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PERFORMANCE OF STATIONARY GUN IRRIGATION SYSTEMS

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ABSTRACT: The field performance of stationary giant gun irrigation systems is evaluated from the results of 70 distribution tests conducted in the interior of British Columbia, Canada. Three measures of field performance are quantitatively evaluated including maximum application rate, evaporation and spray loss and distribution uniformity. Maximum application rate is found to be a function of average wind speed in the principal wind direction. Evaporation and spray losses were dependent on climatic and operating conditions, primarily the atmospheric vapor density deficit and the average wind speed. The uniformity of application is strongly influenced by both the gun spacing and the average wind speed. The influence of operating variables such as nozzle size and pressure are accounted for in the parameters used to nondimensionalize these relationships. The equations representing these findings are derived using multiple regression and are presented algebraically. Measured values are plotted against predicted values to give a visual impression of scatter in the data. The utility of the relationships in designing and operating giant gun systems is illustrated.

INTRODUCTION

The purpose of modern irrigation systems is to distribute water evenly over the soil surface in an amount sufficient to meet the irrigation requirement of the crop. In addition, this amount of water should be consistent with the moisture storage capacity of the soil within the crop root zone. To avoid the soil and crop problems caused by runoff and ponding the rate of water application should be less than the infiltration rate of the soil. Lastly, the rate of water application should result in no direct physical damage to the crop or fruit being grown.

These are the requirements of the ideal irrigation system, and the degree to which these objectives are met varies from system to system. However, more recently it has been recognized that the selection and operation of an irrigation system is not based on these criteria alone, but also on economic considerations (6,8,9,11). For instance, as Walker (11) has pointed out, there is a tradeoff between increasing water application efficiency and increasing capital and operating costs. Higher efficiencies may increase yields and reduce water and power requirements; but unless these increased returns more than compensate for the increased expense, the improvements are not justified. Before economic decisions of this nature can be made, the field performance of various irrigation systems must be quantitatively determined.

One irrigation system alternative which as become widely accepted in

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Note.—Discussion open until August 1, 1984. To extend the closing date one month, a written request must be filed with the ASCE Manager of Technical and Professional Publications. The manuscript for this paper was submitted for review and possible publication on July 14, 1983. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 110, No. 1, March, 1984. ©ASCE, ISSN 0733-9437/84/0001-0075/$01.00. Paper No. 18663.

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agricultural practice is the giant gun. Giant gun systems are particularly attractive for the irrigation of forage corn because of the larger spacings available and because of the height required to clear the stalks. Many people feel there is a labor-saving aspect involved in the use of giant guns. In addition, giant guns are often considered for effluent irrigation systems.

Yet, despite the widespread use of giant gun systems, little quantitative information is available concerning the water distribution characteristics of this method of irrigation. The objectives of this study were to carefully evaluate the field performance of giant guns under realistic operating conditions. Particular attention was given to three areas of performance: (1) The influence of wind conditions on the uniformity of the water distribution of giant guns; (2) the maximum precipitation rates resulting from stationary gun operation; and (3) the evaporation and spray loss occuring under typical irrigation conditions with this method of irrigation. This information will allow designers of giant gun systems to begin incorporating a "stagegy" accounting for variations in soil type, climate and operating conditions in a way which will balance the trade-offs between benefits and costs.

LITERATURE REVIEW

Measures of sprinkler irrigation effectiveness have proliferated and concerted attempts have been made to relate these various parameters to one another and to the physically significant effects of poor distributions. Recently, Chaudhry (6), Walker (11) and Elliott, et al. (7) have summarized much of the previous work and made significant contributions to the scientific description of the water distribution of irrigation systems. There seems to be a consensus that the normal distribution provides a good and yet practical description of distributions over the higher ranges of uniformity when the skew of the distribution is relatively small (2,5,7,10). Given this and other assumptions, it is possible to relate water application efficiency to the coefficient of variation of the sprinkler pattern and to the average applied depth divided by the average soil moisture deficit (11). These relations provide a rational and convenient basis for system comparison and are thus well suited to the present task.

