Wind powered irrigation in Montana
by Joel Cahoon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

Abstract:
The technical and economical feasibility of wind powered irrigation systems in Montana is considered. The possibilities of incorporating energy conserving irrigation systems, crops, and tillage practices into the wind powered irrigation systems are assessed. The feasibilities of the irrigation systems are determined using six computer models in site specific situations. The results of these models indicate that wind powered irrigation is technically feasible, but not economically feasible. Wind powered irrigation systems are not recommended for production operations in Montana.

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APPROVAL

of a thesis submitted by

Joel Cahoon

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

December 17, 1986
Date

Gerald Westesen
Chairperson, Graduate Committee

Approved for Major Department

17 Dec '86
Date

Theodore E. Long
Head, Major Department

Approved for the College of Graduate Studies

December 17, 1986
Date

Henry L Parsons
Graduate Dean

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ABSTRACT

The technical and economical feasibility of wind powered irrigation systems in Montana is considered. The possibilities of incorporating energy conserving irrigation systems, crops, and tillage practices into the wind powered irrigation systems are assessed. The feasibilities of the irrigation systems are determined using six computer models in site specific situations. The results of these models indicate that wind powered irrigation is technically feasible, but not economically feasible. Wind powered irrigation systems are not recommended for production operations in Montana.

CHAPTER 1

INTRODUCTION

Using alternative energy sources for irrigation pumping has recently become of interest to agriculturalists. When on-farm economic situations are worsening, any practice that may increase a producers profits is worth considering. This project examines the technical and economic feasibility of wind powered irrigation systems in Montana.

Many researchers have considered the technical feasibility of pumping the required water volumes necessary for irrigation via some sort of wind energy system. This project examines the total system, including the wind powered pumping system, the irrigation system, the cropping practices and the overall economics of the system.

Several energy conserving concepts were evaluated for potential use with wind powered irrigation systems. The reason for these evaluations was that these energy conservation methods, if it were determined that they were applicable, might make wind powered irrigation systems more feasible. The concepts evaluated are: the use of crops with low water requirements, the use of crop production functions (mathematical relationships between crop water use and crop yield) to reduce pump energy requirements, the use of energy saving irrigation systems, the use of conservation tillage practices, and the use of reservoirs for off season pumped water storage. The evaluation of these concepts was accomplished by reviewing the available literature on the topics. Based on this literature, the concepts were evaluated to determine their relative applicability to wind powered irrigation systems. Of the topics evaluated, those which would enhance the feasibility of wind powered irrigation systems were incorporated into the models developed in this project.

Literature concerning wind energy conversion, wind powered water pumping, irrigation system energy use, and wind regime assessment was also reviewed. The models developed in this project, and much of the discussion concerning these topics, are based on the information obtained from this literature.

Several wind powered irrigation system models were examined to establish the technical and economical feasibility of such systems. The types of systems that were modeled are: windmill-reservoir systems, systems that offset existing electrical irrigation loads, and stand alone windmill systems.

The windmill-reservoir system models use a mechanical water pumping piston type windmill to supply water to an off season storage reservoir. The water is conveyed from the reservoir to an appropriate irrigation system. The net return of several crops at each site was estimated and the economic feasibility of the systems as designed determined. Four such models are examined in this project.

A second scenario examined offsetting existing electrical irrigation loads. In this model a wind powered electric generator is used which would lessen the dependence of an existing irrigation system on the utility grid. The economic feasibility of offsetting existing electrical irrigation loads was then assessed.

The third model considered replacing an electrical irrigation pump motor with a small mechanical water pumping piston type windmill. In this model it is assumed that the existing irrigation system is one that will allow large variations in flowrates and pressures, such as a drip/trickle system. The economic merits of using a windmill in place of an electric motor were then assessed.

The products and business references used in this project are not recommended as the sole source of components or information. Products and businesses were cited in this project due to their availability at the time of this research and adaptability to the systems examined herein.

CHAPTER 2

EVALUATION OF ENERGY CONSERVING CONCEPTS

The intent of this chapter is to assess the possibility of incorporating several energy saving concepts into the design of wind powered irrigation systems. The applicability of these concepts to wind powered irrigation systems is based on literature reviewed concerning each topic. These topics are: crop production functions, energy conserving crops, energy conserving irrigation systems, conservation farming techniques, and off season pumped water storage reservoirs. If these concepts are deemed applicable to wind powered irrigation systems, they will be incorporated into the system models.

Crop Production Functions

Reducing the amount of irrigation water applied to a crop may be one method of energy conservation. Before this practice is recommended, the effects of this water reduction must be thoroughly examined. Ideally, the decrease in the crop value as a result of water reduction should be more than offset by the resultant savings due to energy reduction. This theory violates the common notion that the optimum production level should be the maximum production level, regardless of the cost of production. For this reason the reduction of irrigation water application has only recently been introduced as an alternative method of maximizing production profit. (Heady and Hexam, 1978)

Crop production functions are mathematical relationships between crop input variables and yield or production. Many researchers have developed crop production functions for a given crop at a given location. It is the authors feeling that these types of production functions are developed rather blindly, as the use of the production functions at another location, or under different conditions, is rarely considered in the research. Some researchers have maintained that production functions developed at one site are transferrable to another (Sammis, 1980), but the transferability was not established on more than a statewide basis.

Crop independent production functions are those that may be applied to any crop at any location. (English and Dvoskin, 1977) The drawback with these production functions is that extensive site specific research and testing is required to establish the yield-water use relationship.

Current literature concerning the actual on-farm use of production functions in a cropping operations suggests that these relationships not be used to lower the energy requirements of the irrigation system. (Vaux and Pruitt, 1983)

Alternative Crops for Montana

Some alternative crops have a lower water requirement than the crops commonly grown in Montana. These lower water requirements could translate into an energy savings for producers. Several crops have been suggested as alternative crops for energy and water conservation in Montana. These crops include; fababean, garbanzo bean, and safflower. (Westesen, 1985)

Fababean

Fababean is an Old World crop that has been grown for centuries in Europe, and used as a supplement in both animal and human diets. Fababean is a tall, upright growing, annual legume, which when inoculated with commercial Rhizobium can provide its own nitrogen. The seeds are large (62-70 lbs/bu) and high in protein (28 - 32%) and carbohydrates. (Lockerman et al., 1982) The fababean is well suited to the climate in most regions of Montana.

The yield of fababeans under irrigated conditions ranged from 2000-5000 pounds per acre. (Lockerman et al., 1982) Reports indicate that fababeans are a poor dryland crop but respond well to low and intermediate irrigation levels. A single value irrigation water requirement has not yet been established for the fababean in Montana.

Current commercial market information indicates that the value of fababeans as a bean crop varies from $.12 to $.13 per pound delivered to the dealer. Current seed prices for fababean seed run from $.15 to $.17 per pound, with an additional cent per pound of seed for Rhizobium inoculant. (Bruce, 1986)

There are several on-farm uses for fababeans which hold some promise of making the crop a viable water saving alternative. The crop may be cut as silage or used as a supplement in the diets of swine, poultry, dairy cattle, beef cattle, and sheep. (Lockerman et. al., 1982)

It seems that Fababeans are quite well suited to the agricultural climate and practices in Montana. There is a fairly stable market for the fababean, but this market is largely out-of-state. In addition to the commercial market, there are on-farm uses for fababean. If these on-farm uses could be successfully incorporated into a farming operation fababeans could be considered a feasible water conserving crop for Montana. Unfortunately, fababeans have not yet been commercially tested on a real production basis in Montana, and are therefore not recommended on any large scale or permanent operation.

Garbanzo Bean

The garbanzo bean, commonly called chickpea, was originally a native of Europe. The chickpea is a low growing, bushy, hairy stemmed annual legume. Chickpeas are grown, harvested and handled much in the same way as the field bean. Chickpeas may be used as a protein substitute in the human diet or prepared in the same manner as dried lima beans. (Welty et al., 1982)

It appears that the growing season length and climatological conditions in Montana are quite satisfactory for chickpea production. Research has been done concerning the water use-yield relationships for the chickpea in Montana, the results of which are presented in Table 1. (Welty et al., 1982)

Table 1. Chickpea yields and water use, based on tests in Montana.

Total Water (in)	Grain Yield (lbs/ac)
32.8	2041
28.8	2312
24.5	3032
22.6	2867

The tests were conducted at Bozeman MT during the 1981 growing season on inoculated UC-5 garbanzo bean. It was reported that the two higher irrigation treatments reduced yield because vegetative growth increased, delaying bloom.

The cost of the garbanzo bean seed is the single highest expense in the production of the crop. The seed prices varies from $35 to $80 per hunderedweight. (Baldridge, 1982; Bruce, 1986)

Current information concerning the market potential of garbanzo beans indicates that the harvested crop is worth $.20 to $.50 per pound on the domestic market. This market value varies substantially. There are few reported on-farm uses of the crop. Garbanzo beans may not be harvested as silage for animal feed, as the plant itself is toxic to most farm animals. (Bruce, 1986)

The current farming practices and equipment used in Montana are very applicable to the production of the garbanzo bean. The factors that could limit the feasibility of garbanzo beans as an energy conserving crop are; the lack of a steady commercial market, relatively few on-farm uses of the crop or its residue, and the extremely variable and high cost of the seed. It is not recommended that garbanzo beans be implemented into any large scale or permanent cropping installation in Montana until further research is conducted.

Safflower

Safflower has been an important oil-seed crop in the United States since the 1940's. The safflower is well adapted to semi-arid and irrigated regions. The required frost free season is about 110 days, which makes safflower a suitable crop for most of Eastern Montana. The average yield in Montana is roughly 4000 lbs of seed per acre. (Baldridge, 1986) The safflower is an annual, erect, glabrous herb, 1 to 3 feet high and branched at the top. Safflower seeds weigh roughly 45 lbs per bushel, are smooth and resemble a small sunflower seed in shape. The unhulled seeds contain 18 to 24 percent protein and 32 to 40 percent oil. (Chapman et al., 1976)

Research concerning the seasonal water use by safflower was done at two locations in Montana. The total seasonal water use by safflower ranged from 9.0 inches at Culbertson to 9.8 inches at Fort Benton. These values are total water use for the growing season, and have not been adjusted for precipitation or stored ground water. (Baldridge, 1986)

Seed cost for safflower appears to be roughly $30 per hunderedweight. The current market value of safflower appears to be between $.15 and $.20 per pound of seed. (Baldridge, 1986)

Safflower is promising as a water conserving crop for montana. There is an in-state market for the crop, and the crop is currently grown on a dry-land basis in the state. Currently, safflower as an irrigated crop is not recommended in Montana until the means and effects of safflower irrigation are further evaluated.

Energy Conserving Irrigation Systems

Those systems which have been singled out as being energy saving systems and being potentially applicable to the farming situations in Montana are; drip/trickle, trail tube center pivots, and low pressure sprinkler systems. (Westesen, 1985)

Drip/Trickle Systems

Drip irrigation is the deposition of water directly to or beneath the soil surface utilizing low flowrates. This is accomplished by using individual lines or laterals equipped with emitters for water dispersion. The laterals and emitters themselves are the means by which pressure is reduced to allow low flowrates in drip form. In a drip irrigation system each plant, or small group of plants, is watered individually by its own emitter. (Pair et al., 1983)

Drip irrigation is the most efficient of all irrigation methods. Very little water is wasted because the water is deposited directly onto the soil. This greatly reduces the evaporative and wind induced losses associated with sprinkler systems. Since only small volumes of water are applied there are no deep percolation losses. (Hansen et al., 1979)

Test results have shown that crop yields and irrigation efficiencies are greatly increased with the use of drip irrigation systems. These test results are typical of those found for other field and vegetable crops. (Sammis, 1980)

The major problems encountered with drip irrigation systems are; emitter clogging, salt accumulation, and mechanical damage by farm machinery. (Pair et al., 1983)

Drip irrigation systems are currently used extensively on vineyards and orchard crops. The current trend is towards establishing drip systems as a viable alternative for row crops. This should become more evident as the drip industry grows, thus reducing the purchase price of drip system components. Research has shown that dramatic yield increases result from the conversion to drip irrigation systems from more conventional methods. With more extensive use of drip systems the problems inherent with the systems are being overcome. This energy efficient means of irrigation should become more widespread in the near future. Currently, the purchase costs of drip irrigation systems may limit their use in Montana cropping practices.

Low Pressure Sprinklers

Low pressure sprinklers have the same basic characteristics as any other sprinkler system, with the difference being the operating pressure of the sprinkler. Low pressure sprinkler systems generally operate in the range of 5 to 30 psi. The sprinklers are fitted with low pressure nozzles to help distribute the water more efficiently. The characteristics of a low pressure sprinkler system may be summarized as: a small wetted diameter, relatively high precipitation rates, the water drops are fairly large due to the low pressure, and the moisture distribution pattern is generally only fair at best. (Pair et al., 1983)

Low pressure sprinkler systems are not recommended for use with wind powered irrigation systems until their commercial availability is established, and the full effects of their use is determined. (DeBoerand Beck, 1983)

Trail Tube Center Pivot Sprinklers

Trail tube center pivot systems are center pivots which have been altered so that small tubes emit water slightly above the ground surface. The trail tube system that has received much attention recently is the LEPA (Low Energy Precision Application) system. (Lyle and Bordovsky, 1982)

The LEPA system distributes water directly into a furrow at very low pressures. The drop tubes with emitters are positioned 2 to 4 inches above the furrow. The system was designed to eliminate climatic and soil variables which adversely affect the uniformity and irrigation efficiencies.

The system is designed to be used in conjunction with furrow diking techniques. Furrow diking involves the placing of small dikes at regular intervals along the length of the furrow. With this technique, the water that is placed in the furrow by the LEPA system cannot run off. Using furrow diking also allows better trapping of rainwater. Without the furrow diking, the LEPA would result in excessive runoff losses. This is due to the low pressure and high application rates of the water applied. (Lyle and Bordovsky, 1983)

The LEPA system is only one form of trail tube sprinkler irrigation. Other systems involve dragging tubes suspended from a center pivot, with emitters fitted to the tubes. (Westesen, 1986) Little interest seems to have been generated concerning these systems, due to the high runoff that could occur without the special tillage practices to complement the irrigation system.

These trail tube systems are not yet commercially available, they must be used in conjunction with a labor intensive tillage system, and are thus not recommended for use with wind powered irrigation systems in Montana.

Conservation Farming Techniques

There are some practices which may be incorporated into a farming operation which save water or energy that do not involve altering the irrigation system. These practices are collectively referred to as conservation tillage practices. These are cultural practices that can be incorporated into any farming system. These tillage systems fall into two general categories, those that attempt to conserve water by reducing field runoff, and systems which reduce tillage to conserve the water stored in the soil column. (Bauder, 1986).

The theory behind reducing runoff to conserve water is a simple one. Water that is prohibited from running off the soil surface, whether it is deposited by irrigation or rainfall, can be absorbed by the soil and used to replenish the soil moisture. The two most promising methods of controlling surface erosion involve altering the soil surface characteristics by residue management or tillage practices. (Bauder, 1986)

Residue management is the practice of leaving or incorporating the stubble from the previous crop on or into the soil surface. For example the straw that remains from a wheat crop may be lightly mulched and incorporated into the top two or three inches of the soil. The placing of loose straw in the furrow row of a field bean crop reduced surface runoff by 50%. (Brown, 1985) Increased water storage, fallow efficiency, and grain yield is achieved with the use of a stubble mulch fallow system. (Bauder, 1986) The obvious drawback of a stubble mulch system is that a crop with good residue production must have been grown in the field during the season prior to that in which residue management is desired or straw must be hauled in.

The other method of controlling surface runoff is to simply alter the surface characteristics of the soil by utilizing certain tillage practices. A simple method of reducing surface runoff is through proper land grading techniques. Soils with deep profiles may be graded to decrease slopes that cause high runoff rates.

Another means of increasing the water use efficiency of a farming system is the use of minimum tillage practices. These practices involve the reduction of the number of tillage passes over a field, or the use of tillage implements that decrease the water loss from a soil column. Each tillage pass depletes the soil moisture by an average of 1/2 inch. (Bauder, 1986)

One drawback of minimum or no-till systems is that herbicides must be substituted for tillage in weed control. If weed control is a serious problem, the herbicide cost may offset the resultant savings in water. (Bauder, 1986)

These are only a few of the many tillage and farming practices that may be incorporated into a farming system to conserve water or decrease tillage. This subject area is very broad and cannot be fully covered in the scope of this project. The use of one or several of these conservation farming techniques in a wind powered irrigation system should boost the overall effectiveness of the system. Many of the more feasible and effective conservation farming techniques are already in use in Montana's farming operations.

