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Wind-Powered Irrigation Tailwater System: Sizing the Wind Turbine and Storage Pit

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ABSTRACT

THE design choices involved in development of a wind-powered irrigation tailwater reuse system were briefly reviewed. Next, computer simulation of the system was used to develop the long-term relationships among monthly runoff volume, runoff pumped, wind turbine pumping capacity, and pit storage capacity in western Kansas. Serial windspeed data from weather records and measured performance data from a wind-powered system were used in the simulation. Results showed which combinations of wind turbine size and pit capacity could be used to pump a given runoff volume.

INTRODUCTION

In many surface irrigation systems, collection and reuse of runoff water are desirable. Reuse systems permit less water to be pumped or diverted to the field and provide a means of altering management practices so that deep percolation losses are reduced (Bondurant, 1969). Tailwater systems also act as pollution control devices that limit losses of fertilizers, chemicals, and soil. Pope and Barefoot (1973) noted there is often a legal requirement to collect runoff water from irrigation.

Tailwater systems are used widely, but their total number is difficult to determine. From results of surveys, White (1976) reported that there were 6,500 tailwater pit and lake pumps in the Texas High Plains and Trans-Pecos area of Texas, and Hay (1978)* reported 4,179 tailwater systems in use in Kansas. Nebraska law requires installation of tailwater systems. Fischbach (1978)* estimated that the number of systems in Nebraska exceeded 20,000 and was rapidly increasing.

To meet user needs, various designs for tailwater systems have been proposed. For example, Bondurant (1969) developed a set of relationships to predict recirculating pump flow rate and volume of storage needed to use the tailwater for establishing a cutback type of furrow irrigation. In another design, Stringham and Hamed (1975) proposed use of constant discharge from the recirculating pump without cutback as a means of reducing labor.

If a successful wind-powered tailwater system could be developed, it might replace some conventional energy sources. It would also encourage new tailwater recovery installations at sites where electricity is not available. Because there is a need to conserve both water and fossil fuels, we conducted field experiments to test a wind-powered tailwater system (Hagen and Sharif, 1979). However certain design variables could not be determined in the short-term field experiments. Thus, the objective of this simulation study was to use the experimental system performance data to determine the long-term relationship between wind turbine size, runoff volume, and storage pit capacity in western Kansas.

REVIEW OF DESIGN VARIABLES

For a specific installation, the designer must select (a) operational mode of wind turbine and pump, (b) a method for conveyance and application of the tailwater, and (c) size of wind turbine and storage pit. All these choices are interrelated.

A major distinction among wind turbine operational modes is between those that use auxiliary power sources and those that do not. An auxiliary power source can be used to maintain a constant pump speed (and flow rate) even though power from the wind turbine varies. Data from tests of a 17-m Darrieus wind turbine and electric motor operating at constant speed were reported by Clark and Schneider (1978). Several modes of wind turbine and pump operation also were compared in a simulation of irrigation pumping from wells (Hagen et al., 1979). Modes with auxiliary power sources likely will be used for pumping wind-powered irrigation wells and perhaps the largest tailwater pits because they have several advantages compared with modes using only wind power.

However, for most wind-powered tailwater pumps, a variable-speed (and flow rate) mode of operation likely would be chosen because it does not require an auxiliary power source. In this mode, the pump power demand and wind turbine power supply are matched over the operational speed range, and some safety device is added to prevent overspeeding at windspeeds above the rated windspeed. Rated windspeed is the lowest windspeed at which the wind turbine develops its maximum design power.

The method selected for conveyance and application of the tailwater must be compatible with the other design choices. When auxiliary power is used to provide constant pump speed (and flow rate), conventional schemes for tailwater management can be used.

When the tailwater system is wholly wind-powered, it is desirable to reduce the variation in flow before applying the water to the field. If the tailwater is returned to a relatively large main supply ditch, short-term fluctuations in tailwater flow will not affect the main system appreciably, and the total flow can be anticipated with aid

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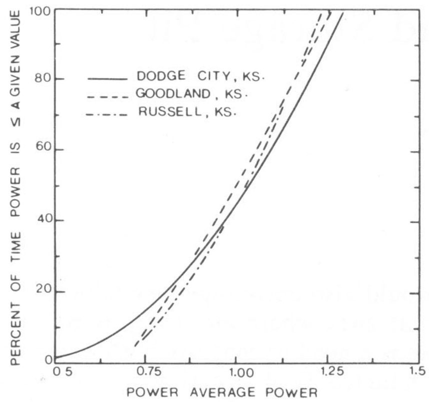

FIG. 1 Calculated cumulative frequency distribution of July and August power from a wind turbine for records of 18 to 26 years at various locations in western Kansas. (Data after Oddette, 1977).

of reasonable windspeed forecasts. To apply tailwater to a separate field, we have successfully used a small reservoir at the head of the field to provide uniform flow to gated pipe. A less-convenient distribution system using large field ditches and siphons to accommodate the variable flow from a wind-powered pump also was tested (Hagen and Sharif, 1979).