Most efficiency models assume that the root zone has been depleted to an idealized uniform level at the start of each irrigation. However, since irrigation systems do not distribute water uniformly and since the soil is an important water storage reservoir, an important averaging process will probably occur whereby areas receiving too much water during one irrigation may receive somewhat less water during the next irrigation. The nonuniform initial conditions will statistically combine with the nonuniform water application to produce a composite distribution. This composite distribution will tend to attenuate the nonuniformities of a single application in a way which will not be accounted for by the assumption of a uniform initial condition. Indeed, the new distribution developed will tend toward a uniform condition, but one that may be characterized by a water storage efficiency approaching 100% over the irrigation season if the deep percolation losses are small.

Redistribution mechanisms may also play a significant role in the water economy of an irrigated field. For instance, if water is applied at a rate greater than the infiltration rate of the soil, ponding and associated local surface runoff could result. In general, runoff will occur from areas of the field receiving the greatest application of water. This water will tend to migrate to areas receiving less water where runoff is not occuring. In this way, runoff can effectively redistribute water from the over-irrigated areas to the areas receiving less water. This runoff may occur on such a small scale as to represent an insignificant source of erosion. In adiditon, there will be important redistribution mechanisms occuring within the root zone. As the water percolates through the root zone, lateral flow as well as vertical flow may occur, tending to make the surface application nonuniformities attenuate as the bottom of the root zone is approached. Thus, the results of traditional analysis should be used with a critical awareness of the assumptions and limitations involved. Some systems, such as the giant gun, may be particularly affected by these considerations because of having high application rates or because it is used on crops with relatively deep root zones.

MATERIAL AND METHODS

Seventy distribution tests were conducted on giant guns between June and August in 1976 and 1977. Table 1 summarizes the number of tests conducted for the stated ranges of wind speed and air temperature. Because of the number of tests carried out and the number of variables measured, it is not convenient to give an exhaustive summary of the conditions encountered during each test.

All giant gun tests were conducted in the Okanagan Valley of British Columbia, Canada, utilizing irrigation equipment made available by a number of farmers and ranchers who were cooperating with the test program. This method of collecting data allowed tests to be conducted under a variety of soil, crop and climatic conditions and permitted a large number of systems and operating conditions to be tested. In ad-

TABLE 1.—Summary of Distribution Test Conditions

Average wind speed, in mile per hr (km/h) (1)	Number of tests conducted (2)	Average air temperature, in degrees Fahrenheit (Celsius) (3)	Number of tests conducted (4)
0–2 (0–3.2)	8	50–60 (10.0–15.6)	5
2–4 (3.2–6.4)	25	60–70 (15.6–21.1)	19
4–6 (6.4–9.7)	26	70–80 (21.1–26.7)	26
6–8 (9.7–12.9)	8	80–90 (26.7–32.2)	15
8–10 (12.9–16.1)	3	90–100 (32.2–37.8)	5
Total	70		70

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dition, this procedure minimized the costs associated with land and equipment rental which would have occurred without the help of the various cooperators.

The procedure for testing the stationary gun was quite simple. A pattern of approximately 400 identical collector cans, centered on the gun, was laid out on a 20 ft (6.1 m) by 20 ft (6.1 m) square grid spacing covering the wetted diameter of the gun. Care was taken to insure growth did not interfere with the water collected in each can. During the time a gun was operating the climatic variables were monitored. After the test was completed and the gun turned off, the amount of water in each receptacle was measured using a volumetric flask and this amount was recorded. New ring orifices were used in the gun whenever ring nozzles were tested.

The detailed procedure for laying out the grid and conducting the test is laid out in the ASAE recommendations "Procedure for Sprinkler Distribution Testing for Research Purposes" (1). This procedure was followed with the following exceptions: tests were run for 2 hr instead of 1 hr in order to increase the catch in each can and thus eliminate some of the random variations in tests; climatic variables were monitored every half hr instead of every 15 min. In addition, wind speed was measured with a hot wire anemometer instead of with a rotating cup totalizing anemometer. The hot wire anemometer was calibrated at the University of British Columbia in the wind tunnel prior to field testing. Dry and wet bulb temperature readings were made using a sling psychrometer, and were measured upwind of the gun.