Off-Season Reservoir Storage

The Soil Conservation Service has published guidelines for the construction and use of irrigation water storage reservoirs. This technology may be easily incorporated into a wind powered irrigation system. The wind powered pumps would provide the water for reservoir storage. Storage reservoirs must be properly sized. There are several major inflows/outflows to a reservoir which must be considered in reservoir sizing. The inflows to the reservoir are; pumped water, precipitation and seepage. The reservoir outflows are: irrigation water, evaporation, and seepage. Seepage is listed as both an inflow and an outflow because in some cases water could be added to the reservoir through groundwater flows. Having identified the major constituents of water movement in a reservoir, a water budget may be constructed (Viessman et al., 1972):

$$S = P + R - E - S_o + S_i$$

where: S = change in storage volume
P = water pumped into reservoir
R = precipitation, E = evaporation
S_o = seepage out of the reservoir
S_i = seepage into the reservoir

The water balance equation may be used to estimate the required reservoir storage volume. The subsequent problem is to accurately estimate the components of the water balance equation. The reservoir should be sized for the period of highest crop water demand and lowest precipitation and pumping capability. If the reservoir can supply sufficient water for the crop in this worst case, excess water will be available for the remainder of the growing season. (Viessman et al., 1972)

The incorporation of an off-stream reservoir into an irrigation system depends largely on the sites topographic and cultural conditions. Conceivably, in some cases a reservoir may decrease the overall water use efficiency of an irrigation system. This would be due to the water losses associated with seepage and evaporation. Even with the lower efficiencies, a reservoir may be required for use with wind powered irrigation systems because of the typical low flow rates inherent with wind powered pumping systems.

Summary of the Applicability of Energy Conserving Concepts

The literature on the topics evaluated provides a basis for the following statements;

1. Crop production functions should not be used to lower the energy requirements of an irrigation pumping system, without substantial on site research concerning the validity of the production function.

2. The alternative crops examined should not be used in a large scale production operation without further research concerning these crops adaptability to Montana's farming situations.

3. The energy conserving irrigation systems examined should not be implemented into a production situation in Montana at this time, with the possible exception of the drip/trickle systems.

4. The conservation tillage practices that are most applicable to production situations in Montana are currently in widespread use.

5. Off-season pumped water reservoirs should be considered for use in wind powered irrigation systems.

With these statements justified, the remaining parameters concerning wind powered irrigation systems may now be considered.

CHAPTER 3

WIND POWERED IRRIGATION SYSTEM DESIGN CONSIDERATIONS

The design procedures for wind powered irrigation systems involves the examination of several critical parameters. Based on these parameters, decisions concerning the design of the system can be made. These parameters must be assessed on a site specific basis.

The parameters that must be assessed in the planning of a wind powered irrigation system are; the soil type, the crop water requirements and irrigation schedule, the irrigation system type, the growing season length, the pumping head, timing considerations, wind powered irrigation system compatibility, and the wind regime. In this section these parameters and the decisions to be made concerning them are individually discussed.

Soil Type

The soil type of the site is always a necessary consideration. The U.S. Soil Conservation Service has developed a system of rating a soils characteristics for agricultural considerations. Under the system the soil and the surrounding topography is ranked and said to be in one of eight classes, numbered I to VIII. Class I land is fit for any agricultural use. The limitations on land use increase with class number. The class number is determined from the soil texture, depth, and structure. Additional factors involved in soil classification are the slope, erodibility, drainage, stoniness and vegetation of the plot and surrounding areas. (Brady, 1974)

When considering a wind powered irrigation system, land classes I,II, and III are considered acceptable. In some cases class IV land may be used, but care in land management and improvement should be taken. (Brady, 1974)

Crop Water Requirements and Irrigation Schedule

A crops water requirements are the basis for establishing the flowrates that are necessary from a pumping system. The pumping system, be it stand alone or in conjunction with some type of water storage system, must be capable of meeting the peak crop water requirement. The timing of monthly and seasonal water requirements are estimated from climatic or lysimeter data. The required flow rate is determined using the water requirement for the acreage irrigated and the period of time considered. (Hulsman, 1985)

The peak flowrate must be within the limits of the wind powered pumping unit. Crops with low water consumption may be chosen as principle crops in order to decrease the water flowrate required of the irrigation system. These crops must be compatible with the site conditions and must show economic potential.

Irrigation System Type

The type of irrigation system type is also a factor in determining the flowrates pumped. If an irrigation system is already in existence at the proposed site, it may be unreasonable to alter the irrigation system for the sake of installing wind power. The factors associated with the irrigation system type that influence design decisions for a wind powered irrigation system are the required pressures and flowrates and the system efficiencies.

Growing Season Length

The growing season at a site is usually considered the period of frost free days. For this period of time the wind regime and pumping parameters are critical in a system with no water storage facility. During this time period the wind powered irrigation unit must be able to supply the irrigation needs of the crop. If the system is to have some type of water storage facility, the months surrounding the growing season should also be considered. During this time water may be pumped and stored for later use. The number of frost free days on a regional basis for particular Montana areas is available from the Soil Conservation Service or the Agricultural Extension Service.

Pumping Head

The head against which the pump is operating is one parameter which determines the amount of power that must be available to the pump. Pumping head includes both the elevation head and the friction head. The friction head is a function of the pipe lengths, diameters, and roughness coefficients, as well as the flowrates required by the irrigation system. The elevation head is a function of the height that the water must be raised to bring it to the level of the irrigation system.

Timing Considerations

In considering a wind powered irrigation system, the matching of timing between irrigation needs and wind power availability must be favorable. If it can be assumed through wind regime evaluations that sufficient winds are available when irrigation is scheduled, then the wind powered pumping system can be designed to supply water directly to the irrigation system. If the wind regime evaluation shows little consistency or predictability in the wind speeds, or that the windy periods do not coincide with the irrigation needs, then a water storage system should be considered in the design.

Wind Power Irrigation System Compatibility

The means by which wind power is incorporated into an irrigation system is important when considering the conversion of an existing conventional irrigation system to a wind powered or wind assisted system. This decision should be based primarily on the way the existing system is powered. Internal combustion engines and electric motors may be fitted with a wind machine via an overrunning clutch.

Electric motors on irrigation pumps may also be assisted electrically with a wind turbine in situations where excess energy is sold back to the utility. (Clark, 1985) It has been determined that mechanical wind assist systems provide about 12% more energy to the pump than do electrical wind assist systems. The electrical wind assist mode will pay for itself much quicker than the mechanical system if utility buy back is considered. (Clark, 1983) It is logical to suggest that if the current irrigation system is electrical, than electrical wind assist should be considered. If the irrigation pump is driven by an internal combustion engine, then mechanical wind assist is appropriate. In either case, alterations to the existing pumping unit should be kept to a minimum.

For new installations it seems logical that stand alone wind systems possibly in conjunction with water storage facilities should be considered. If it were economical to install an electric or internal combustion engine driven pump in conjunction with a wind system, it seems likely that these systems would have been previously installed without the wind assist.

Wind Regime

Wind regime assessments on a site specific basis should be carried out. There are no hard rules concerning the minimum quality of a wind regime acceptable for a wind powered irrigation site. (Barnett, 1985)

Other consideration in the planning of a wind powered irrigation system are (Barnett, 1985):

1. Site accessibility and the quality of roads leading to the site.

2. The possibility that the wind machine may not be usable in extreme weather conditions, due to winter snow or ice buildup.

3. The distance of the wind machine from existing residences or dwellings, for noise and safety considerations.

Site specific conditions may require design decisions not covered in this report. It is expected that the designer will make sound decisions based on logic and good judgment.

CHAPTER 4

WIND ENERGY CONVERSION SYSTEMS

Wind energy systems have been developed in many sizes and configurations. The technology concerning wind energy systems is well developed and has improved greatly over the past decade. (Gipe, 1983) This chapter reviews the basic operating principles and types of systems which make up wind energy technology.

The two basic wind machine configurations are horizontal and vertical axis. The aerodynamic principles in either situation are similar, but the construction and operation of the two differ greatly. (Barnett, 1985)

Horizontal axis machines have a horizontal axis which is parallel to the wind, about which the blades rotate. The horizontal axis machines were the first developed, and date back to the fifteenth century. In 1890 the Danes were generating electricity with a 23 m diameter horizontal axis wind turbine. Horizontal axis technology was used extensively in the Midwest and Western United States during the nineteenth and twentieth centuries to pump domestic and stock water or produce electricity at remote locations. During the late 1970's NASA, in conjunction with Boeing Engineering and Construction Company, built several large wind-electrical conversion turbines. The largest of these turbines was rated at 2.5 MW at a wind speed of 12.4 m/s. This verifies that horizontal axis machines have been well proven over the years. (Johnson, 1985)

There are two configurations of horizontal axis machines, upwind and downwind. The upwind machines are equipped with a tail or a mechanical orientation device so they continuously face the wind. The downwind machines are mounted in a caster situation, and the drag on the blades keeps them positioned such that their axis is parallel to the wind. The upwind machines have been used for more total hours, and are a more proven technology. The downwind machines, although simpler in design, block a small portion of the wind that strikes the tower. (Barnett, 1985) Some researchers still dispute the desirability of each configuration. (Gipe 1983)

Vertical axis machines spin around an axis that is perpendicular to the wind. The most common type of vertical axis is the Darrieus turbine, which was patented by G.J.M. Darrieus in the U.S. in 1931. There are curved and straight bladed Darrieus machines. The curved bladed machines are unique because the blades form troposkien shapes, or the shape formed by swinging a rope. This results in the blades sustaining almost pure tension forces. Since the blades are in pure tension a light, inexpensive blade is adequate. The curved blades are commonly formed from extruded aluminum. (Barnett, 1985)

The vertical axis machines are usually not self-starting. A small motor is used to start rotation when an acceptable wind speed is reached. After start-up is achieved, natural rotation will be sustained until low wind speeds reoccur. The major advantage of vertical axis machines is that the generator or power take off unit is at ground level instead of on a high tower. Installation and maintenance are thus much easier. The vertical axis machine does not have to be oriented to a particular wind direction. Since the axis of rotation is perpendicular to the wind, the wind may come from any direction. (Barnett, 1985)

Extensive research has been done in Texas using vertical axis machines to pump irrigation water. A vertical axis machine was coupled to an irrigation pump to obtain a 65% savings in energy in the wind assist mode. (Clark, 1979) This research proved the system to be technically feasible, but did not consider an actual cropping system served by the water pump. Total economic feasibility was not considered in the research.

The installation of modern wind energy conversion machines is often difficult and sometimes hazardous. A great deal of preparation and planning must go into the installation of a wind machine. Only experienced personnel should undertake the installation of a wind machine. Wind machines are often installed by the dealer from which the machine is purchased. If the dealer does not provide installation, this service should be contracted out to a firm with the proper equipment and facilities. Improper installation of a wind machine could result in a hazardous situation after the wind system is operating. (Gipe, 1983)

The designers of wind energy conversion machines have always attempted to minimize machine maintenance. Maintenance of a wind machine primarily involves keeping lubricating fluids at the proper levels. For a vertical axis machine this is simple because the gears and equipment are at ground level. Some horizontal axis machines are designed to be tipped over to simplify maintenance. Other horizontal axis machines require climbing the tower to check the lubrication fluid levels. Fortunately this need not be done very frequently with a well designed modern machine. (Gipe, 1983)

Other factors to consider when choosing a wind machine type are the cost per unit of power generating or water pumping capability, the service and reliability record of the manufacturer, and the installation and maintenance costs of the system. After all these factors have been considered, a wind machine type may be chosen. (Barnett, 1985)

The decision as to the type of machine most suitable to a wind powered irrigation system depends on several factors. The most important factor to consider is the means by which the wind machine is to be coupled to the irrigation system.

If electricity is to be generated to lessen the amount of power drawn from the utility lines, any electricity producing wind energy configuration will work well as long as the wind turbines power output is well matched to the load being drawn by the pumping plant. If mechanical coupling of a wind machine to an existing irrigation pump is to be used, perhaps a vertical axis machine is more desirable because the power take off is at ground level, making the power transmission system less complicated. For those wind machines which pump water directly, a traditional horizontal axis system is commonly used. Commercially units of this type are available. (Patterson, 1986) Because of the relatively large water volumes involved, wind powered irrigation pumping is new technology. There is room for innovative thinking and new design configurations.

Wind Regime Assessments

Climatological considerations constitute the most crucial factor in the design of a wind powered irrigation system. (Barnett, 1985) The best designed systems and machinery will not function if there is not enough, or too much, wind available. This section covers the methodology followed in assessment of the amount of energy available in a given regime.

The siting of a wind machine must be based on sufficiently accurate wind data. Wind data from nearby monitoring stations such as airports or research stations is normally accurate only for that site. (Gipe, 1983) For the data to be transferrable, the geographic conditions at the site and the monitoring station must be similar. A minimum of two years of data must be available for siting wind machines. Factors that may decrease the accuracy of data from a monitoring site are; obstructions near the monitoring site such as buildings and trees, "sloppy" data recording and gathering techniques, inconsistencies in the time interval at which the data was collected, or sites that have been falsely unobstructed by the clearing of natural vegetation such as runway clearings at airports. (Barnett, 1985)

The height of the anemometer used for recording the data must either be consistent with the height of the wind machine, or the wind data must be adjusted for the difference in height. This adjustment is accomplished by using the following equation (Johnson, 1985):

$$u(z_2)/u(z_1) = (z_2/z_1)^a$$

where: u = the windspeed
z = the elevation
a = a constant at approximately 1/7

The most extensive wind records have been collected by the National Weather Service (NWS), and the Federal Aviation Administration (FAA). A good compilation of wind data for Montana is available through the Energy Division of Montana Department of Natural Resources and Conservation (DNRC). (GeoResearch, 1986)

Once the designer is satisfied that his wind data is accurate and fairly representative of the site being considered, the data must be analyzed to determine if enough wind exists at the site to justify a wind energy conversion system.

There are many ways that the wind data may be analyzed. Wind patterns can be explained but not predicted using some basic mathematical principles. Therefore wind data is analyzed statistically rather than deterministically. The most often used wind statistic is the average or mean wind speed. This statistic is easily computed, and is usually included in any wind data set. The mean is computed as (Johnson, 1985):

$$U = 1/n \{\text{sum } U_i\}$$

where the data set contains wind readings U_i, and n is the number of data points in the set. Although mean wind speeds are frequently used in describing a wind regime this statistic can be misleading. For example, high wind speeds in the spring may increase the mean wind speed but there may be periods during the summer when the wind is almost nonexistent. To help clarify the validity of the mean wind speed, the standard deviation can be calculated. The standard deviation is an indicator of how the individual wind data deviates from the mean wind speed. The standard deviation may be calculated using (Johnson, 1985):

$$\text{eta} = [1/(n-1)\{\text{sum } (U_i - \overline{U})^2\}]^{1/2}$$

A low value of the standard deviation indicates that the wind data is consistently close to the mean speed. Both of these statistics give a good rough estimate of the quality of a wind regime and are easily calculated. (Barnett, 1985)

The most complete method of analyzing wind data is to establish the Weibull parameters for a site. (Barnett, 1985) The Weibull function utilizes recorded data, which is often too erratic to evaluate on a simple histogram, and smooths it to a general shape. The Weibull function is a very good model of real wind conditions. (Johnson, 1985)

The Weibull function is a two-parameter probability distribution function which appears as (Johnson, 1983):

$$f(U) = [(k/c)(U/c)^{k-1} (exp(-(U/c)^{k})]$$

where k is a shape parameter and c is a scale parameter. The calculation of k and c is a complicated procedure. Commercially available computer software is now commonly used to estimate the Weibull parameters for a site. A computer program for computing these parameters is included in Appendix 1, Figure 20. Much of the wind data currently being generated includes a listing of the Weibull parameters.

The probability distribution function provides the preliminary information necessary to determine the amount of power that can be produced or the water flowrates that can be expected with a given wind powered irrigation system.

The Weibull parameters are those necessary for design considerations that are associated with the wind regime. Determining these parameters is the first step in an overall system design.

Pumping Capabilities of Wind Powered Irrigation Systems in Known Wind Regimes

The conversion of raw wind energy into usable energy is dependent on the type and efficiencies of the system and its components. In this section a method of estimating the water pumping capacity of a wind system is developed. A discussion of the means by which wind energy may be used to pump irrigation water is included.

Conversion of Wind Energy to Usable Energy

Given a wind speed it is possible to assess the total amount of power which is contained in that wind. The power of a given wind speed is given by (Johnson, 1985):

$$Pt = 1/2 \times p \times A \times U^3$$

This equation gives the amount of power that an ideal wind turbine would extract from the wind if the swept area of the turbine were A, the density of air p, and the windspeed at the time of evaluation, U. Of course no wind machine can extract all the power from the wind, and it can be shown that the theoretical maximum that a wind turbine can extract is about 60% of Pt. The actual factor is .593, which is referred to as the Betz coefficient. (Johnson, 1985) Most wind machines are able to extract 20 to 40% of the power in the wind. (Gipe, 1983) Transmission losses must be deducted from this estimated power. The means of determining the available power for water pumping varies with the method by which the wind machine is coupled to the irrigation pump.