Size of the wind turbine and storage pit must be selected to produce the desired output. If water were always available from the tailwater pit or other water source, then output would vary directly as the windpower, and windpower data in the literature could be used to determine output. However, variation in output among years as well as average output should be considered.

For example, Oddette (1977) calculated monthly wind turbine power outputs based on hourly windspeed data at several locations in Kansas. A cumulative frequency distribution of the July and August power outputs (normalized by their average) is shown in Fig. 1. Typical irrigation design is usually based on supplying adequate water in all but 20 percent of the years (USDA, 1970). If this criterion is applied to a wind-powered system, then Fig. 1 shows that the wind turbine must be sized to supply adequate water whenever monthly power output exceeds 83 percent of the average.

Usually, the design is further complicated because water is not always available in the tailwater pit when windpower is available. To determine output of a wind-powered system in this case, one must simulate operation of a representative system.

SIMULATION OF SYSTEM OPERATION

Three components of the wind-powered tailwater system were simulated. These were the input runoff to the tailwater pit, various sizes of tailwater pit, and various sizes of wind turbine pumping from the pit. Pumping rates for each wind turbine size were determined from serial windspeed data. Four years of hourly July and August windspeed data from Dodge City and Garden City, Kansas, were used. These locations were chosen because their windspeeds are typical of much of the irrigated area in the western Great Plains (Reed, 1975). Most irrigation pumping occurs in the two chosen months.

To determine the influence of timing of runoff to the storage pit, three runoff variations were simulated: (a) a constant runoff rate, (b) runoff at 0.5 and 1.5 times the average rate during alternate 12-h periods, and (c) constant runoff rate unless the storage pit was full. If the pit was full, no runoff was permitted for a maximum of 10 percent of the time each month. The last variation implies no irrigation for up to 10 percent of the month. This may often occur in years when precipitation is above average, because the recommended design size for irrigation systems is that they supply adequate water 80 percent of the years (USDA, 1970).

TABLE 1. PERCENT CHANCE OF RECEIVING 71 MM OR MORE OF PRECIPITATION IN A 1-WEEK PERIOD FOR VARIOUS LOCATIONS IN WESTERN KANSAS*

Week beginning	Location: Colby	Tribune	Garden City	Elkhart
July 5	2.4	2.3	1.3	2.3
July 12	1.8	4.0	2.0	4.0
July 19	2.2	4.3	2.4	4.3
July 26	2.0	4.4	2.5	4.4
August 2	2.3	2.8	2.0	2.8
August 9	1.4	1.9	1.4	1.9
August 16	1.3	0.9	1.0	0.9
August 23	0.8	0.9	0.3	0.9

*Data after Bark (1963).

Choice of when to irrigate from the tailwater pit was based on the long-term weather records. Bark (1963) has shown that the chances of receiving 71 mm of rain in a given week in western Kansas are always < 5 percent during July and August (Table 1). Thus, rainfall rarely replaces the 75 to 100 mm needed to fill the soil profile in a typical irrigation. For this reason, it was assumed in the simulation model that pumping from the tailwater pit would occur whenever windspeeds were between cut-in and cut-out windspeeds of the wind turbine. At cut-in windspeed, there is enough windpower to begin pumping, while at cut-out windspeed, the turbine must be shut down for safety reasons.

Performance data for the wind turbine and pump used in the simulation model were based on results of field tests. The system tested consisted of a 6-m-diameter, 9-m-tall Darrieus vertical-axis wind turbine (VAWT)† connected to a vertical turbine pump (Fig. 2). A speed-increasing transmission with constant ratio of 9.85 provided a suitable match between the pump and VAWT. Centrifugal spoilers mounted at the maximum blade diameter provided overspeed control and limited maximum VAWT speed to 230 r/min. A caliper brake acting on a horizontal disk connected at the base of the rotor was used for stopping the VAWT. An electric motor connected through an overrunning clutch was used for starting.