During the testing, both taper bore and ring type guns were evaluated and are represented in the final results. Nozzle size varied from approximately 1/2 in. (1.3 cm) to 1-1/4 in. (3.2 cm) in diameter. For this range of nozzle sizes a complete set of manufacturer's recommended pressures (in ten psi or 69 kN/m^2 increments) were tested. The wetted diameter ranged from 220–400 ft (67–122 m), based on manufacturer's information. Flow rate estimates were made on the basis of measured pressures and manufacturer's data. Pressure measurements were usually made using the elbow mount attachment fitted on the top of the gun.

The method of generating overlapped distribution patterns from single sprinkler tests proposed by Branscheid and Hart (4) was used to calculate overlapped distributions under rectangular and triangular configurations. A computer program was written to calculate, as a function of spacings, the following distribution coefficients; the coefficient of variation and the coefficient of skew of the sample, the mean application (actually measured), the theoretical mean application and the loss coefficient. The theoretical mean application is the water application which would be expected according to manufacturer's specifications alone. The loss coefficient is an index representing evaporation and wind drift losses, calculated from the difference between the actual and theoretical application rates.

ANALYSIS

Three areas of field performance are qualitatively evaluated in terms

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of the primary environmental and operating conditions found to influence them. A flexible statistics program called TRP (Triangular Regression Package) was used to obtain regression equations and evaluate the significance of the various parameters. This program performs multiple regression analysis including forward and backward stepwise regression and orthogonal polynomial regression analysis.

It should be noted that the true complexity of the water application process will not be reflected in the generated equations. This paper attempts to define practical equations which would aid designers and operators *without unduly misrepresenting the phenomena being studied.* For this reason, nondimensional forms of parameters were used when most practical and only the most significant parameters were used in the final equations. Thus, pressure and nozzle size effects were found to be secondary and together could be lumped in a single variable, the wetted diameter of the gun (based on manufacturer's information). Other parameters of obvious possible significance, such as the rotation rate of the sprinkler, do not appear in any of the regression equations. This might be accounted for by the parameters being relatively uniform over the range of tests made and may not indicate that they are insignificant in general. For instance, if a sprinkler were to have a very nonuniform rotation rate, all the other parameters such as uniformity and maximum application rate would be greatly affected.

Maximum Application.—Since giant guns almost invariably operate without interaction or overlap with other guns, the physically significant application rate is determined by a single gun operating alone. Originally, the maximum application occurring in any catch can was selected as this maximum rate. However the catch in one can was subject to too much statistical uncertainty to have much validity, and experience with the data substantiated that this value was highly unstable. To avoid this problem, a cutoff had to be determined which would adequately represent the single gun maximum application rate. Field experience indicated that a value representing between 5–15 catch cans was representative, depending on the size of the actual test. Finally, a value representing 7% of the measured application rates was chosen as the cutoff. Experience has demonstrated that his value does have the desired stability and yet is not an unreasonably low estimator. When cutoffs of 10% and 5% were also tested, it was found that the results were not very sensitive to the specific percentage chosen.

Next, attempts were made to account for the various environmental and operating conditions that influence the maximum application rate. Field experience indicated that, in general, increasing either wind speed or gun discharge tended to increase the maximum application rate. In order to account for the gun discharge rate, the maximum application rate was normalized by dividing it by the average application rate occurring over the wetted circle of the gun. Regression of this new dimensionless application rate with average wind speed showed promise of being the desired relationship, but still showed disconcerting scatter. At this time it was noticed that variable wind direction tended to decrease the maximum application rate of the gun. To account for this, the average wind speed was normalized by considering only the component of wind speed in the principal wind direction. This further reduced the scatter and resulted in a usable design plot. In addition, the maximum application rate was adjusted to account for wind drift and evaporation losses; the regressed relation thus represented the maximum application occurring under conditions of no water loss. This will allow some reduction in maximum precipitation rate in practical situations in which some loss will occur.