A wind system that may be applicable to some conditions in Montana could supply electrical power to an existing irrigation pumping plant. This load would probably be a synchronous one. A synchronous system has a fixed rotational speed. At some low wind speed (cut in speed, Uc) the turbines will begin to rotate. The turbines will rotate at a constant speed (rated speed, Ur) until the wind becomes too strong. At this high wind speed (furling speed, Uf) the blades will furl or a braking device will be engaged. (Johnson, 1985)

The manufacturers of wind turbines should supply the buyer with accurate values of Uc, Ur, Uf and the rated power (Pr). Using these values and the Weibull coefficients determined from the sites raw wind speed data, an estimate can be made of the electrical power expected from a known wind regime. This power (Pe,ave) is expressed as (Johnson, 1985):

$$P_{e,ave} = CF \times P_r$$

where CF is the capacity factor. The capacity factor is dependent on the characteristics of both the wind regime and the wind turbine. The capacity factor is derived from the integration of the product of the rated power output from a wind machine and the probability density function of wind speeds over the entire theoretical wind speed range. In integral form this appears as (Johnson, 1985):

$$Pe,ave = \int_0^\infty Pe \times f(U)\, du$$

where f(U) is the Weibull density function of wind speeds. After substitution, integration, and simplification, the capacity factor can be expressed as (Johnson, 1985):

$$CF = \frac{\exp(-(Uc/c)^k) - \exp(-(Ur/c)^k)}{(Ur/c)^k - (Uc/c)^k} - \exp(-(Uf/c)^k)$$

where c and k are the Weibull parameters. From this equation it can be seen that given the parameters c and k we would like to choose a machine with values of Uc, Ur, and Uf that maximize CF.

Those systems which pump water using direct mechanical power are often sold as a complete package. (Patterson, 1986) To estimate the volume of water that these systems will pump, the manufacturer will normally supply a graph depicting flowrate vs. windspeed. This type of test data has been compiled by the Drainage Branch, Alberta Agriculture in Lethbridge Alberta, and is available to the public. The flowrates are read for each windspeed and multiplied by the number of hours in the time period and the percent probability of that windspeed occurring as given by the Weibull density function. The sum of these values is the expected volume of water pumped for the given time period.

Some manufacturers provide a table giving values of flowrate for certain pump head values and an average wind speed. The user determines the head which the pump is working against, then locates the flowrate for this value. If the average wind speed at the site is equal to the wind speed at which the manufacturers table was developed, this number is correct. If not, the flowrate must be adjusted to make up for the deviation in average wind speed.

There is no general way to estimate pumping capabilities for wind powered water pumping units. (Paterson, 1986) The pumping capabilities can only be ascertained by actual tests and trial runs of the units in question. Using this actual test data, the pumping capacities may be calculated for any site.

Feasibility Considerations in Assessing Wind Powered Irrigation Systems

In assessing site adaptability for a wind powered irrigation system, there are more factors to consider than wind regime quality. The economics of the system must be accurately predicted. The integration of a wind power system with a particular irrigation system must also be technically feasible.

Economic Considerations

There are two basic scenarios for which the economics of a wind powered irrigation system may be evaluated. The first is the situation where irrigation pumping is currently accomplished using some non-renewable energy source. This fuel would be displaced either partially or fully by wind energy. The second scenario occurs when an irrigation system is not presently installed, and a wind powered system could to be installed to pump irrigation water. Both of these situations could occur in Montana.

The percent of the current energy bill which can be eliminated by adding wind power is a major concern to a producer. This addition could involve the complete conversion of an existing system to wind power or the use of wind energy for supplementary power.

After the wind regime at the proposed site is evaluated, the system economics may be estimated. First the energy consumed by the pumping system should be plotted versus time based on historic data (eg. past electric bills). Expected power from the wind system can then be plotted versus time. Resemblance of the plots indicates that wind power substitution may be desirable. Having the cost of power bought and using the plots of power load and gain versus time, an economic assessment of the wind system can be made. If wind power offsets existing irrigation loads it may be desirable to also have a residential heating load that can be offset during the months when irrigation is not necessary.

A situation where the economics are assessed in a slightly different manner occurs when the wind powered system is used in the initial irrigation system development. In this case the amount of water that will be provided by the wind system is estimated from the quality of the wind regime, the wind machine parameters, and the water availability. The economic considerations then involve a cost-benefit analysis with benefits based on crop yield. If the increased revenue from the crop yields is enough to offset the cost of installing and maintaining the wind system then the wind system may be considered feasible.

The quantity and combinations of variables involved in assessing the economic feasibility of a wind powered irrigation system require that all evaluations be done on a site specific basis.

The most comprehensive assessment of the economics of wind energy for irrigation pumping has been developed and is available through the U.S. Department of Energy. (Lansford et.al., 1980)

Technical Feasibility

The technical feasibility of a wind powered irrigation system must be assessed in the preliminary design of the system. Past research and experience indicates that it is definitely possible to pump water using power generated from the wind. The problem lies in adapting this technology to a complete irrigation system.

Researchers in the field of wind powered water pumping have different opinions as to the state of wind powered pumping. Some researchers are enthusiastic concerning the technology of wind powered irrigation pumping. (Clark, et al., 1980) Others say the technology could stand much improvement in the way of reliability. (Patterson, 1986) It is my feeling that the technology exists and is available at the commercial level. The problem lies in adapting this technology on a site specific basis.

CHAPTER 5

WINDMILL-RESERVOIR SYSTEM MODELS

In this chapter, four site specific scenarios are discussed. The wind powered irrigation systems utilize mechanical windmills to pump water to a storage reservoir. The stored water is then routed into an appropriate irrigation system as needed based on crop irrigation requirements.

Site Selection

The sites for the four scenarios were chosen based on several parameters. These were; topography, applicability to cropping situations, availability of water source, availability of wind data, and land ownership. (Westesen, 1986)

Wind data sites were first chosen to provide a good geographic distribution of sites. The data from the wind site also had to be statistically valid and continuous. This eliminates errors due to poor data recovery.

Having the wind data sites, topographic maps were used to locate the actual field sites. Those sites that had rough and irregular topographies or ground slopes greater than three or four percent were eliminated. From the locations that were of adequate topography, the possible sites were narrowed down to those being on public land, and within one mile from the nearest water source. State or Federal land was used for these site scenarios to eliminate the need for interaction with the owners of private land. (Westesen, 1986)

Having chosen sites according to the above procedures, those with good soil characteristics were selected as the final field sites. The soil types were determined from the Montana Soil Surveys.

Since the sites were chosen based on information taken from maps and surveys which can be vague or misleading, it is possible that the actual sites may not be suitable for a farming operation. These sites are not suggested for actual implementations of wind powered irrigation systems, but are to be used solely for the models presented herein.

Methodology

The methodology used in the site specific scenarios may be broken down into a series of design problems:

1. Irrigation System Design
2. Wind Data Analysis
3. Sizing the Windmills and Reservoir, and Determining the Number of Windmills Needed
4. Earth Moving Calculations
5. Pump Sizing (backup and booster)
6. Bill of Materials
7. Economic Analysis

Irrigation System Design

The design procedures for each site differ with the irrigation system used. In all cases, the design procedures used are those specified by the Soil Conservation Service as outlined in the National Engineering Handbook, Section 15.

The irrigation system that is used on each site is determined by the crops that are appropriate at the site, the soil characteristics and the field slope. Guidelines for irrigation system selection are available in the SCS National Engineering Handbook.

For any given irrigation system there are several parameters that are crucial to the design of the system; the appropriate crops and crop water requirements, the soil type and slope considerations and, the field shape and size. (Hulsman, 1985)

The crops selected are those that have economic potential and are compatible with the climate at the site. (Dalton 1986) Having identified these crops, the irrigation requirements were determined via a computer program that John Dalton developed. The computer program uses the SCS TR-21 (Blaney-Criddle) method with adjustments for elevation differences. The soil type at each site was determined from the Montana Soil Survey maps and data. The ground slopes were determined by measuring the contour lines on the topographic maps. In actual design cases, soil samples should be evaluated for each site and a survey of the field area should be done to more accurately determine the field slopes.

The field size used in these scenarios is 40 acres, and the field shape used was a square to simplify design procedures. These 40 acre blocks may be expanded in a modular fashion to increase the total on-site acreage. (Westesen, 1986)

Sizing mainlines, laterals and manifolds was done either on the Rainbird slide rule, using the energy equation and continuity equation, or the Hazen-Williams equation. The Rainbird slide rule is an engineering aid that uses a nomogram technique to solve the equations relevant to irrigation system design. (Hulsman, 1985)

Wind Data Analysis

The wind data for each site is from the Montana Wind Energy Atlas. If the data in the Wind Energy Atlas included the Weibull parameters for the site, these values were used. For those sites at which the Weibull parameters were not presented, they were determined using the computer program given in Appendix 1, Figure 20.

Sizing the Windmills and Reservoir

The pumping and reservoir system consists of one or more water pumping windmills, a reservoir, and the pipeline connecting the two. The reservoirs must be lined, as the subsoil at each site is assumed unsuitable for use as a reservoir lining.

The methodology used in sizing the reservoir is centered around three basic relationships: the Weibull parameters, the relationship between wind speed and flow from the windmills, and the balance equation for reservoirs. The monthly net irrigation requirements of the crop are also used in the calculations. A computer program was developed for each site to expedite the calculations.

The computer program for each site must contain site specific data. The expected precipitation and evaporation for each site may be found in NOAA Climatological Data reports. The net crop water requirements are the irrigation requirements divided by the irrigation system efficiency. The Weibull parameters for each site are also included in the data statements of each program.

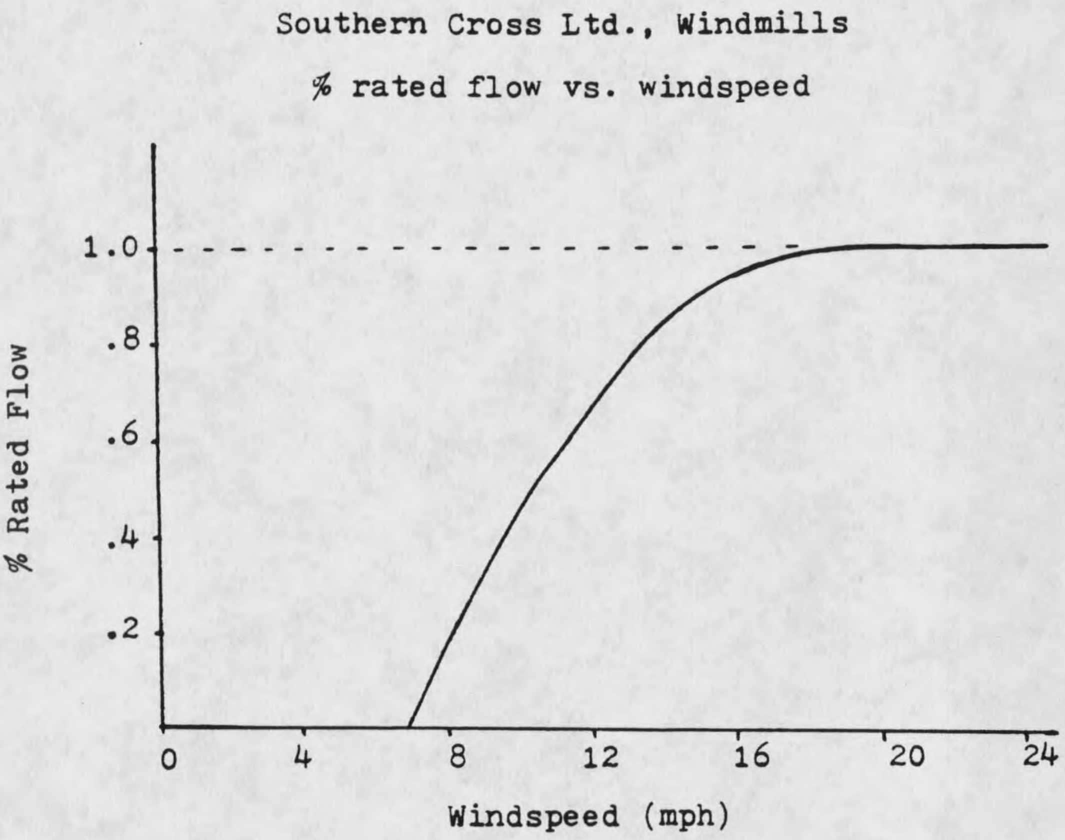
The computer program first prompts for an initial assumption of the rated flow from the windmills, and prompts for an initial reservoir surface area. The program then estimates the total monthly flow volume expected of the windmill. This is accomplished by calculating the expected frequency of each windspeed, f(ui) via the Weibull parameters. The flowrate from the windmill at that windspeed is then calculated. Then the number of hours per month is multiplied by the frequency of each windspeed and the flowrate at each windspeed. These products are then summed to provide an estimate of the total monthly flow volume from the windmills at the assumed rated flowrate.

The program then does a reservoir water balance on a monthly basis. The inflows to the reservoir are the flow from the windmill, and the precipitation at the site. The reservoir outflows are evaporation and the crop irrigation requirements. There are no seepage flows as the reservoir is to be lined. If at any time the resultant reservoir volume is less than zero, the calculations terminate and begin again using a larger rated flow from the windmills. This process is continued until the rated windmill flows are enough to maintain adequate reservoir volume throughout the irrigation season.

The relationship between windspeed and flowrates from the windmills was developed using the information provided by Southern Cross Ltd. of Australia as shown in Appendix 4, Table 27. Using this information, a regression analysis was performed to provide an accurate measure of the percent of rated flow as a function of windspeed. The resultant relationship is shown in Figure 1.

The computer program is first run, (run #1) with a preliminary estimate of the reservoir surface area. The program outputs the required rated flow that will keep the reservoir volume above zero at all times throughout the year. It is assumed that the system will be installed in the summer and is brought on-line in October. Bringing the system on-line in October reduces the pumping requirements of the windmills, because of the additional water storage during the winter months. After the system is on-line off season storage is maintained.

Figure 1. Percent of rated flow as a function of windspeed for Southern Cross Ltd., windmills.



The elevation head against which the windmills are pumping is determined from site characteristics. Thus a wind machine is chosen that has the highest flowrate and will overcome at least the elevation head, with a reasonable allowance for friction head losses in the pipeline. Having chosen the appropriate windmills, the number of windmills required may be determined. This value must be rounded up to the next whole number.

The computer program is again used (run #2) to determine the maximum volume of the water in the reservoir. The required rated flow (number of windmills multiplied by the rated windmill flowrate) and the preliminary surface area are inputs for run #2. The output for run #2 is the maximum reservoir volume. From this the approximate reservoir depth can be determined. This depth is the average depth of the reservoir. The reservoir will have side slopes, requiring a slight increase in maximum depth to hold the average depth at required levels. It is assumed that the limiting reservoir depth due to soil stability and structure is 15 feet. The required reservoir surface area may be determined by dividing the maximum reservoir volume by 15 feet. The actual construction of a reservoir should meet state approved standards and be certified by a registered engineer.

Running the program a third time (run #3) with the new surface area and actual rated flowrate as inputs, the final maximum reservoir volume may be determined from the program output.

Using this procedure, the windmill size, number of windmills, reservoir surface area, depth, and maximum volume may be determined. The reservoir dimensions are approximations that will suffice in the assessment of the feasibility of the wind powered irrigation systems. These parameters and the need for a reservoir lining medium may change given actual site surveys and soil tests.

The reservoir inlet and outlet pipe sizes are determined based on the head loss allowable for the system. The friction loss allowable for the inlet pipe is the head at which the windmills are rated minus the elevation difference and the windmill junction loss. The junction loss for the windmills in parallel is assumed to be ten feet. The reservoir outlet pipe is sized to provide the irrigation system with the required pressures and flowrates. Reservoir inlet and outlet pipes are sized with the following limitations:

1. The energy equation (Euler's equation integrated between two points, known as the Bernoulli equation) is used in conjunction with the continuity equation;

2. Minor losses are ignored;

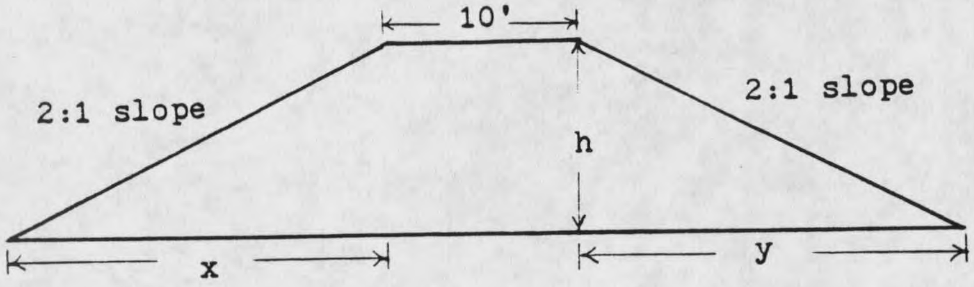
3. The friction factor is assumed to be constant at a value of 0.02. This assumption is checked by comparing the results of the analysis with those achieved using the Rainbird slide rule. In all cases the results are valid using f = 0.02.

The windmills, reservoir calculations and pipe sizing are given in the analysis of each site.

Earth Moving Calculations

Earth moving must be done to build the reservoirs. It is assumed that the reservoirs are circular, and the volume of cut will provide the fill volume for the embankments which have a 2:1 side slope. The reservoir must be lined due to the soil in the subsurface layers. The shape shown in Figure 2 is that recommended for irrigation reservoir embankments in the SCS engineering guidelines. A freeboard depth of 2 feet should be used to accommodate fluctuations in maximum volume, wind, excessive precipitation, etc.

