditions which were imposed.

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APPENDIX

Table 6. Summary of the multiple regression analysis.

Variable	Coefficient	Standard Partial	Standard Deviation	T-Value	Type I Error Probability
AT	-0.22755707E 00	-0.52514533E 01	0.60295655E-01	-0.37740212E 01	0.000305
W	0.24255180E 00	0.15181624E 01	0.59176228E-01	0.40988046E 01	0.000132
RH	0.87365801E-01	0.16550845E 01	0.39811903E-01	0.21945089E 01	0.030402
C	0.21286694E 00	0.59879762E 00	0.16250052E 00	0.13099461E 01	0.193073
WT	-0.34244233E 00	-0.11309855E 01	0.25529692E 00	-0.13413493E 01	0.182701
(AT) ^{1/2}	0.18153194E 01	0.26655121E 01	0.61229990E 00	0.29647554E 01	0.003750
W ^{1/2}	0.20633426E 00	0.23699458E 00	0.14716338E 00	0.14020760E 01	0.163842
(RH) ^{1/2}	-0.68118977E 00	-0.84463160E 00	0.44679077E 00	-0.15246281E 01	0.130359
C ^{1/2}	-0.78121885E-01	-0.86762252E-01	0.90589829E-01	-0.86236928E 00	0.390450
(WT) ^{1/2}	0.95232571E 00	0.30269196E 00	0.14950513E 01	0.63698530E 00	0.525521
AT x W	-0.14897699E-02	-0.76561818E 00	0.42385826E-03	-0.35147832E 01	0.000734
AT x RH	-0.33214763E-03	-0.61352396E 00	0.20222536E-03	-0.16424628E 01	0.103486
AT x C	-0.19646243E-03	-0.42997402E-01	0.10867602E-02	-0.18077809E 00	0.856890
AT x WT	0.45861293E-02	0.36000890E 01	0.12150637E-02	0.37743940E 01	0.000305
RH x W	-0.18604553E-02	-0.81780937E 00	0.32297427E-03	-0.57603825E 01	0.000015
W x C	-0.68475297E-02	-0.21182819E 00	0.24659708E-02	-0.27768090E 01	0.006503
W x WT	0.17291619E-02	0.28502339E 00	0.31760243E-02	0.54444226E 00	0.587292
RH x C	0.13828061E-03	0.25918284E-01	0.91935490E-03	0.15041047E 00	0.880729
RH x WT	-0.11228342E-02	-0.62096216E 00	0.11758136E-02	-0.95494235E 00	0.341801
C x WT	-0.75581367E-02	-0.61031429E 00	0.76861623E-02	-0.98334337E 00	0.327699

Multiple 'R-Square' = 0.98151859E 00

R-Value = 0.99071620E 00

Analysis of Variance:

Source	DF	SS	MS	F
Total	125.	0.27102731E 03	0.13300917E 02	0.27881922E 03
Due to Regression	20.	0.26601834E 03	0.47704447E-01	
Error	105.	0.50089670E 01		

Square Root of Mean Square Error = 0.21841347E 00