Several regression relationships between the nondimensionalized maximum application rate and measured environmental variables were investigated using the TRP program. It was found, however, that the effect of all other parameters was insignificant compared to the influence of wind speed in the principal wind direction. Regression using fourth degree polynomials were tested, but little improvement in the standard error of the prediction was observed beyond what was achieved using a quadradic relationship. Since the quadradic relationship was both simple and accurate, it was felt that no greater complexity was justified. The final regression equation is

$$PMAX = 1.25 + 0.15(W) + 0.014(W)^2 \qquad (1)$$

in which $PMAX$ is the normalized maximum application rate, and W is the average wind speed in miles per hr. The standard error for this equation is 0.23 and the analysis of residuals indicates that the residuals may be considered to be normally distributed. The equation is represented by a coefficient of determination (R-Squared) of 0.86. A plot of predicted

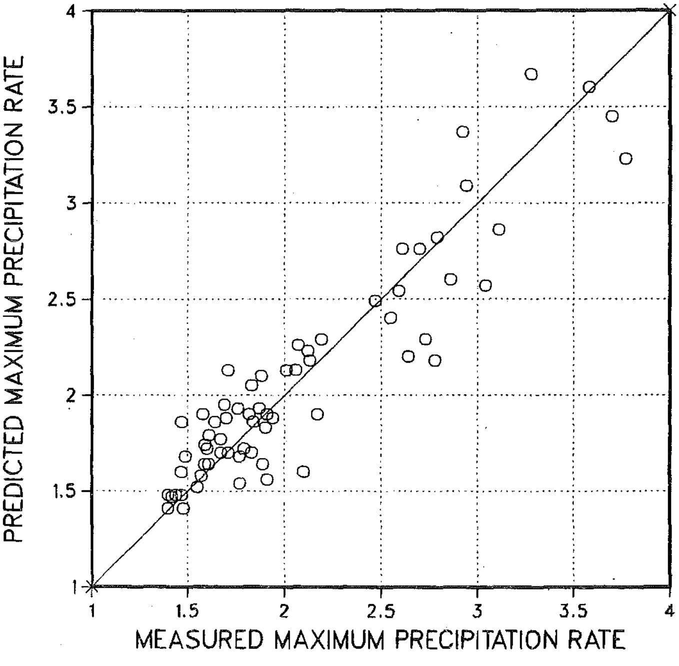

FIG. 1.—Predicted versus Measured Values of Non-Dimensional Maximum Application Rate Based on Final Regression Equation. (R-Squared = 0.86)

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maximum application rate based on the regressed equation versus the measured value is shown (Fig. 1) to give a visual impression of the scatter as well as indicating the range of test values. The equation is generally valid for wind speeds in the range of 1–10 mile per hr (1.6–16 km/h). Measured values of *PMAX* ranged from 1.4–3.6 times the average application occurring over the wetted diameter of the gun.

An example calculation demonstrates the usefulness of this equation. Suppose a designer knows that the prevailing winds in a given design area are approximately 5 mile per hr in a constant direction. The equation then indicates that the average value of $PMAX = 2.35$. The designer wishes to be 90% sure he does not exceed this value under these conditions. Since the standard error is 0.23 and errors may be considered normally distributed, the correction is $1.28\ (0.23) = 0.29$, in which the factor of 1.28 is obtained from standard normal tables (e.g., 3) at a 90% confidence level. Therefore the designer can be 90% sure the real value of *PMAX* is 2.64 or less. Thus, if the designer had information on the acceptable application rates for the soil in the area, he could use the *PMAX* value along with the soil data to calculate the allowable average application rate of the gun. This value would indicate a range of alternative pressures, nozzle sizes and discharges available for meeting his requirements. Note that if, on a given day, the average wind speed were to increase to 10 miles per hr, then the *PMAX* value would increase to 4.15 and the operator may begin to run into problems such as runoff or surface ponding as a result of the much higher maximum application rate.

Uniformity of Application.—The Wilcox-Swailes coefficient of uniformity (12) was chosen as the parameter to represent sample dispersion. This coefficient efficiently describes sample scatter and can easily be manipulated to calculate other parameters (such as Christiansen's coefficient of uniformity or pattern efficiency). In addition, the Wilcox-Swailes coefficient allows the most direct calculation of sample coefficient of variation. The Wilcox-Swailes coefficient of uniformity (UCW) is defined by

$$UCW = 1 - \frac{s}{\bar{x}} \quad \text{.......................................} \quad (2)$$

in which s is the standard deviation of the sample and $\bar{x}$ is the average of the sample.