Figure 2. Reservoir embankment shape as specified by the Soil Conservation Service.



Knowing the average reservoir depth, the height of the embankments may be determined by equating the cut volume and the fill volume. Given the embankment height, the approximate volume of earth that must be moved to construct the reservoir may be determined. This volume is an approximation only, because the average reservoir depth is used. This approximate value will yield the maximum amount of earth to be moved in constructing the reservoir. The actual volume of earth to be moved may be lessened if the site has some natural topographic relief to aid in the construction of the reservoir. The earth moving calculations are provided in the analysis of each site.

Pump Sizing

A backup pump is required for each site to be used if the wind powered system fails to operate. The backup pump used in each case is a small gasoline powered unit. The brake horsepower required is determined for each pump.

In cases where there is insufficient elevation head from the reservoir to charge the irrigation system, a small booster pump is used to increase the reservoir outlet pressure. The seasonal energy use by the booster pump is determined based on the net crop water requirements.

Bill of Materials

For each scenario there is a list of the materials and costs that are associated with the wind powered irrigation system. These are the costs that are independent of the enterprise costs of crop production.

From this bill of materials a total system cost may be determined. There are several assumptions in the bill of materials. First, it is assumed that the cost of installing the wind and irrigation system not including the reservoir is 25% of the purchase cost of the system components. This figure will vary as bids are taken for the labor to install the system. There is a miscellaneous charge of $2000 to cover those expenses that will be incurred as a result of unforeseen site conditions (eg. check valves, thrust blocks, windmill bases, etc).

From the total system cost, the yearly fixed payment may be determined. It is assumed that the system has a 15 year life and is to be financed at an interest rate of 10 percent. This yields the yearly fixed payment on the wind powered irrigation system investment.

Economic Analysis

The economic analysis was accomplished via a computer spread-sheet. (Greiman, 1986) The spreadsheet evaluates enterprise costs for various crops given the crop yield, crop market value, fixed costs and land costs. All other variables (eg. machinery, seed, labor, fertilizer, etc.) are part of the spreadsheet. For this application, the inputs were; the crop yield, the crops market value, the fixed cost per acre, and the energy costs where a booster pump is used.

The spreadsheet outputs the net profit per acre for each crop. The crop yields and market values are normally taken from the Montana Agricultural Statistics Bulletin.

The system costs are then revaluated assuming the following:

1. The reservoir is eliminated and the reservoir inlet pipe is connected to the reservoir outlet pipe.

2. The windmills are replaced with appropriately sized pumps that use a non-renewable energy source. (diesel and electric)
3. The piping and irrigation systems as designed are suitable for use with the conventional pumping plants.
4. Electricity lines 1 mile long are required where electrical pumps are used, and cost $9000/mile.

The adjusted yearly per acre costs are then determined. These costs are used to determine the economical advantage or dissadvantage of using the traditionally powered pumping units over the wind powered units.

Site 1, Jefferson River, Broadwater County

The Jefferson River site is located in South-Central Montana in the Jefferson Valley in Missouri Headwaters region as shown in Figure 28, Appendix 3. The site is roughly 10 miles South of Three Forks, MT, and is situated on the gently sloping plains that characterize this portion of the Jefferson Valley. The specific site location data is as follows:

Site Location: 45° 47.5' N 111° 40' W
Section 36, T1N, R1W
Elevation: 4200 ft
Distance from water source to reservoir: 5793 ft
Distance from reservoir to field: 1030 ft
Vertical lift to reservoir: 90 ft
Vertical drop to field from reservoir: 75 ft
Soil type: Manhattan very fine sandy loam, 40" soil profile, Class III soil
Moisture holding capacity of soil: 2.0 in/ft
Crops: Spring Grain, Potatoes, Peas and Alfalfa

The following section includes the calculations and methodology used in designing the wind powered pumping system, the reservoir for off season water storage, and the irrigation system.

The wind data for the site is from the Montana Wind Energy Atlas. The site (THREE FORKS, Broadwater County) at which the wind data was taken is roughly 13.5 miles from the field site. The wind data should adequately describe the wind regime at the field site, as the topography is roughly identical. The elevation of the wind data site is 4580 ft, and the anemometer tower height is 10 meters (32.81 ft).

The data recovery for the site is good, at 93.7%.

The Weibull parameters for the site were developed using the computer program in Appendix 1, Figure 20, and are presented in Table 2. The site had an annual average wind speed of 8.6 mph.

Table 2. Weibull parameters at the Jefferson River Site.

Month	Weibull Parameters Scale (c) mph	Shape (k)
Jan	12.0335	1.7752
Feb	10.2853	2.0567
Mar	10.7508	1.7221
Apr	11.0400	1.8757
May	9.6473	1.5579
Jun	7.1149	1.6632
Jul	10.0365	1.9073
Aug	8.1084	1.6818
Sep	8.3692	1.7032
Oct	9.7184	1.7159
Nov	9.2849	1.9824
Dec	9.3819	1.7057

Irrigation System

The irrigation system chosen for this site is a wheel line sprinkler system. The slopes at the site are too steep to use surface irrigation and only two of the four recommended crops are suitable for drip/trickle irrigation. All of the crops recommended for this site are suitable for sprinkler irrigation, and the soil intake rate is within the ranges specified for sprinkler systems.

The output from the irrigation requirement computer program runs is given in Appendix 2, Table 14. The system is designed to satisfy the peak water requirements of all four crops. The irrigation schedule would be altered for each crop to accommodate variations in weekly and seasonal water use.

Sprinkler System Design

The irrigation system design is based on the peak consumptive use of potatoes. Potatoes have the highest peak consumptive use of the four appropriate crops.

Given: Root depth = 3.33 ft.
Peak water use rate = .344 in/day.
Moisture holding capacity = 2.0 in/ft.
Infiltration rate = .75 in/hr.
Average windspeed = 8.6 mph.
Desired sprinkler spacing = 40' x 60'.
Desired time period per set = 8 hours.

The total available water using the 50% depletion rule:

TAW = 3.33 ft (2.0 in/ft)(.50) = 3.33 in.

The maximum irrigation interval:

DI = (3.33 in)/(.344 in/day) = 9.68 days

Preliminary gross application assuming a water use efficiency (Ew) of .75:

V' = 3.33 in/.75 = 4.44 in.

Preliminary application rate using 8 hours per set:

I' = 4.44 in/8 hrs = .56 in/hr.

From SCS National Engineering Handbook, Sec. 15, Ch. 11, pp. 36 and 24, and for an average windspeed of 8 mph, and an application rate of .56 in/hr:

Coefficient of uniformity (Cu) = .85
Effective portion of water applied (Re) = .97

Actual water use efficiency:

$E_w = C_u \times R_e = .85\ (.97) = .82$

Actual gross application:

$V = 3.33\ \text{in}/.82 = 4.06\ \text{in}$

Actual application rate using 8 hour sets:

$I = 4.06\ \text{in}/8\ \text{hrs} = .508\ \text{in/hr}$

(ok, less than soil intake rate)

Sprinkler discharge:

$q = I\ S_l\ S_m/96.3 = .508(40)(60)/96.3 = 12.65\ \text{gpm}$

Number of sprinklers per lateral:

$n = 1320\ \text{ft}/40\ \text{ft} = 33$

Total flowrate:

$Q = 33\ \text{sprinklers}\ (12.65\ \text{gpm/sprinkler}) = 417\ \text{gpm}$

Actual irrigation interval:

$DI = 40\ \text{ac}(4.06\ \text{in})(453)/(417\ \text{gpm})(24\ \text{hrs/day}) = 7.35\ \text{days}$

(ok, less than maximum DI)

From Rainbird slide rule:

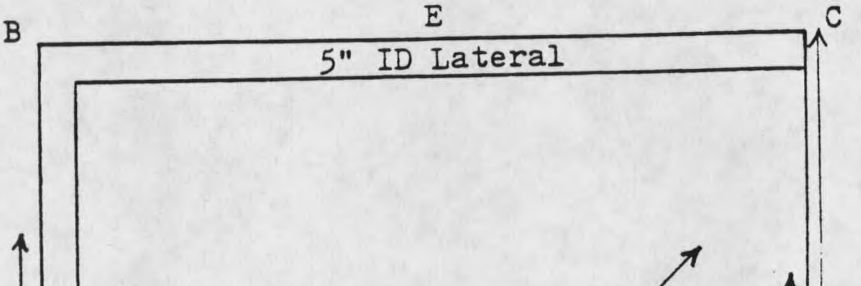
Use 3/16" x 1/8" nozzles at 68 psi nominal pressure. The required pressure is greater than that supplied by the elevation head of the reservoir. A booster pump must be used, or the reservoir will have to be moved to a point of greater elevation.

Mainline and Laterals

Since the ground slopes are uniform, pressure extremes will occur at the endpoints of the lateral and mainline. A pressure regulator (68 psi out) will be used at the midpoint of the lateral to prevent excessive pressure at the end of the lateral.

In designing the mainline and lateral the pressures are allowed to vary from 61 to 75 psi. A standard wheel line sprinkler system pipe diameter is 5 inches. The mainline and lateral configurations are shown in Figure 3. The friction losses are calculated using the Rainbird slide rule.

Figure 3. Mainline and lateral layout on field, Jefferson River site.



The pressures are calculated at the points at which the extremes occur:

Point A- water enters mainline at 68 psi.
Points B,C, and D- locations of pressure extremes.
Points E and F- locations of pressure regulator.

Checking these pressures at the points of extremes:

Point A- Source pressure = 68 psi
Pressure at point A = 68 psi (ok)

Point B- Source pressure = 68 psi
Friction loss = 22.44 psi
Elevation gain = 16.57 psi
Pressure at Point B = 62.13 psi (ok)

Point E- Source pressure = 62.13 psi
Friction loss = 6.67 psi
Elevation gain = 8 psi
Pressure at Point E = 63.46 psi (ok)

Point F- Source pressure = 68 psi
Friction loss = 6.67 psi
Elevation gain = 8 psi
Pressure at point F = 69.33 psi (ok)

Points C and D- Source pressure = 68 psi
Friction loss = 6.67 psi
Elevation gain = 8 psi
Pressure at Points C and D = 69.33 psi (ok)

Sprinkler System Specifications

The sprinkler system design calls for:

Wheel line system:
1 - traveler unit
33 - wheeled lateral line joints, 40' length, 5" dia.
33 - self leveling risers
33 - impact type sprinkler heads (3/16" x 1/8" nozzles)
1320' - 5" diameter main line, hydrants at 60' spacing

Pumping System and Reservoir

The computer program used to expedite the calculations is listed in Appendix 1, Figure 21.

Run #1:

Input: Preliminary surface area = 130680 ft^2
Preliminary rated flow = 1000 gph

Output: Required rated flow = 10460 gph
Maximum volume = 2638269 ft^3

It is known that the head that the windmills are pumping against is at least 90 feet (elevation difference from river to reservoir). Thus a wind machine is chosen that has the highest flowrate and will overcome at least 90 feet of head, with a reasonable allowance for friction head losses in the pipeline.

The proper wind machine selection is:

Southern Cross "R" Pattern, 25 ft diameter
12 in stroke, 6" diameter
2820 gph at 125 ft of head

Number of windmills:

= 10460 gph/2820 gph = 3.71 wind machines (use 4)

Actual rated flow = 4(2820 gph/windmill) = 11280 gph

Run #2

Input: Surface area = 130680 ft^2
Rated flowrate = 11280 gph

Output: Maximum volume = 2867249 ft^3

Reservoir depth = vol./area = 2867249/130680 = 21.9 ft

It is assumed that the limiting reservoir depth due to soil stability and structure is 15 feet. For an average depth of 15 ft, the required surface area is 191149 ft^2, the reservoir diameter = 493 ft. Again, these are approximations and the actual reservoir dimensions will depend on the topography of the site.

Run #3

Input: Surface area = 191149 ft^2
Rated flowrate = 11280 gph

Output: Maximum volume = 2852032 ft^3

∴ This yields a new average depth of 14.9 ft (ok).

Sizing the Reservoir Inlet Pipe

The wind machines chosen are designed to pump against 125 ft. of head. The elevation head is 90 ft. and 10 ft. of head is assumed to be lost in the junction of the four windmills. Thus, not considering minor losses, 25 ft. of head should be consumed by the friction loss of the pipe.

Using:

$$hl = (f \times L \times V^2)/(2d \times g) \text{ and } V = Q/A$$

where: L = 5793 ft
Q = .4189 cfs
g = 32.2 ft/sec
hl = 25 ft

Solving this equation for the pipe diameter yields a required pipe size of 5.5 inches (use 6" pipe). The final system sketch is presented in Figure 4.

Pumping System and Reservoir Design Summary

4 - Southern Cross "R" Pattern windmills
12" stroke, 6" diameter
2820 gph at 125 ft head

4 - Southern Cross 40 ft towers

5793 ft - 6" class 150 pvc pipe

reservoir diameter = 493 ft
reservoir surface area = 191149 ft^2 (4.39 ac)
reservoir volume = 2852032 ft^3 = 65.47 acre-ft

Backup Pumping Unit

A backup pumping unit is required in case the wind powered system fails. The backup pump to be used is a small gasoline powered unit.

Flow required = 15250 gph = .5654 cfs

Head required = 125 ft

Power = .5654 cfs(62.4 lb/ft^3)(125 ft) = 4403 ft-lb/s.

Assuming a pumping plant efficiency of 50%:

Req'd. HP = 4403/(550 ft-lb/sec/hp)*(1/.50) = 16 hp.

Backup pump required: 254 gpm at 125 ft, 16 horsepower.

A small booster pump is needed to boost the reservoir outlet pressure to 68 psi. The reservoir could be moved to a point of higher elevation, but in this case that would result in excessive expenses for additional pipe and the friction losses in that pipe. A 18 hp pump, with Q = .9292 cfs at 86 ft of head is required.

Using the net seasonal irrigation requirements to determine the seasonal energy consumption of the pump (air cooled diesel engine) yields an average energy cost for the four crops of $29.81/ac-yr.

Sizing the Reservoir Outlet Pipe

The reservoir outlet pipe is to be sized such that the necessary flow and pressure requirements for the irrigation system are maintained. This is done using the energy and continuity equations, and solving for the necessary diameter of pipe. A system sketch is presented in Figure 5.

The relevant equations are:

$$Z1 + Hp = P2 + V2^2/2g + f(L\ V^2)/2dg \text{ and } V = Q/A$$

where:

P2 = 157 ft
Q2 = .9292 cfs
Z1 = 75 ft
L = 1030 ft
Hp = 85.5 ft

An approximate solution to this equation yields a desired pipe diameter of 8 in.

Earth Moving Calculations

Earth moving must be done to build the reservoir. It is assumed that the reservoir is circular, and the volume of cut will provide the fill volume for the embankments. The reservoir must be lined due to the soil in the subsurface layers. From the dimensions given in Figure 2:

$x = 2h$
$y = 2h$

Embankment volume = $(h^2 + 10h)$(pi x diameter)

Cut volume = $(16.9-h)$(area of reservoir)

Equating the above equations and solving for h:

$h = 13.07$ ft

An embankment height of 13.07 ft yields a volume of soil to be moved of 27115 yards.

A diagram showing the major system components and parameters is presented in Figure 6.

Figure 4. Reservoir inlet pipe, Jefferson River site.

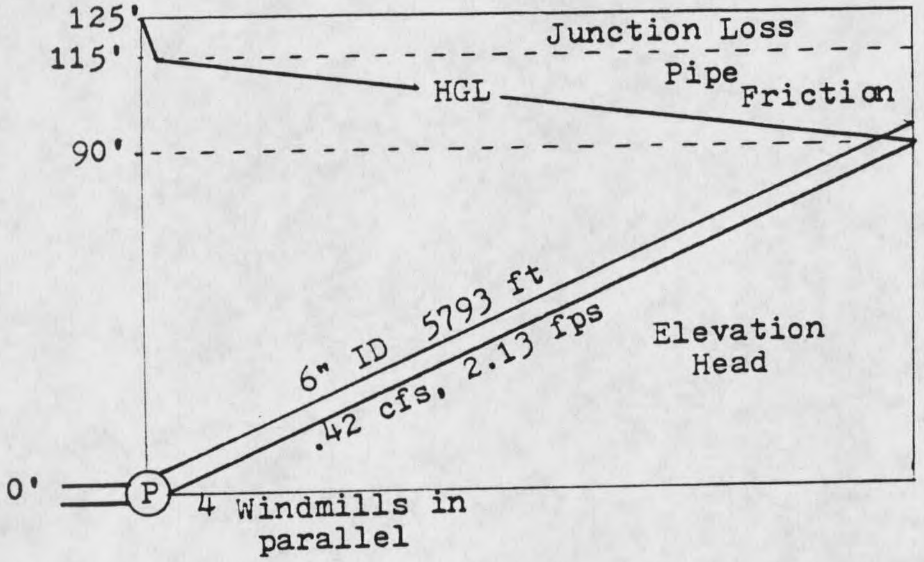


Figure 5. Reservoir outlet pipe, Jefferson River site.