Average performance data for 0.25 m/s windspeed increments while pumping at a dynamic head > 6 m is shown in Fig. 3. A theoretical output also was calculated assuming constant efficiencies of 0.6 for the pump. 0.3 for the VAWT, and 0.9 for the transmission. The pump efficiency was > 0.6 over most of the operational speed range, but < 0.6 as pump shutoff head was approached near windspeeds of 5.5 m/s. To simplify simulation of the wind-powered system, constant efficiencies were

† Wind turbine was manufactured by Dominion Aluminum Fabricating Ltd. of Mississauga, Ontario. Mention of a specific product is for information only and does not constitute an endorsement by USDA-SEA.

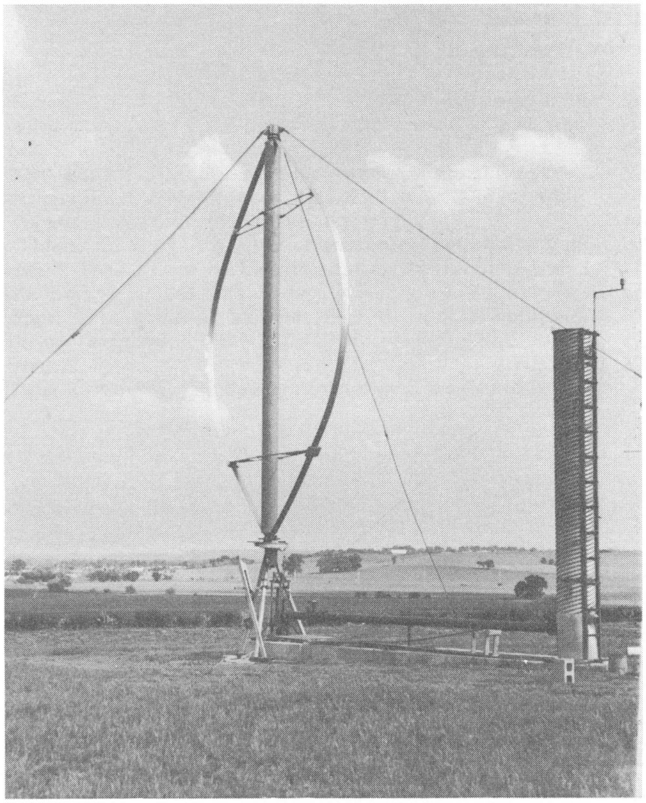

FIG. 2 The 6-m-diameter, 9-m-tall vertical axis wind turbine coupled to a vertical turbine installed at irrigation tailwater pit.

used, and water pumped (Q in L/s) per m² of wind turbine swept area was calculated from the equation:

$$Q = (0.0625\ C_pN_p/H)\ u^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [1]$$

where u is windspeed (m/s) at the center height of the VAWT, C_p is VAWT efficiency, N_p is transmission and pump efficiency, and H is dynamic head (m).

Using equation [1] with fixed efficiencies for a range of tailwater pit sizes implies that the wind turbine and pump can be scaled up or down without changes in efficiency. This assumption appears reasonable. Pumps are presently available in a wide range of sizes and their efficiency increases only slightly with size (Karassik et al., 1976). The scaling parameters for Darrieus vertical-axis wind turbines are well-defined and several sizes have been constructed. Again, only a slight efficiency improvement with size has been predicted (Strickland, 1975).

TABLE 2. INPUT VARIABLES FOR MASS-BALANCE COMPUTER PROGRAM

Variable	Magnitude	Units
Wind turbine		
Cut-in windspeed	5.5	m/s
Rated windspeed	10.0	m/s
Cut-out windspeed	15.0	m/s
Efficiency (C_p)	0.3	
Pump and transmission		
Efficiency (N_p)	0.54	
Total head (H)	5.0	m
Storage pit		
Initial water stored	50.0	% of maximum capacity
Height of windspeed data		
Dodge City, KS	17.7	m
Garden City, KS	6.0	m

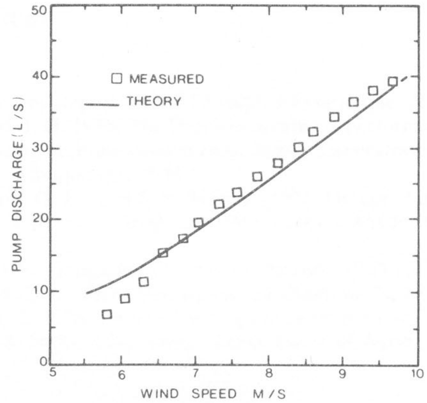

FIG. 3 Measured and theoretical performance of wind turbine and pump as a function of windspeed. Theoretical output was calculated using efficiencies of 0.3, 0.6, and 0.9 for the wind turbine, pump, and transmission, respectively.