The environmental and operating conditions which combine to produce the final distribution of field application values are exceedingly complex. Some of the factors influencing the distribution from giant guns were previously noted. Others include nozzle size and construction, riser height and angle as well as minor effects such as air and water temperature. After several different approaches were tried, the following procedure for incorporating these effects was determined.

In order to account for variation in scale between large and small guns, the spacing of the giant guns was nondimensionalized. This was accomplished by taking the square root of product of the spacing in both directions and dividing the result by the diameter of the wetted circle. It was found that this procedure accounted for both nozzle size and pres-

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sure variations as well as square, rectangular and triangular gun spacings.

Numerous regression fits with a wide variety of variables, filters and polynomial equations were used in analyzing the uniformity data. Originally, the uniformity data was filtered to eliminate all values less than 10% and the data was regressed against wind speed, wind gust, gun spacing and gun discharge. With this selection of independent variables, the regression equation found had a standard error in the prediction of uniformity of almost 10%. This uncertainty was unacceptable and new relationships were sought that would reduce the sample error.

Over 40 different combinations of independent variables were tried in the regression analysis, ranging from sixth order orthogonal polynomials of wind speed and gun spacing to very simple linear fits in only the most significant parameters. In the end, significant improvement was achieved by recognizing that uniformity, like maximum application rate, is sensitive not only to wind speed but also to persistence in wind direction. That is, since uniformity is subject to accumulation, the appropriate wind speed is that component of the varying wind which occurred in the principal wind direction. In addition, the lower values of uniformity were not only of the least practical significance for design purposes but almost invariably had the largest residuals associated with them. Thus, the lower values of uniformity were progressively eliminated until a balance was reached between the breadth of range represented and the accuracy of the regression relation. This balance was achieved with a cutoff uniformity of 50%. These two simple devices had a far greater impact in reducing the uncertainty in the uniformity prediction than even the most complex regression using higher order polynomial fits and the complete data set. The final regression equation representing the Wilcox-Swailes uniformity coefficient (*UCW*) as a percentage is

$$UCW = 110.9 - 54.5(S) - 2.64(W) \quad \text{.............................} \quad (3)$$

in which W is average wind speed (mile per hr) in the principal wind direction, and S is the dimensionless gun spacing. The coefficient of determination (R-Squared) for this equation is 0.84 and the standard error in prediction over the 300 tested data points is 3.5%. The equation is generally valid for wind speed between 1–10 mile per hr (from 1.6–16 km/h) and for dimensionless spacings over the range from 0.3–0.9. The standard error in the coefficients are 1.5 for spacing and 0.125 for wind speed. This formula quantitively demonstrates how increasing wind speed by 2 mile per hr reduces the uniformity by approximately 5%. However, the formula also shows how this reduction can be compensated for by reducing the gun spacing by approximately 10% of the wetted diameter of the gun.

Lack of homogeneity in the variance was not observed in the variance plots of Eq. 3. This further validated the simple linear expression by demonstrating that variance stabilizing techniques such as log transformations were not only unnecessary but also inappropriate. A scatter plot showing measured versus predicted values of uniformity is shown in Fig. 2.

The coefficient of skew was also calculated for each of the data points used and was regressed against the uniformity data. This procedure was

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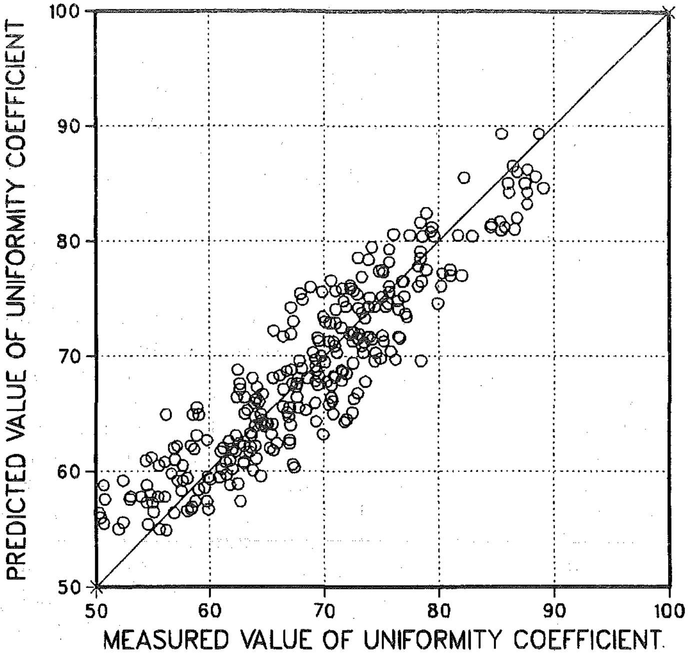