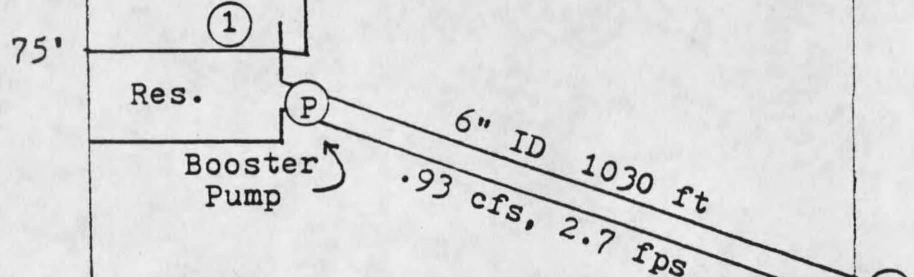
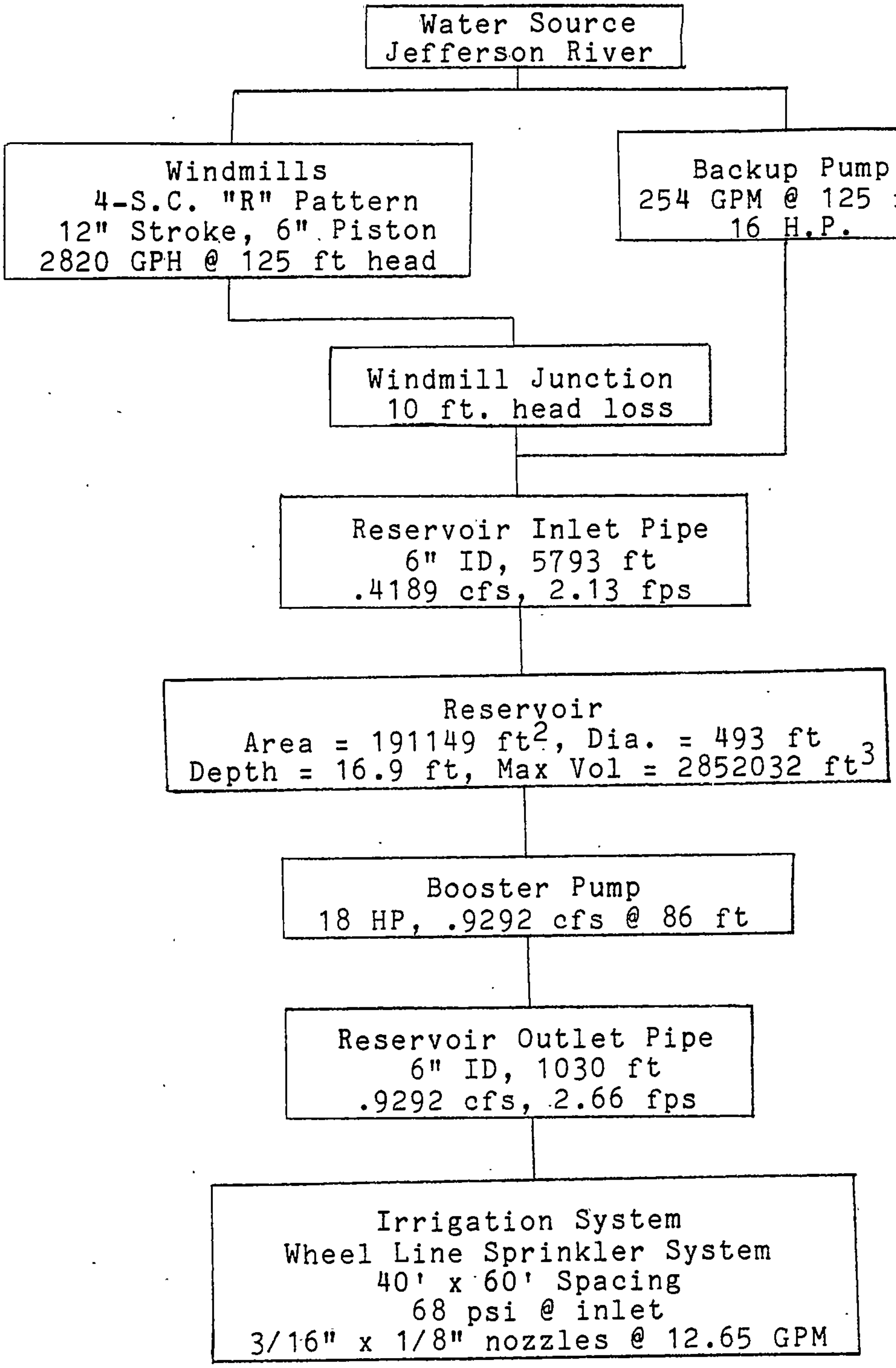


Figure 6. Major system components, Jefferson River site.



Crop Independent Costs

The following is a bill of materials for the wind powered irrigation system. These are the costs that are independent of the enterprise costs associated with crop production.

Table 3. Wind powered irrigation system capital costs at the Jefferson River site.

Qty	Description	Unit$	Tot$	% of P
	Irrigation and Wind System			
4	Windmills, Southern Cross "R" 25' dia, 12" str. 6" dia	6514	26056	24
4	Towers, 40 ft	1297	5188	5
5793 ft	6" Class 150 pvc pipe	3.73	21613	20
1030 ft	7" Class 100 pvc pipe	4.00	4120	4
1320 ft	5" main line	2.50	3300	3
33	40' wheeled lat. joints risers and sprinklers	137	4521	4
1	backup pump and fittings 16 hp, .5654 cfs @ 125 ft	1900	1900	2
1	traveler unit	2000	2000	2
1	pressure reg. 5" dia, 60-90 psi in, 68 psi out	300	300	~
1	8" gate valve	160	160	~
1	6" gate valve	120	120	~
1	water funnel and trash hood	50	50	~
1	Booster pump 18 hp, .9292 cfs @ 89 ft	2100	2100	2
~	miscellaneous expenses	2000	2000	2
	installation cost at 25% of system cost		18356	17
	Reservoir			
16283 yd	earth moving for reservoir	.70	11906	11
95.5 tons	bentonite lining (1 lb/sq ft)	58	5543	5
	P = Total system costs =		$ 109233	

Assuming that the capital expenses are to be financed for 15 years (n) at an interest rate of 10% (i), the yearly payment is:

$$Yp = P \frac{i(1+i)^n}{(1+i)^n - 1} = P(.1315) = \$14364/\text{year or } \$359.1/\text{ac-yr}$$

Economic Analysis

For this application, the inputs to the economic analysis spreadsheet are:

Alfalfa: Yield = 5 tons/acre (Greiman, 1986)
Market Value = $60/ton

Peas: Yield = 16.36 cwt/acre
Market value = $16.9/cwt

Sp. Grain: Yield = 64.15 bu/acre
Market value = $3.83/bu

Potatoes: Yield = 250 cwt/acre
Market value = $7.85/cwt

Fixed cost: $359.1/ac-yr

Energy cost: $29.81/ac-yr

The spreadsheet outputs the net profit per acre for each crop. The output from the program is presented in Table 4. (Greiman, 1986)

The system costs are now determined assuming a non-renewable energy source is to be used.

With a diesel powered pump:

Pump Requirements: TDH = 246 ft
flow = .92 cfs

$$H.P. = 246\text{ ft}(.92\text{ cfs})(62.4\text{ lb/ft}^3)/.5(550\text{ ft-lb/sec/hp})$$

$$H.P. = 52\text{ horsepower}$$

The average fuel cost based on the number of hours that the pump must be run to satisfy the net irrigation requirements is $86.12/acre-yr. The estimated cost of the pumping plant is $6000. The new yearly payment using the diesel pump is $193/acre-yr. This translates into a benefit of $80/acre-yr if the diesel pump is used instead of the wind powered system. Using the same methodology, an electrical pump would save $118/ac-yr.

Table 4. Economic analysis spreadsheet output for the Jefferson River site.

	Profit (loss)	Break even price @ yield	Break even yield @ price
Alfalfa	$(258)/ac	$112/ton	9.3 ton/ac
Spr. Grain	$(267)/ac	$7.98/bu	133.8 bu/ac
Peas	$(421)/ac	$42.65/cwt	41.3 cwt/ac
Potatoes	$ 646 /ac	$5.27/cwt	167.7 cwt/ac

Results

As seen in Table 4, the only crop that produces a positive net yearly return at this site is potatoes. This seems optimistic, but potatoes should not be grown more than once every three to four years to prevent diseases. The break even price at the expected yield for potatoes is $5.27/cwt, and the market value of potatoes has been known to fall below this level. Even if the potatoes are grown in a four year rotation with the other crops, and the market value of potatoes holds, the net yearly return will be negative if the wind powered irrigation system is used.

The use of a diesel pump would save $80/ac-yr and an electrical pump would save $118/ac-yr. Even though the traditional systems are not desirable at this site, the wind powered system is less desirable. Based on this, the wind powered irrigation system as designed is not recommended at this site.

Site 2, Milk River, Blaine County

The Milk River site is in the North-Central section of Montana as shown in Figure 29, Appendix 3. The site is roughly 12 miles West of the town of Dodson. Rolling plains characterize the topography in this section of the state. The site specific location data is as follows:

Site Location: 46° 18' 30" N 106° 32' 20" W
Section 36, T32N, R24E
Elevation: 2380 ft
Distance from water source to reservoir: 3760 ft
Vertical lift to reservoir: 75 ft
Vertical drop to field from reservoir: 5 ft
Soil type: clay loam, deep profile
Class II soil Intake Family 1.0
Moisture holding capacity of soil: 1.4 in/ft
Crops: Sunflower, Alfalfa, Winter Wheat, Spring Grain

The following section includes the calculations and methodology used in designing the wind powered pumping system, the reservoir for off season water storage, and the irrigation system.

The wind data for the site is from the Montana Wind Energy Atlas. The site (GLASGOW NWS AIRPORT Valley County) at which the wind data was taken is roughly 60 miles from the field site. The wind data may not exactly describe the field site conditions, but this is the closest source of reliable data. The elevation of the wind data site is 2280 ft, with an anemometer height of 6.1 meters (20 ft). The wind data is the result of a ten year compilation.

The Weibull parameters for the site are those reported in the Montana Wind Energy Atlas. These parameters are listed in Table 5. The site had an annual average windspeed of 11.6 mph.

Table 5. Weibull parameters at the Milk River Site.

Month	Weibull Parameters Scale (c) m/sec	Shape (k)
Jan	5.6660	1.9680
Feb	6.6380	2.6350
Mar	6.2470	2.1430
Apr	6.9250	2.3220
May	6.4370	2.2040
Jun	6.6400	3.0260
Jul	6.5940	3.1830
Aug	6.3260	3.2680
Sep	6.6630	3.1570
Oct	6.7230	3.0130
Nov	6.3180	2.6950
Dec	6.1650	2.8210

Irrigation System

The irrigation system chosen for this site is a surface flow graded border system. The slopes and soil types are such that a graded border system is applicable. The crops appropriate for this site are not well suited for a drip/trickle irrigation system.

The output from the computer program that calculates crop irrigation requirements is given in Appendix 2, Table 15. The irrigation system is designed to satisfy the peak water requirements of the crops. The irrigation schedule would be altered for each crop to accommodate variations in weekly and seasonal water use.

Graded Border System Design

The irrigation system is designed based on the peak consumptive use of Alfalfa.

Given:

Soil Intake Family: 1.0
Border Slope: 1.7 % (So)
Manning Roughness Coefficient: .15 (n)
Estimated Application Efficiency: 60% (E)
Soil Moisture Holding Capacity: 1.4 in/ft
Border Strip Length: 660 ft (L)
Border Strip Width: 40 ft (W)
Crop: Alfalfa (5.0 ft root depth)

Net moisture to be replaced per irrigation (Fn):

$$Fn = .5(5.0\ ft)(1.4\ in/ft) = 3.5\ in$$

Peak irrigation requirement (Ip):

$$Ip = .277\ in/day$$

Minimum irrigation interval (Days):

$$Days = 3.5\ in/(.277\ in/day) = 12.6\ days$$

Opportunity time (Tn):

$$Tn = ((Fn-c)/a)^{1/b}$$

For an intake family of 1.0: a = .0701
b = .785
c = .275

$$Tn = ((3.50-.275)/.0701)^{1/.785} = 131\ minutes$$

Unit stream size (Qu):

$$Qu = \frac{L\ (Fn)}{7.2(Tn-Tl)E} \qquad \text{assuming recession lag} = 0:$$

$$Qu = \frac{660\ ft(3.50\ in)}{7.2(168\ min)\ (60)} = .0408\ cfs/ft$$

Having this stream size, the assumption that the recession lag time (Tl) is zero must be verified.

Verifying Tl = 0:

$$Tl = \frac{Qu^{0.2}}{120(1.486/n)^{1.2}\ (So)^{1.6}}$$

$$Tl = \frac{.0408^{0.2}}{120(1.486/.15)^{1.2}(.017)^{1.6}}$$

$$Tl = .5205/(120)(15.67)(.0015) = .19 \text{ min} \sim 0 \text{ (ok)}$$

Maximum non-erosive stream size (Qumax):

$$Qumax = .0019(So)^{-.75} = .0019(.017)^{-.75}$$

$$Qumax = .0404 \text{ cfs/ft (ok, since } Qumax \sim Qu)$$

Decreased flow due to use of end blocks: (Que):

$$Que = \frac{Qu}{1 + (1-E/100)ri(rn)}$$

where: $ri = .7$, $rn = .75$

$$Que = \frac{.0408}{1 + .4(.7)(.75)} = .0337 \text{ cfs/ft}$$

Total flowrate per border (Qt):

$$Qt = 40 \text{ ft } (.0337 \text{ cfs/ft}) = 1.349 \text{ cfs } (567 \text{ gpm})$$

Total irrigation time (Tt) for 40 acres:

Tt = 66 borders(131 min/border) = 8646 min = 6.0 days

(ok, Tt < Days)

The field layout, dimensions, and distribution system are shown in Figure 7.

Pipe Sizing

The irrigation water is to be distributed via underground pipe with one alfalfa valve per border. The pressure requirement is that 2 ft of pressure head will be available at the last alfalfa valve on each of the two lines. Using the points as labeled in Figure 8, the relevant equations are:

assume $f = .02$ and ignore minor losses

Point 1 to point 2 :

$$Z1 = P2+Z2+f(L\ V2^2)/(2dg) \text{ and } V2 = V3 = V4 = Q/A$$

where: $Z1 = 100$ ft, $Z2 = 95$ ft
$P2 = 2$ ft
$Q = 1.349$ cfs
$L = 1635$ ft

Solving for pipe diameter (d1): d1 = 10.17", use 10" pipe.

Pressure at point 3 :

$$Z1 = P3 + Z3 + f(L\ V3^2)/(2dg)$$

where: $Z1 = 100$ ft, $Z3 = 95$ ft
$V3 = 2.347$ ft/sec
$L = 315$ ft

Solving for pressure at point 3 (P3): P3 = 4.28 ft

Point 3 to point 4 :

$$P3 + Z3 = P4 + Z4 + f(L\ V4^2)/(2dg)$$

where: $P3 = 4.28$ ft, $P4 = 2$ ft
$Z3 = 95$ ft, $Z4 = 84$ ft
$L = 1980$ ft

Solving for pipe diameter (d2): d2 = 7.8 in, use 8 in pipe.

Graded Border System Specifications

The irrigation system calls for:

40 ft border width
660 ft border length
1635 ft 10 in irrigation pipe
1980 ft 8 in irrigation pipe
33 10 in alfalfa valves
33 8 in alfalfa valves
1.349 cfs flow rate

Figure 7. Field layout, dimensions and pipe placing, Milk River site.

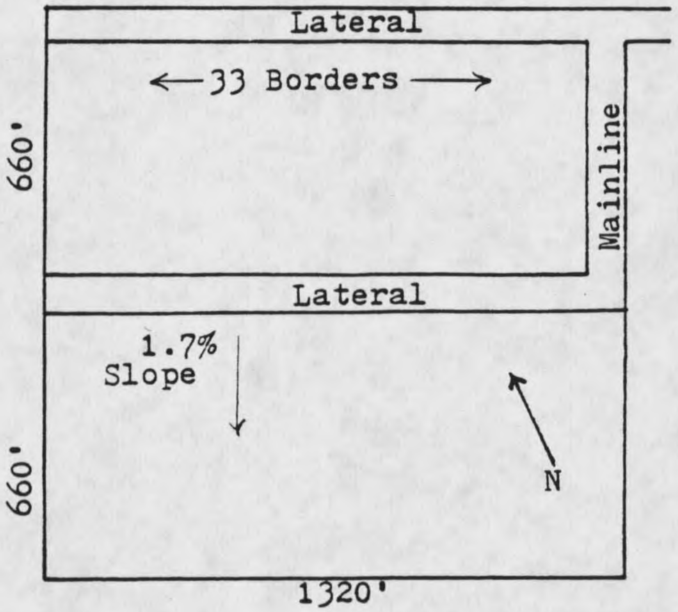
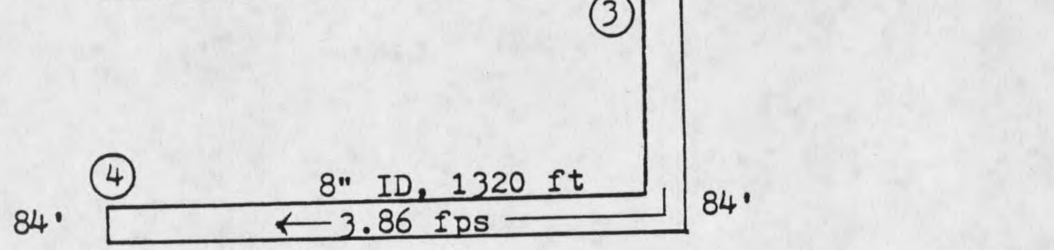


Figure 8. Pipe sizing diagram, Milk River site.