A simple, mass-balance computer program performed the calculations in the simulation model on an hourly basis. Input variables used in the program are given in Table 2. At the beginning of July, the storage pit was assumed to be at 50 percent capacity from rainfall or previous irrigation runoff.

Given a runoff rate to the pit, the program calculated the monthly runoff volume to the pit (ROV) and monthly volume of water pumped (ROP) by various sizes of wind turbine. Calculations were carried out for storage pit capacities which ranged from 5 to 50 percent of monthly ROV. A monthly wind turbine pumping capacity (WTC) also was calculated. The WTC was defined as the average monthly volume of water a wind turbine could pump if water was always in the pit. Of course, ROP was usually less than WTC, because the pit was sometimes empty.

RESULTS AND DISCUSSION

In a conventional tailwater pit, a storage volume of 1 to 2 days' runoff (3 to 6 percent ROV) is often used. The proper storage capacity depends on rate of runoff as well as frequency of pumping from the pit (Bondurant, 1969). In a wind-powered system, the pit should hold most of the runoff between periods of turbine operation and also supply adequate water during periods of high windspeeds.

The effect of storage pit capacity on monthly ROP of simulated wind-powered systems is illustrated in Figs. 4 and 5. The ROP by a given wind turbine depends on turbine size relative to the ROV and pit capacity. For this reason, the results were made dimensionless by using monthly ROV as the scaling factor. The results are then applicable to the whole range of tailwater pit sizes. Generally, ROP increased with increasing storage capacity. Increasing pit capacity from 5 to 15 percent of ROV increased ROP by 5 to 8 percent. Note that for the largest size wind turbines, ROP can be larger than ROV, because the pit was assumed to be half full at the beginning of July.

The ratio ROP/WTC is a measure of wind turbine utilization and can be calculated from the equation

$$ROP/WTC = (ROP/ROV)/(WTC/ROV) \quad \ldots\ldots\ldots\ldots \quad [2]$$

The ratio WTC/ROV is a measure of relative wind tur-

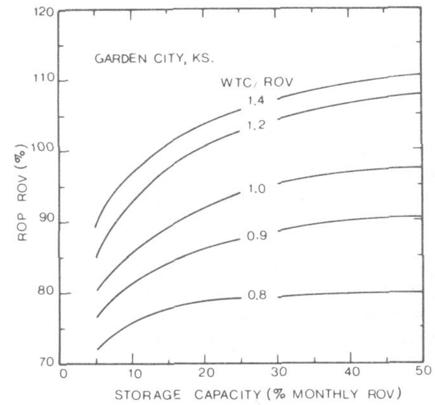

FIG. 4 Percent of net runoff volume pumped (ROP/ROV) as a function of pit storage capacity and relative wind turbine size (WTC/ROV) at Garden City, Kansas, for 4 years during July and August.

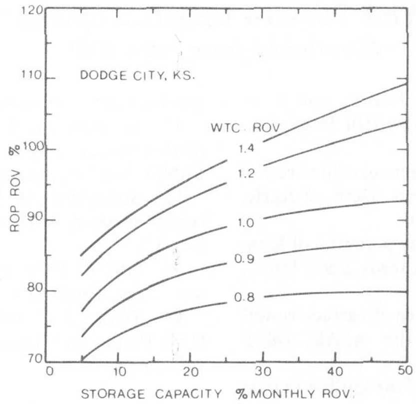

FIG. 5 Percent of net runoff volume pumped (ROP/ROV) as a function of pit storage capacity and relative wind turbine size (WTC/ROV) at Dodge City, Kansas, for 4 years during July and August.