FIG. 2.—Predicted versus Measured Values of Wilcox-Swailes Uniformity Coefficient Based on Final Regression Equation. (R-Squared = 0.84)

used to see if skew was a significant parameter or whether the simple relationships developed by Walker (11) which assume skew is zero could be considered to be generally valid. The average value of skew overall tests was found to be 0.06 although it ranged from 0.4–0.35. However the skew had no significant correlation to uniformity or any other parameter of interest. Thus, reported relationships between the various measures of water use efficiency and the variance of the distribution will provide a good basis for system comparison.

Evaporation Loss.—Once the water storage efficiency has been determined, the only value that needs to be estimated in order to estimate the water application efficiency is the evaporation loss. Evaporation from an irrigation gun depends on many factors including the water droplet size and size distribution of the gun, the travel time of the droplets in the atmosphere, (the vapor density deficit is defined as the saturation density of water at the wet bulb temperature minus the vapor density of the water in the surrounding air), the initial water temperature, the radiant energy regime, the vapor density deficit of the atmosphere and the wind conditions such as turbulence conditions and mean variability.

Superimposed on the complexity of the evaporation process are the problems associated with evaporation measurement and field sampling. Evaporation does not only occur during the passage of the water droplets through the air, but continues to occur in the catch cans used for field measurement. Although diesel fuel was used as an evaporation

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suppressant in the majority of the tests, this would only restrict evaporation and by no means eliminate it. Evaporation also occurs from the collection unit walls, with generally greater proportions of small droplets adhering and evaporating than large droplets. Furthermore, the collection unit changes the wind speed and turbulence conditions, alters the radiation and thermal regime and is subject to splash and other rain gage errors. All of these factors will influence the measurement of evaporation loss and, to some extent, the actual measured distribution of the sprinkler.

On several occasions evaporation control tests were conducted by placing a known amount of water in a typical catch can and monitoring this volume as a function of time. Results from these tests indicated values of evaporation of between 1–3 ml per h, depending on the exposure, temperature and humidity at the time the test was carried out. This in itself would indicate moderate evaporation losses from the measuring cans. However, this may be an optimistic estimate of this error since there is a large difference between water evaporating from an otherwise dry can and the process occurring during field distribution tests.

Despite these problems, a model was sought which would test at least the first order relationship between evaporation and wind drift loss and operating conditions. Originally, attempts were made to simply relate evaporation to the relative humidity. Although this relationship was straightforward, it simply did not have the required accuracy. In an ef-

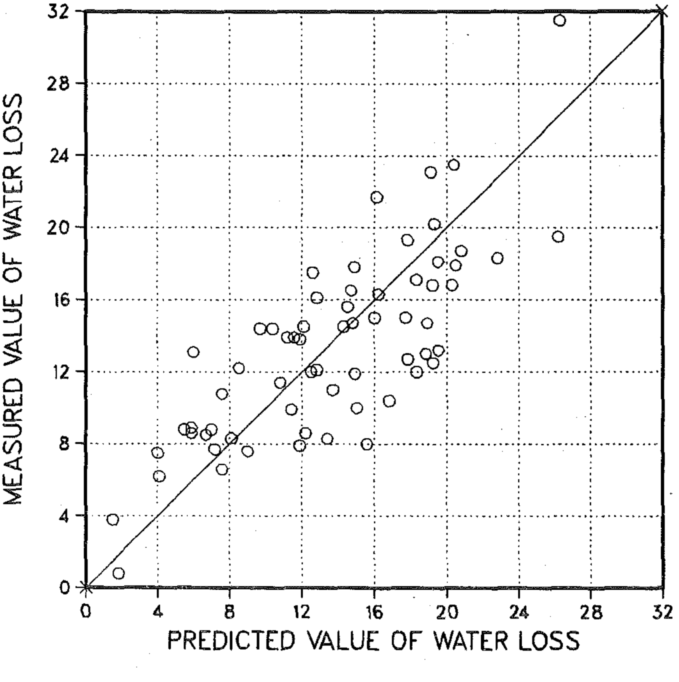

FIG. 3.—Predicted Values of Evaporation and Spray Loss versus Measured Values. (R-Squared = 0.61)