Pumping System and Reservoir

The data statements in the computer program shown in Figure 22, Appendix 1 have been altered to reflect the conditions at this site.

Run #1

Input: Preliminary reservoir surface area = 100,000 ft^2
Initial rated flowrate = 1000 gph

Output: Required rated flow = 6600 gph
Maximum volume = 2983054 ft^3

Choosing the windmill with the largest flowrate that will satisfy the elevation head requirements with an allowance for friction losses, the appropriate choice is:

Southern Cross "R" machine, 25 ft dia.
2820 gph at 125 ft head
12 inch stroke, 6 inch dia.

Number of windmills:

= 6600 gph/2820 gph/machine = 2.34 machines (use 3)

Actual rated flowrate = 3 (2820 gph) = 8460 gph

Run #2

Input: Surface area = 100,000 ft^2
Rated flowrate = 8460 gph

Output: Maximum volume = 3851692 ft^3

The resultant reservoir depth = 38.52 ft. Restricting the reservoir depth to 15 ft, the required surface area is 256780 ft^2 with a diameter of 572 ft.

Run #3

Input: Surface area = 256780 ft^2
Rated flowrate = 8460 gph

Output: Maximum volume = 3860052 ft^3

This yields a new average depth of 15 ft (ok).

Sizing the Reservoir Delivery Pipe

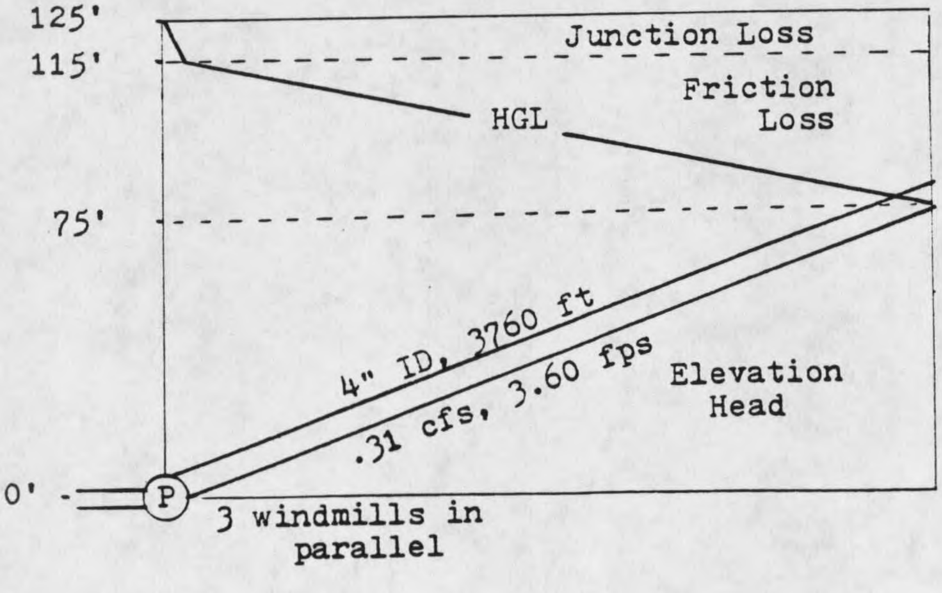
The windmills will produce the rated flowrate at 125 ft of head. The machines are pumping against 75 ft of elevation head and it is assumed that 10 ft of head is lost in the junction of the three pumps. Thus, the pipe should be sized such that 40 ft of head is allowed for friction loss. With reference to Figure 9, the simplified energy equation is:

$hl = f(L\ V^2)/2dg$

where: $f = .02$, $L = 3760$ ft
$Q = .3142$ cfs, $hl = 40$ ft

Solving for the pipe diameter, the required diameter is 4.1 in, so 4 inch pipe should be used.

Figure 9. Reservoir inlet pipe, Milk River site.



Earth Moving Calculations

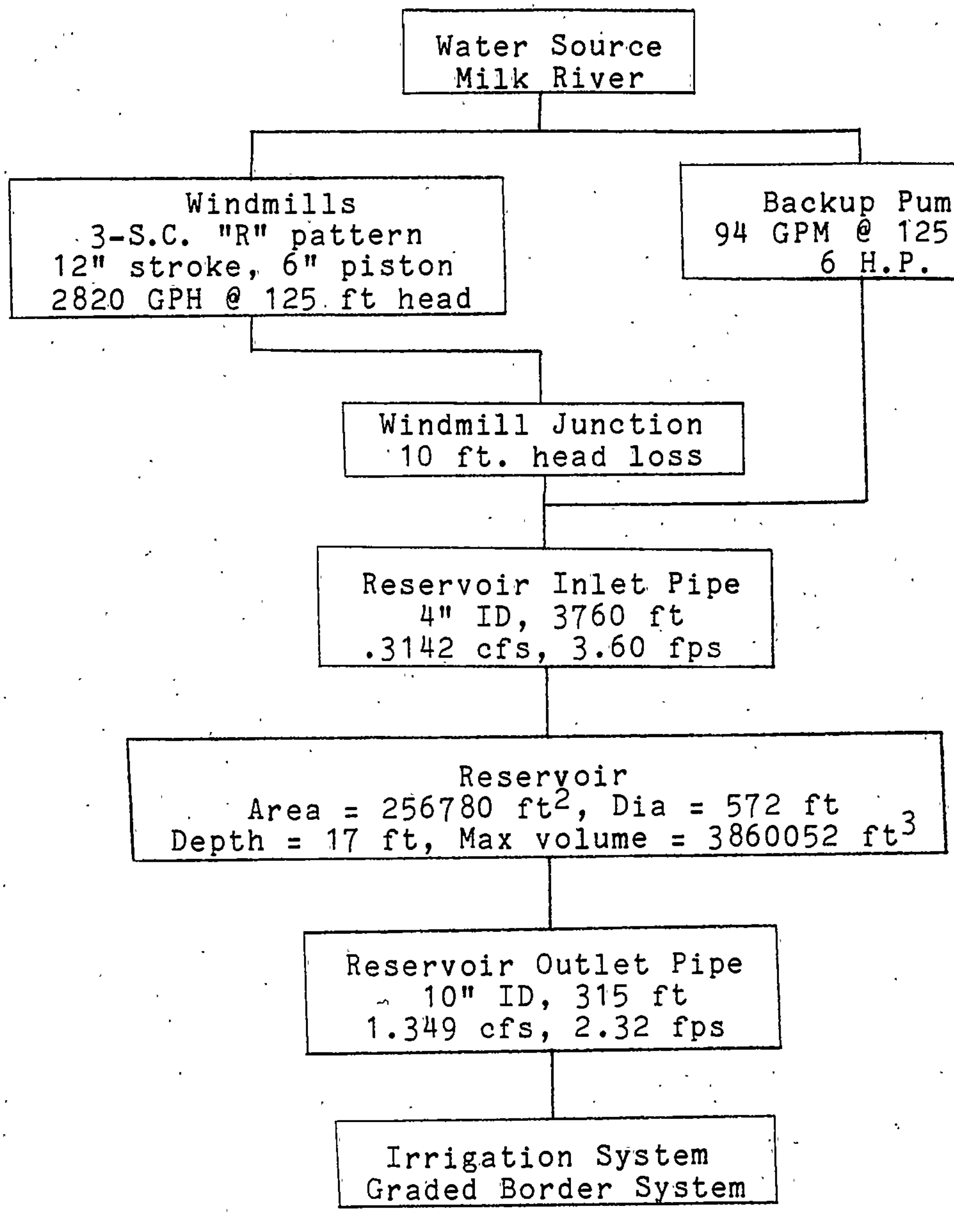
Earth moving will have to be done to construct the water storage reservoir. It is assumed that the cut volume will satisfy the volume needed to construct the earth embankment. Two feet of freeboard is used to prevent spillage in the event of over filling the reservoir. The embankment shape used in Figure 2 is appropriate. Equating the cut volume and fill volume and solving for the height of the embankment yields an embankment height of 13.77 ft. The volume of earth that must be move in the process of creating the reservoir is 30178 cubic yards.

Backup Pump

A backup pump is required in case the wind powered system fails. Using a small gasoline engine, the required backup pump is: 6 hp pump, 5640 gph at 125 ft of head.

A diagram showing the major system components and parameters is presented in Figure 10.

Figure 10. Major system components, Milk River site.



Crop Independent Costs

The following is a bill of materials for the wind powered irrigation system. These are the costs that are independent of the enterprise costs associated with crop production.

Table 6. Wind powered irrigation system capital costs at the Milk River site.

Qty	Description	Unit$	Tot$	% of P
	Irrigation and Wind System			
3	Windmills, S.C. 25 ft dia "R" 12" str., 6" dia	6514	19542	22
3	40' windmill towers	1297	3891	4
5640 ft	class 150 pvc pipe 4"	2.28	12859	14
1635 ft	irrigation pipe 10"	2.20	3597	4
1980 ft	irrigation pipe 8"	1.76	3484	4
33	alfalfa valves 8"	60	1980	2
33	alfalfa valves 10"	75	2475	3
1	gate valve 10"	200	200	~
1	backup pump 6 hp, 94 gpm @ 125 ft head	750	750	~
1	water funnel & trash hood	50	50	~
	misc.		2000	2
	installation cost @ 25% of system cost		12707	14
	Reservoir			
30718 yd	Earth moving	.70	21502	24
85.89 ton	bentonite @ 1lb/sq ft	58	4982	6
	P = Total system cost =		90019	

Assuming that the above capital is to be financed for 15 years at an interest rate of 10%:

Yearly payment:

Yp = P(.1315) = $11837/yr = $295.9/acre-yr.

Economic Analysis

The spreadsheet inputs for this site are:

Alfalfa: Yield = 5 ton/acre
Market value = $60/ton

Sunflower: Yield = 29.08 cwt/acre
Market value = $6.48/cwt (National Sunflower Assn., 1986)

Winter Wheat: Yield = 55 bu/acre
Market value = $3.77/bu

Spring Grain: Yield = 55 bu/acre
Market value = $3.77/bu

Fixed cost: $295.9/ac-yr

The spreadsheet outputs the net profit per acre for each crop. The output from the program on a yearly basis for 40 acres is presented in Table 7. (Greiman, 1986)

The system costs are now determined assuming a non-renewable energy source is to be used.

With a diesel powered pump:

Pump requirements: TDH = 116 ft
flow = 1.349 cfs

H.P = 36 horsepower

The average fuel cost based on the number of hours that the pump must be run to satisfy the net irrigation requirements is $38.27/ac-yr. The estimated cost of the pumping plant is $4100. The new yearly payment using the diesel pump is $113/ac-yr. This translates into a benefit of $145/ac-yr if the diesel pump is used instead of the wind powered system. Using the same methodology, an electric pump would save $140/ac-yr.

Table 7. Economic analysis spreadsheet output for the Milk River site.

	Profit (loss)	Break even price @ yield	Break even yield @ price
Alfalfa	$(164)/ac	$93/ton	7.7 ton/ac
Sp. Grain	$(206)/ac	$7.52/bu	109.7 bu/ac
Winter Wheat	$(206)/ac	$7.52/bu	109.7 bu/ac
Sunflower	$(244)/ac	$14.87/cwt	66.8 cwt/ac

Results

As seen in Table 7, all the crops at this site had a negative net yearly return. The use of a diesel pump would save $145/ac-yr and an electric pump would save $140/ac-yr. Even though the traditional systems are not desirable at this site, the traditional systems are much more cost effective than the wind powered system as designed.

Site 3. Yellowstone River, Rosebud County

The Yellowstone River site is in the South-Eastern portion of Montana as shown on the map labeled Figure 30 in Appendix 3. The site is roughly 2 miles West of Rosebud, MT. The site is in the relatively flat plains that characterize the Yellowstone River basin. The site specific location data is as follows:

Site Location: 46° 18' 58" N 106° 32' 30" W
Section 36, T7N, R41E 40 acres
Elevation: 2520 ft
Distance from water source to reservoir: 4290 ft
Vertical lift to reservoir: 45 ft
Vertical drop to field from reservoir: 5 ft
Soil type: clay loam, well drained, Class II soil
Moisture holding capacity of soil: 1.00 in/ft
Crops: Sugar Beets, Corn Silage and Dry Beans

The following section includes the calculations and methodology used in designing the wind powered pumping system, the reservoir for off season water storage, and the irrigation system.

The wind data for the site is from the Montana Wind Energy Atlas. The site (MILES CITY FAA AIRPORT, Custer County) at which the wind data was taken is roughly 35 miles from the field site. The elevation of the wind data site was 2631 ft, and the anemometer height was 12.2 meters (40 ft). The data reported is the result of a 15 year compilation. The wind data should adequately describe the conditions at the site.

The Weibull parameters for the site were developed using the computer program presented in Figure 20, Appendix 1, and are presented in Table 8. The site had an annual average windspeed of 11.1 mph.

Table 8. Weibull parameters at the Yellowstone River site.

	Weibull Parameters	
Month	Scale (c) m/sec	Shape (k)
Jan	5.5802	1.5902
Feb	5.5938	1.6024
Mar	6.0120	1.6027
Apr	6.4164	1.7234
May	6.2187	1.7448
Jun	5.6613	1.7021
Jul	5.9878	1.5525
Aug	5.4299	1.5167
Sep	5.6096	1.5684
Oct	5.4475	1.5784
Nov	5.4908	1.5013
Dec	5.5355	1.5660

Irrigation System

The irrigation system chosen for this site is a drip/trickle above ground system. The soil type, crops and topography are all suited for drip irrigation.

The irrigation requirements are given in Table 16, Appendix 2. The system is designed to be used with all three crops, with adjustments in the irrigation schedule to accommodate variations in weekly and seasonal water use.

Drip Irrigation System Design

The irrigation system design is based on the peak consumptive use of dry beans.

Given:
Field slope: .66%
Estimated application efficiency: 100%
Soil moisture holding capacity: 1.0 in/ft
Dripperline length: 440 ft
Manifold length: 660 ft

Based on cost considerations, adaptability to 440 ft rows, and installation and retrieval ease, the dripperline choice is:

TYPHOON Dripperline by Netafim Irrigation Inc.

The supporting technical and cost data for the dripperline is supplied in Appendix 4, Figures 32 and 33, and Table 26.

Per row calculations:

Peak ET = .34 in/day

Wetted area per row = 36"(440 ft) = 1320 ft^2

Peak water use = 1320 ft^2 (.34 in/day)(1ft/12 in)

Peak water use = 37.4 ft^3/row-day

At 7.5 psi:

Qd = .33 gal/emt-hr(1 emt/2 ft)(440 ft) = 72.6 gal/hr

Qd = 9.71 ft^3/hr

Peak use = 37.4 ft^3/row-day = 279.7 gal/row-day

Peak use = 1.27 gal/emt-day

Hours per set = Peak use/Qd = 3.85 hrs/day

(ok, 6 sets may be irrigated daily)

Lateral Calculations

Head gain due to slope:

Hg = .0066(440 ft) = 2.904 ft = 1.26 psi

Head loss due to friction:

$Hl = 1.5$ psi

Net pressure at end of lateral:

$Hn = 7.5 + 1.26 - 1.5 = 7.26$ psi

(ok, variation less than 10% of inlet pressure)

Manifold Calculations

Maximum flowrate in manifolds:

$Qm = 158$ rows(9.71 ft^3/hr-row) = 1538 ft^3/hr

$Qm = 3.43$ gpm = .4272 cfs

Allowable head loss:

$Ha = 7.5$ psi(.05) = .375 psi

Using the Hazen-Williams equation:

$$Ha = F\ K\ (L/100)\ (Q/C)^{1.852}\ D^{-4.87}$$

where:

F = .347 for greater than 100 outlets
K = 473 for english units
L = pipe length (660 ft)
Q = flowrate at pipe inlet (.4272 cfs)
Ha = allowable head loss (.4 ft)
C = roughness coefficient (150)
D = pipe diameter

Solving for pipe diameter yields a diameter of 5.5 inches.