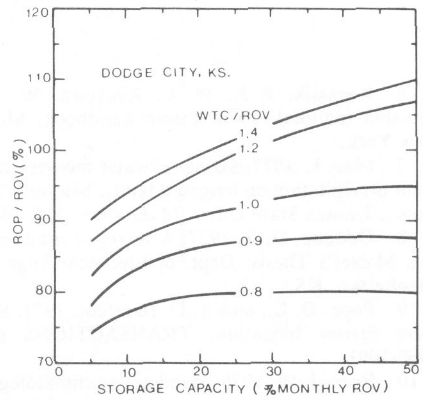

FIG. 6 Percent of net runoff volume pumped (ROP/ROV) as a function of pit storage capacity at Dodge City, Kansas, with runoff stopped up to 10 percent of the time.

bine size, and as wind turbine size increases, utilization decreases. For example, Fig. 4 shows that with a storage capacity of 10 percent of ROV, ROP/WTC is 0.91, 0.86, and 0.78 for WTC/ROV of 0.9, 1.0, and 1.2, respectively. Decreasing wind turbine size increases utilization but also increases the frequency of pit overflow.

To test the effect of daily runoff cycles, alternate 12-h periods of 0.5 and 1.5 times the mean runoff rate were simulated. The ratios of ROP/ROV calculated using this daily cycle varied only about 1 percent from the values obtained using a constant runoff rate. Thus, daily cycles in runoff do not affect the results appreciably if storage capacity is $\geqslant$ 5 percent of monthly ROV.

Stopping runoff to the pit when the pit was full for up to 10 percent of the time each month increased ROP/ROV 3 to 6 percent at Dodge City (Fig. 6) but had little effect on ROP/ROV at Garden City. The ROP/ROV was always larger at Garden City than at Dodge City even though the WTC was about 0.50 L/s ($\cong$ 1340 m^3/mo) per m^2 of wind turbine swept area at both locations. Evidently, periods with windspeeds greater than cut-in windspeed occurred more regularly at Garden City than at Dodge City.

A brief example will be used to clarify the utility of the simulation results. Suppose an irrigator wants to pump at least 85 percent of the net runoff (i.e., runoff less seepage and evaporation losses) from a 65-ha irrigated corn field in western Kansas. Further assume that the net runoff is about 50 mm (ROV $\cong$ 32,500 m^3) per month in July and August. Then Fig. 5 can be used to determine a conservative estimate of the needed pit capacity and wind turbine size. Obviously, a WTC/ROV ratio ranging from 0.88 to 1.4 could be used; or in dimensional terms, wind turbine swept area must increase from 21.3 to 34.0 m^2 as pit storage capacity decreases from 50 to 5 percent of ROV.

The wind turbine size range was determined using the calculated WTC of 1340 m^3 per m^2 of wind turbine swept area. However, WTC can be adjusted to other heads and efficiencies using the relationships in equation [1]. The final choice of wind turbine size and storage capacity should be based on an economic analysis of the discrete wind turbine sizes available within the needed size range.

If a large tailwater pit is used with a wind turbine, the pit may also be useful as a rainfall runoff collector. Mao (1977) reported that in a conventional tailwater system in western Kansas a storage capacity of 5 days' runoff (17 percent of monthly ROV) would enable 70 percent of the precipitation runoff to be utilized with a storage capacity of 1 day's runoff.

SUMMARY AND CONCLUSIONS

In development of a successful wind-powered tailwater system, the designer must select (a) operational mode of the wind turbine and pump, (b) method for conveyance and application of the tailwater, and (c) size of wind turbine and storage pit. All these choices are interrelated. To aid in sizing the wind turbine and storage pit of a wholly wind-powered system, computer simulation was used to determine the long-term relationships among the monthly runoff volume (ROV), runoff pumped (ROP), wind turbine pumping capacity (WTC), and pit storage capacity in western Kansas.

During July and August, WTC averaged 0.5 L/s (1340 m^3/mo) per m^2 of swept area of wind turbine with a 5 m head. However, ROP/ROV depended on wind turbine size relative to ROV and pit capacity. Increasing pit storage capacity from 5 to 15 percent of monthly ROV increased ROP/ROV by 5 to 8 percent. Because the pit was occasionally empty, ROP was usually less than WTC. Daily cyclic variations in runoff did not affect ROP/ROV appreciably, but stopping runoff up to 10 percent of the month when the pit was full increased ROP/ROV 3 to 6 percent at Dodge City.

The simulation results showed the same ROP could be achieved with various combinations of pit capacity and wind turbine size; thus, the final size selection should be based on an economic analysis for a specific site.

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