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fort to increase the accuracy and flexibility of the evaporation relationship, the combination of dry and wet bulb measurements was converted to vapor density deficit. A relation of this form was felt to far more realistically represent the actual driving force in the evaporation process. It was considered that the evaporation loss primarily originated from atomized water droplets. These droplets would attain the wet bulb temperature very quickly, thus creating an evaporation driving force very similar to the vapor density deficit of the atmosphere.

The regression analysis clearly showed that only two parameters, namely wind speed and vapor density deficit, were significantly correlated with the measured value of evaporation and spray loss. Several regression relationships using these parameters were investigated but little improvement in accuracy occurred beyond what was achieved by using a simple linear fit. The regression equation was forced through the origin so that the predicted value of this loss would be zero when the vapor density deficit and the wind speed were both zero. The final regression equation for the loss index (as a percentage) is

$$\text{LOSS} = 1.74(W) + 21{,}800(VDD) \quad \text{(4)}$$

in which W is the time weighted average wind speed in mile per hr and VDD is the vapor density deficit of the atmosphere in lb/cu ft. The coefficient of determination (R-Squared) is 0.61 and the standard error in the prediction is 3.5%. The standard error in the wind speed coefficient is 0.22 and in the vapor density deficit coefficient is 3200. A plot of the measured values of the loss coefficient versus the predicted values based on the regression equation is shown in Fig. 3. Not surprisingly, this relationship represents a significantly poorer fit than the previous two equations found. Measured values of the evaporation and wind drift loss ranged from 2%–26%.

Past review has often indicated that evaporation losses may be very significant within the receptor itself. This could certainly be the case in the present study. However, the regression equation indicates that wind drift losses may still be significant, especially in high wind situations. Little of the water losses due to wind drift would actually penetrate the root zone and it is recommended that at least this portion of the loss be accounted for in designing and operating giant gun systems. Even if only a fraction of the loss dependence on the vapor density deficit is accepted as valid, the water loss in a dry or windy environment could significantly effect the economics of giant gun systems.

CONCLUSION

For many years giant gun systems have been operated with little accurate data available concerning their performance under field conditions. This paper interprets the results of field tests conducted on giant gun systems in an attempt to provide a quantitative framework on which to make design and operational decisions. This work makes no pretense of being authorative, but it is hoped it will stimulate other researchers to report not only on their theoretical findings but on the results of their field testing as well.

Ultimately the decision of which irrigation system to choose is an economic one. This economic decision must take into account energy and horsepower requirements, labor maintenance and capital costs and water use requirements as well as expected changes in these costs. The simple algebraic relationships derived in this paper from the field performance of giant gun systems will begin to allow these important design and operation decisions to be conveniently made.

Although specific economic decisions cannot be presented at the present time, the following qualitative observations are in order. Currently the goal of minimizing the labor requirements of various irrigation systems is given a high priority, and low equipment and operating costs are sometimes sacrificed in order to achieve this end. The giant gun is a good example of this tradeoff. Although giant guns are characterized by low application efficiencies and high power costs, they are used quite extensively because of their labor-saving features. Whether or not the current emphasis on energy and environmental conservation will influence this situation remains to be determined. The information provided in this paper should help to specify how large a price an operator must pay in terms of water use and power efficiency if he chooses a giant gun system.

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

$PMAX$ = maximum measured precipitation occuring over a representative field area, nondimensionalized by dividing by the average precipitation occuring over the wetted diameter of the gun;

S = geometric mean of the gun spacing nondimensionalized by the wetted diameter of the gun;

s = sample standard deviation;

UCW = Wilcox-Swailes uniformity coefficient;

VDD = vapor density deficit of the atmosphere;

W = time averaged wind speed in the principal wind direction; and

x = sample mean.

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