(Use 6" manifold lines)

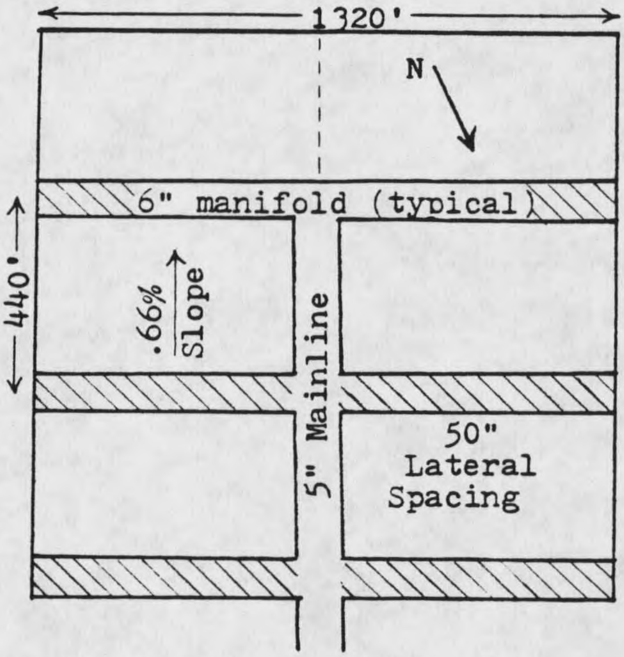
Main Line Calculations

For constant pressure in main lines, equate friction loss to elevation gain:

$L\ (\text{slope}) = f(L\ V^2)/2dg$ and $V = Q/A$

Solving for pipe diameter yields a required pipe size of 5 inches. A final sketch of the system and dimensions is presented in Figure 11.

Figure 11. Drip system layout at Yellowstone River site.



Booster Pump

Since there is only 5 ft of elevation drop from the reservoir to the inlet of the drip system, a small booster pump is required to bring the inlet pressure up to 7.5 psi.

For a flowrate of .4242 cfs at 20 ft of head, a 1.25 hp pump is required. The estimated average yearly fuel cost for the booster pump (gasoline engine) is $4.12/ac-yr.

Reservoir and Pumping System

The data statements in the computer program shown in Appendix 1, Figure 23 have been altered to reflect the conditions at this site.

Run #1

Input: Preliminary reservoir surface area = 100,000 ft^2
Initial rated flowrate = 1000 gph

Output: Required rated flowrate = 7030 gph
Maximum volume = 2024659 ft^3

Choosing the windmill with the largest flowrate that will overcome the elevation head requirement with a reasonable allowance for friction losses, the appropriate choice is:

Southern Cross "R" machine, 25 ft dia.
9 1/2" Stroke, 8" diameter piston
3970 gph @ 87 ft of head

Number of windmills:

= 7030 gph/3970 gph/windmill = 1.77 windmills (use 2)

Actual rated flow = 2 (3970) = 7940 gph

Run #2

Input: Surface area = 100,000 ft^2
Rated flowrate = 7940 gph

Output: Maximum volume = 2537511 ft^3

The resultant reservoir depth is 25.37 ft. Restricting the reservoir depth to 15 ft, the required surface area is 169167 ft^2, with a diameter of 464 ft.

Run #3

Input: Surface area = 169167 ft^2
Rated flowrate = 7940 gph

Output: Maximum volume = 2505983 ft^3

This yields a new average depth of 14.81 ft, which is an approximation that depends greatly on the sites actual topography.

Sizing the Reservoir Inlet Pipe

Following the diagram in Figure 12:

Allowable head loss = 33 ft.

$33 = f(L\ V^2)/(2dg)$ and $V = Q/A$

Solving for pipe diameter yields a required diameter of 5 inches.

Sizing the Reservoir Outlet Pipe

Following the diagram in Figure 13:

Allowable head loss = 6.76 ft

$6.76 = f(L\ V^2)/(2dg)$ and $V = Q/A$

Solving for the necessary pipe diameter, the required pipe size is 5 inch pipe.

Earth Moving Calculations

Earth moving must be done to construct the reservoir. The embankment shape shown in Figure 2 is appropriate. Equating the cut volume to the fill volume and solving for the height of the embankment yields a height of 14.81 feet. Two feet of freeboard is recommended. The required volume of soil to be moved is 24811 yards.

Backup Pump

A small backup pump is necessary in the event that the windmills are not able to operate. For a flowrate of .2949 cfs against 88 ft of head the required pump size is 6 hp.

A diagram showing the major system components and parameters is presented in Figure 14.

Figure 12. Reservoir inlet pipe, Yellowstone River site.

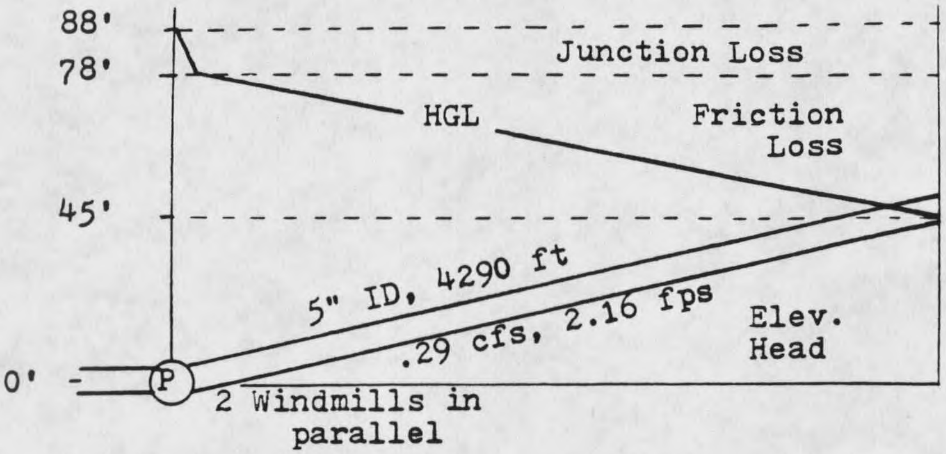


Figure 13. Reservoir outlet pipe, Yellowstone River site.

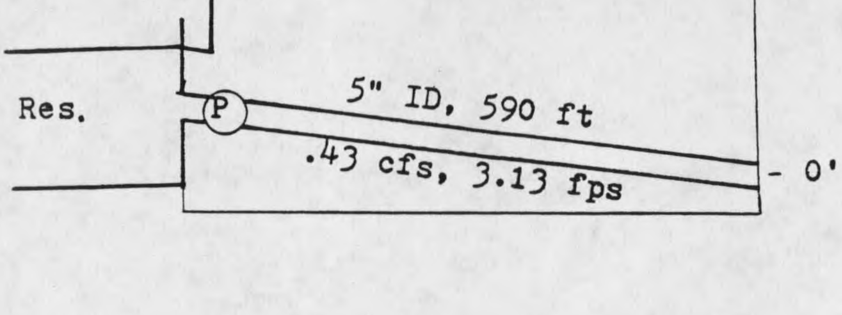
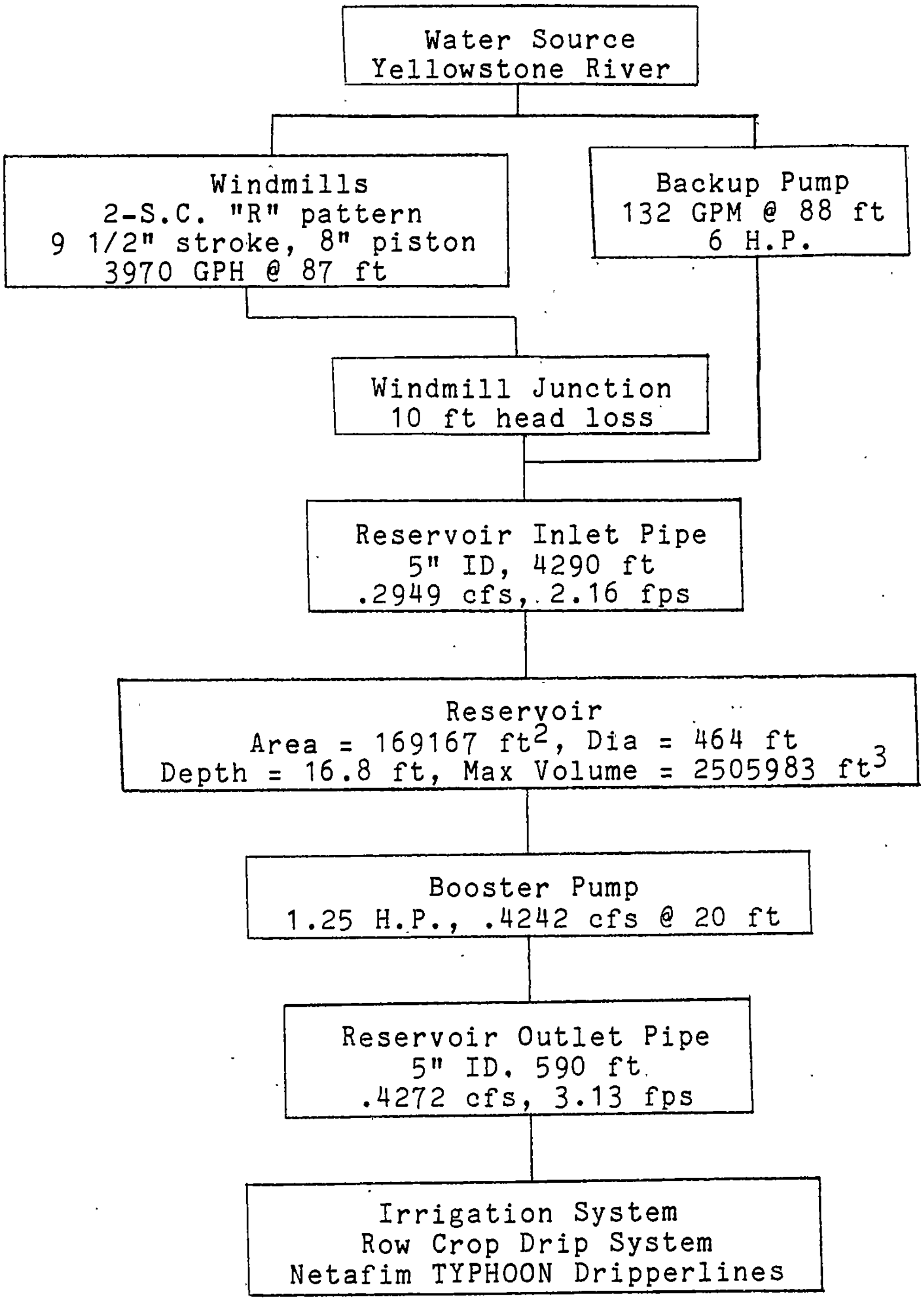


Figure 14. Major system components, Yellowstone River Site.



Crop Independent Costs

The following is a bill of materials for the wind powered irrigation system. These are the costs that are independent of the enterprise costs associated with crop production.

Table 9. Wind powered irrigation system capital costs, Yellowstone River site.

Qty	Description	Unit$	Tot$	% of P
	Irrigation and Wind System			
2	Windmills, S.C. 25'dia "R" 9.5"str, 8" dia	6514	13028	12
2	40 ft windmill towers	1297	2594	2
4290 ft	Class 150 pvc pipe 5"	3.11	13346	12
590 ft	Class 100 pvc pipe 5"	2.50	1475	1
79.2 mi	Netafim TYPHOON Dripperline	252.8	20022	18
948	Manifold connectors	0.53	502	~
880 ft	Mainline pipe 5"	2.50	2200	2
3960 ft	Manifold pipe 6"	3.00	11880	11
1	Backup pump, 6 hp	750	750	1
1	Booster pump, 1.25 hp	250	250	~
6	Time operated valves 5 1/2"	220	1320	1
1	Gate valve 6"	120	120	~
1	Dripperline install. equip.	3000	3000	3
1	Water funnel & trash hood	50	50	~
	Miscellaneous		2000	2
	Installation @ 25%		18134	16
	Reservoir			
84.58 ton	Bentonite (1 lb/sq ft)	58	4906	4
24811 yd	Earth moving	.70	17367	15
	P = Total system cost =		112944	

Assuming that the above capital is to be financed for 15 years at 10% interest:

Yearly payment:

Yp = P(.1315) = $14852/year = $371.3/acre-yr

Economic Analysis

The economical analysis spreadsheet inputs for this site are:

Sugar beets: Yield = 23.2 tons/acre
Market value = $42.15/ton

Corn (silage): Yield = 18 tons/acre
Market value = $22/ton

Dry beans: Yield = 15.75 cwt/acre
Market value = $16.90/cwt

Fixed cost: $371.3/ac-yr

Energy cost: $4.12/ac-yr

The spreadsheet outputs the net profit per acre for each crop. The output from the program on a yearly basis for 40 acres is presented in Table 10. (Greiman, 1986)

The system costs are now determined assuming a non-renewable energy source is to be used. A 11 horsepower diesel pump is required. The average fuel costs based on the number of hours that the pump must be run in order to satisfy the net irrigation requirements is $24.51/ac-yr. The estimated cost of the pumping plant is $1265. The new yearly payment using the diesel pump is $239/ac-yr. This translates into a benefit of $108/ac-yr if the diesel pump is used instead of the wind powered system. Using the same methodology, and electric pump would save $96/ac-yr.

For each crop at this site, the net yearly return is negative with the exception of sugar beets. The projected return on the sugar beets is $40/acre, and the break even price is $40.42/ton at the expected yield. The market value of sugar beets is not very stable, thus the risk is high that the return on sugar beets will be negative in an actual cropping situation. The possibilities of crop rotation are nil, given the poor return on the other two crops. The economic feasibility of the wind powered irrigation system at this site is questionable as designed. The system would be profitable if a conventional pumping system were used.

Table 10. Economic analysis spreadsheet output for the Yellowstone River site.

	Profit (loss)	Break even price @ yield	Break even yield @ price
Silage corn	$(324)/ac	$40/ton	32.7 ton/ac
Sugar Beets	$ 40 /ac	$40.42/ton	22.2 ton/ac
Dry Beans	$(411)/ac	$43.05/cwt	40.1 cwt/ac

Site 3. Revaluation with Furrow Irrigation System

The site conditions at the Yellowstone River site make it suitable for furrow irrigation. This may enhance the economics of a wind powered irrigation system at the site, as the system cost for a furrow irrigation system is less than that for a drip system.

The methodology used in this revaluation is identical to that used in the drip system analysis at this site, with the exception of the irrigation system design procedures.

Irrigation System

The irrigation system is designed using the methods suggested in the SCS National Engineering Handbook.

Given: Intake family = .5
Net depth per irrigation = 1 in.
Furrow length = 1320 ft
Furrow slope = .0066 ft/ft
Furrow spacing = 4.17 ft
Roughness coefficient = .04
Intake family parameters: a = .0471, b = .7475
c = 26.1436, d = 1.235E-03

Results: Furrow flowrate = 12.5 gpm/furrow
Application time = 495 minutes/set
Runoff = .35 in.
Deep percolation = .45 in
Application Efficiency = 55%

The irrigation system requires a total flowrate of 494 gpm/set for 8 sets at 495 minutes each. Ten inch gated pipe is required with outlets on 4.17 inch centers.

Windmill and Reservoir System

The following are the results of the analysis concerning the parameters of the wind powered irrigation system. The methodology used in determining these parameters is identical to those used in the analysis of the drip/trickle system.

Windmills 4 - S.C. "R" machines, 25 ft dia
9 1/2" stroke, 8" piston diameter
3970 gph at 87 ft of head

Maximum windmill flowrate = 15880 gph

Reservoir surface area = 341,374 sq ft = 7.84 ac

Reservoir diameter = 660 ft

Maximum reservoir volume = 5010580 cubic feet

Backup pump: 12 hp, .5898 cfs at 87 ft of head

Reservoir inlet pipe: 6" dia, 4290 ft long

Earth moving requirements:

Embankment height = 14.51 ft

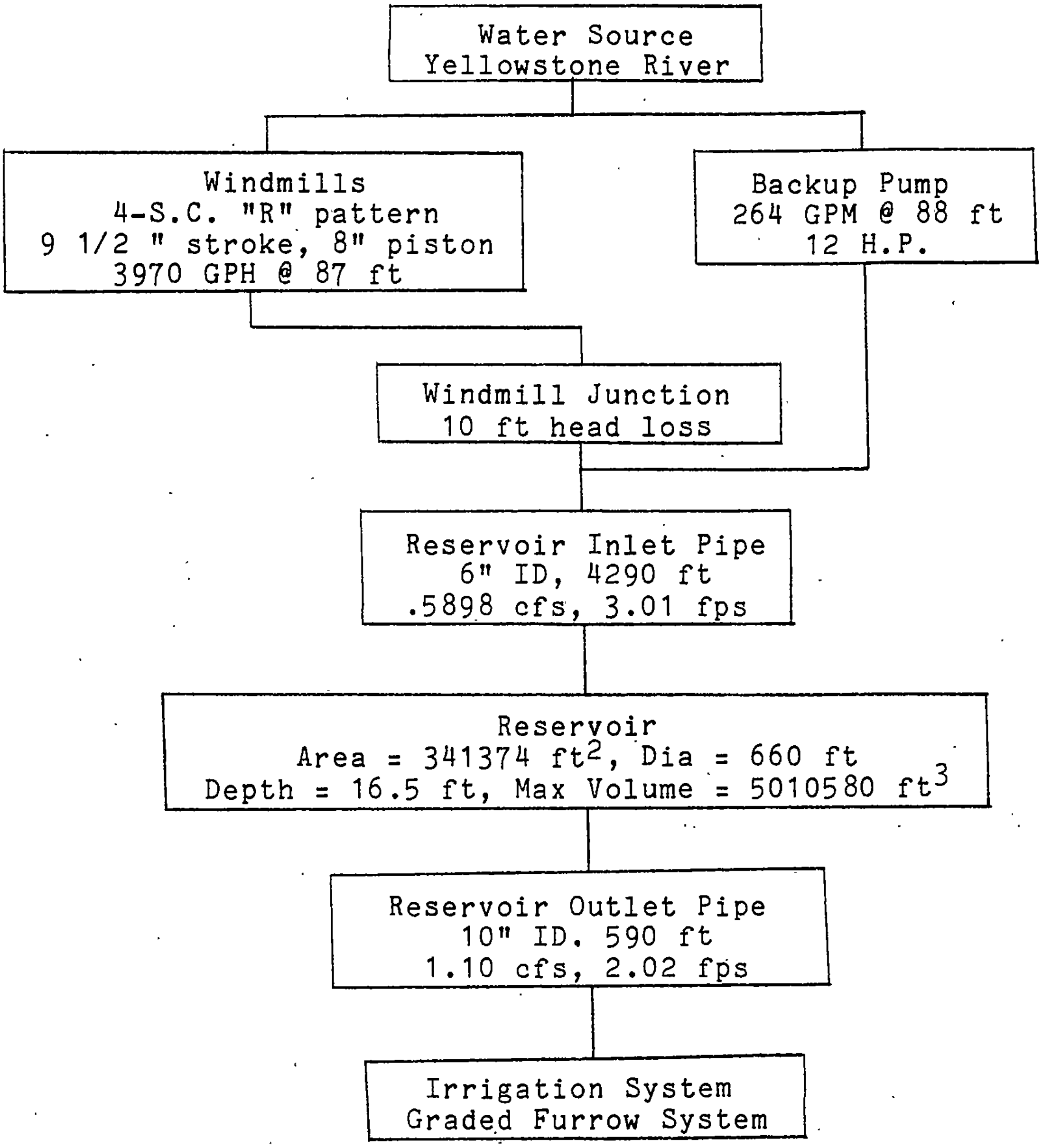
Volume of earth to be moved = 27370 yards.

A diagram showing the major system components and parameters is presented in Figure 15.

With the above information, the economic analysis is done as before. The total system cost on a yearly basis is $332.6/ac yr. The economic analysis spreadsheet was used with the same input as before, with the alteration to the yearly fixed cost and the deletion of the energy cost for the booster pump. The results show a net yearly return of $-285/ac for silage corn, $78.7/ac for sugar beets, and $-372.3/ac for dry beans. A savings of $69/ac-yr could be expected if a diesel pump were used, and a savings of $86/ac-yr if an electrical pump were used.

The return for sugar beets is again positive. The furrow irrigation system is cheaper than the drip/trickle system, but the furrow system requires a larger reservoir which lessens this differential. The variability of the market value of sugar beets, coupled with the fact that crop rotation is not feasible makes the wind powered irrigation system at this site economically dismal even with the lower priced irrigation system. Again, the system economics are considerably more desirable with the use of a conventional pumping plant.

Figure 15. Major system components, Yellowstone River site revaluation on graded furrow irrigation system.



Site 4, Bynum Reservoir, Teton County

The Bynum Reservoir site is in the North-Central section of Montana as shown in Figure 31, Appendix 3. The site is roughly 18 miles Northwest of Choteau, MT. The site is situated in the drainage basin of the Bynum Reservoir. The site specific data is as follows:

Site Location: 47° 58' 02" N 111° 27' 11" W
Section 36, T26N, R7W 40 acres
Elevation: 4220 ft
Distance from water source to reservoir: 1532 ft
Distance from reservoir to field edge: 510 ft
Vertical lift to reservoir: 80 ft
Vertical drop from reservoir to field: 10 ft
Soil type: Silty clay loam, deep soil profile
Class II soil, Soil Intake Family 1.5
Moisture holding capacity of soil: 1.0 in/ft
Appropriate crops: Alfalfa and Spring Grain

The following section includes the calculations and methodology used in designing the wind powered pumping system, the reservoir for off season water storage, and the irrigation system.

The wind data for the site is from the Montana Wind Energy Atlas. The wind data site (CHOTEAU, Teton County) is roughly 20 miles from the field site. The elevation of the wind data site was 4320 ft, and the anemometer height was 10 meters (32.81 ft). The percentage data recovery was good at 83.1%.

The Weibull parameters for the site were developed using the computer program presented in Appendix 1, Figure 20, and are presented in Table 11. The data recovery was poor for the month of January, therefore the Weibull parameters were estimated for that month. The site had an annual average wind speed of 10.29 mph.

Table 11. Weibull parameters for the Bynum Reservoir site.

Month	Weibull Parameters Scale (c) m/sec	Shape (k)
Jan	5.5000 *	1.2500 *
Feb	5.4916	1.2504
Mar	5.9406	1.6256
Apr	6.0806	2.2936
May	5.8950	1.7790
Jun	4.7379	1.7467
Jul	4.8661	1.8147
Aug	4.3276	1.7681
Sep	4.9832	1.8542
Oct	6.0758	1.9157
Nov	5.5697	1.9847
Dec	5.8277	1.4221

* estimate

Irrigation System

A graded border irrigation system was chosen for this site. The soil type, crops and topography are all suited for graded border irrigation. The net irrigation requirements are shown in Table 17, Appendix 2.

Graded Border Irrigation System Design

Given: Strip length = 660 ft (L)
Strip width = 40 ft (W)
Soil intake family = 1.5
Border slope = 1.7% (So)
Mannings roughness coefficient = .15 (n)
Estimated application efficiency = 60% (E)
Soil moisture holding capacity = 1.0 in/ft
Root depth = 5.0 ft

The irrigation system was designed based on the peak consumption of spring grain.

Net moisture replaced per irrigation (Fn):

$Fn = .5\ (5.0\ ft)(1.0\ in/ft) = 2.5\ in$

Peak daily consumption = .301 in/day

Minimum irrigation interval (Days):

$Days = 2.5\ in/(.301\ in/day) = 8.3\ days$

Opportunity time (Tn):

$Tn = ((Fn - c)/a)^{1/b} \quad a = .0899,\ b = .799,\ c = .275$

$Tn = ((2.5-.275)/.0899)^{1/.799} = 55.48\ minutes$

Unit stream size (Qu): (assuming Tl = 0)

$$Qu = \frac{L\ Fn}{7.2(Tn - Tl)\ E} = \frac{660(2.5)}{7.2(55.48)60} = .0688\ cfs/ft$$

Verifying Tl = 0:

$$Tl = \frac{Qu^{0.2}}{120\ (1.486/n)^{1.2}\ (So)^{1.6}}$$

$$Tl = \frac{.0688^{0.2}}{120\ (1.486/.15)^{1.2}\ (.017)^{1.6}} = .211\ min\ (ok)$$

Maximum non-erosive stream size (Qumax):

$Qumax = .0019(So)^{-.75} = .0019(.017)^{-.75} = .0404\ cfs/ft$

Since Qumax < Qu, the length of the field will have to be shortened to prohibit erosive stream size.

Using: Border length = 440 ft (L)

Unit stream size (Qu):

$Qu = (440)(2.5)/(7.2(55.48)(60)) = .0459\ cfs/ft$

Even though Qu > Qumax, continue with analysis because Qu is lessened with the use of end blocks.

Again, verifying Tl = 0:

$$Tl = \frac{.0459^{0.2}}{120(1.486/.15)^{1.2}\ (.017)^{1.6}} = .1914 \text{ (ok)}$$

Total irrigation time (Tt):

Tt = 99 borders(55.48 min/border) = 3.814 days (ok)

Decreased flow due to use of end blocks (Que):

$$Que = \frac{Qu}{1 + (1 - E/100)(ri)(rn)} \quad \text{where } ri = .65,\ rn = .75$$

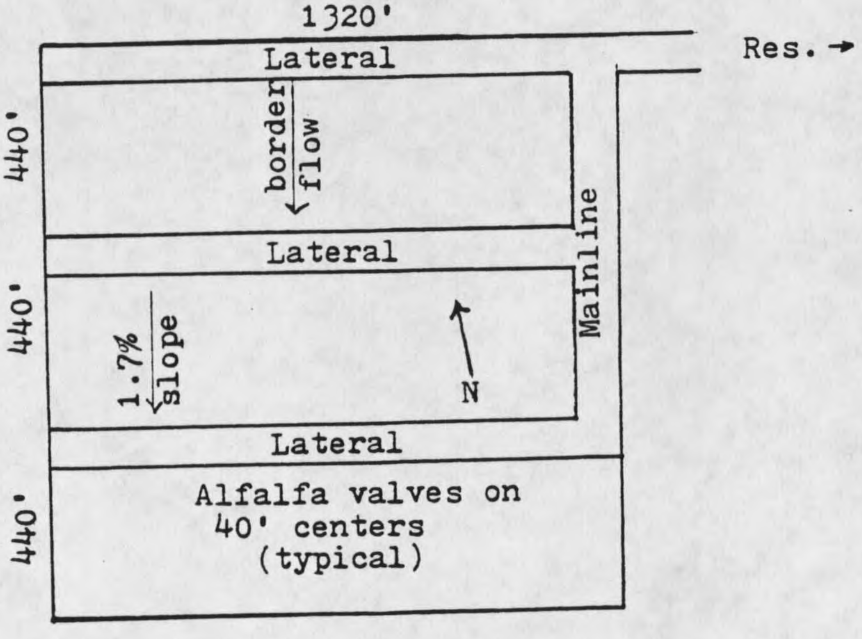
Que = .0384 cfs/ft (ok, Que < Qmax)

Total flowrate (Qt):

Qt = 40 ft (.0384 cfs/ft) = 1.5364 cfs = 689 gpm

The irrigation system layout and dimensions are shown in Figure 16.

Figure 16. Irrigation system layout, Bynum Reservoir site.



Pumping System and Reservoir

The data statements in the computer program shown in Appendix 1, Figure 24 have been altered to reflect the conditions at this site.

Run #1

Input: Preliminary reservoir surface area = 100,000 ft^2
Initial rated flowrate = 1000 gph

Output: Required rated flow = 9310 gph
Maximum volume = 3057690 ft^3

Choosing the windmill with the largest flowrate that will satisfy the elevation head requirements with an allowance for friction losses, the appropriate choice is:

Southern Cross 25 ft dia "R" machines
12 in. stroke, 6 in. diameter
2820 gph @ 125 ft of head

Number of windmills:

= 9310 gph/2820 gph/machine = 3.3 machines (use 4)

Actual rated flowrate = 4 (2820 gph/machine) = 11280 gph

Run #2

Input: Surface area = 100,000 ft^2
Rated flowrate = 11280 gph

Output: Maximum volume = 3723390 ft^3

The resultant reservoir depth is 37.23 ft. Restricting the reservoir depth to 15 ft, the required surface area is 248226 ft^2, with a diameter of 562 ft.

Run #3

Input: Surface area = 248226 ft^2
Rated flowrate = 11280 gph

Output: Maximum volume = 3704367 ft^3

This yields a new average depth of 14.9 ft (ok).

Sizing the Reservoir Inlet Pipe

The windmills are designed to pump against 125 ft of head, 80 ft of head is consumed by the elevation loss, and 10 ft by the junction loss. This leaves 35 ft of head available for friction loss. According to the diagram in Figure 17:

$$35\ \text{ft} = f(L\ V^2)/2dg \quad \text{and} \quad V = Q/A$$

Solving for the pipe size yields a required diameter of 5 inches.

Sizing the Reservoir Outlet and Irrigation Systems Pipes

The energy equation is used with the subscripts as noted in Figure 18. Two feet of pressure is desired at the last alfalfa valve on each line.

Point 1 to 2 : (ignoring minor losses)

$$P1 + Z1 + V1^2/2g = P2 + Z2 + V2^2/2g + fLV2^2/2dg$$

and $V = Q/A$

where: $P1 = 0$, $P2 = 2$ ft
$Z1 = 100$ ft, $Z2 = 90$ ft
$V1 = 0$
$L = 1830$ ft
$Q = 1.5364$ cfs

Solving for pipe size yields a diameter (d1) of 9 inches.

Repeating the above procedure to find the pressure at point 5 , and the diameters d2, and d3 yields:

$P5 = 7.26$ ft
$d2 = 7$ inches
$d3 = 10$ inches

Earth Moving

Earth moving must be done to construct the reservoir for off season water storage. The embankment shape shown in Figure 2 is appropriate. Equating the cut volume to the fill volume and solving for the height of the embankment yields a height of 13.39 ft. Two feet of freeboard is recommended. The required volume of soil to be moved is 32269 yards.

Backup Pump

A backup pump is required in the event that the windmills do not operate. For a pump supplying 11280 gph at 125 ft of head and using a gasoline powered engine, the required motor size is 12 hp.

A diagram showing the major system components and parameters is presented in Figure 19.

Figure 17. Reservoir inlet pipe, Bynum Reservoir site.

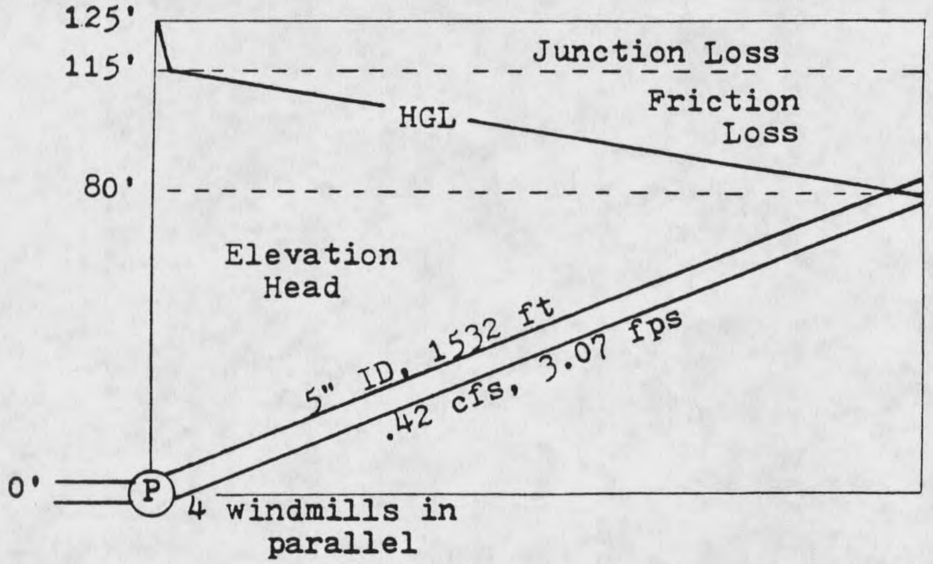


Figure 18. Reservoir outlet and irrigation system pipe, Bynum Reservoir site.

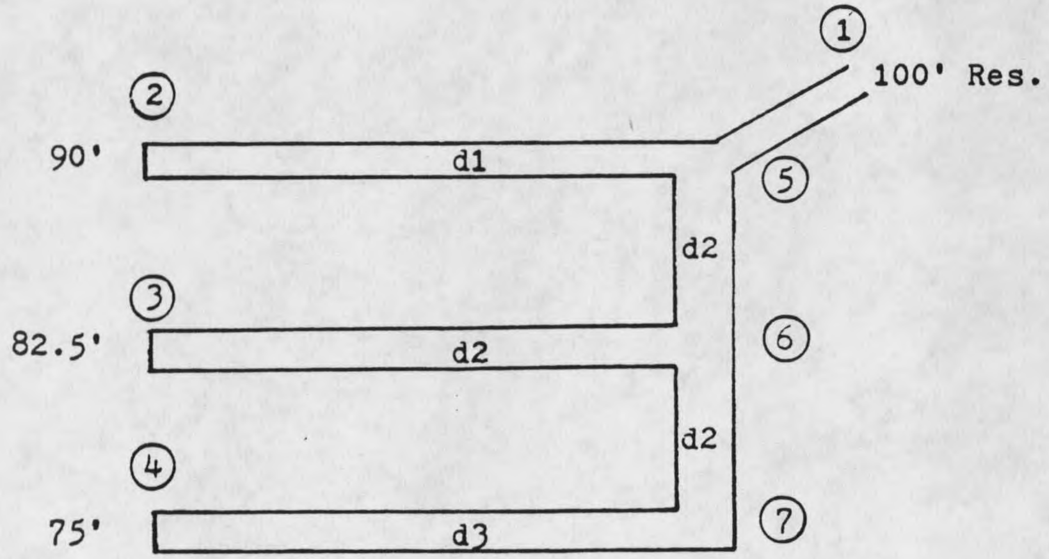
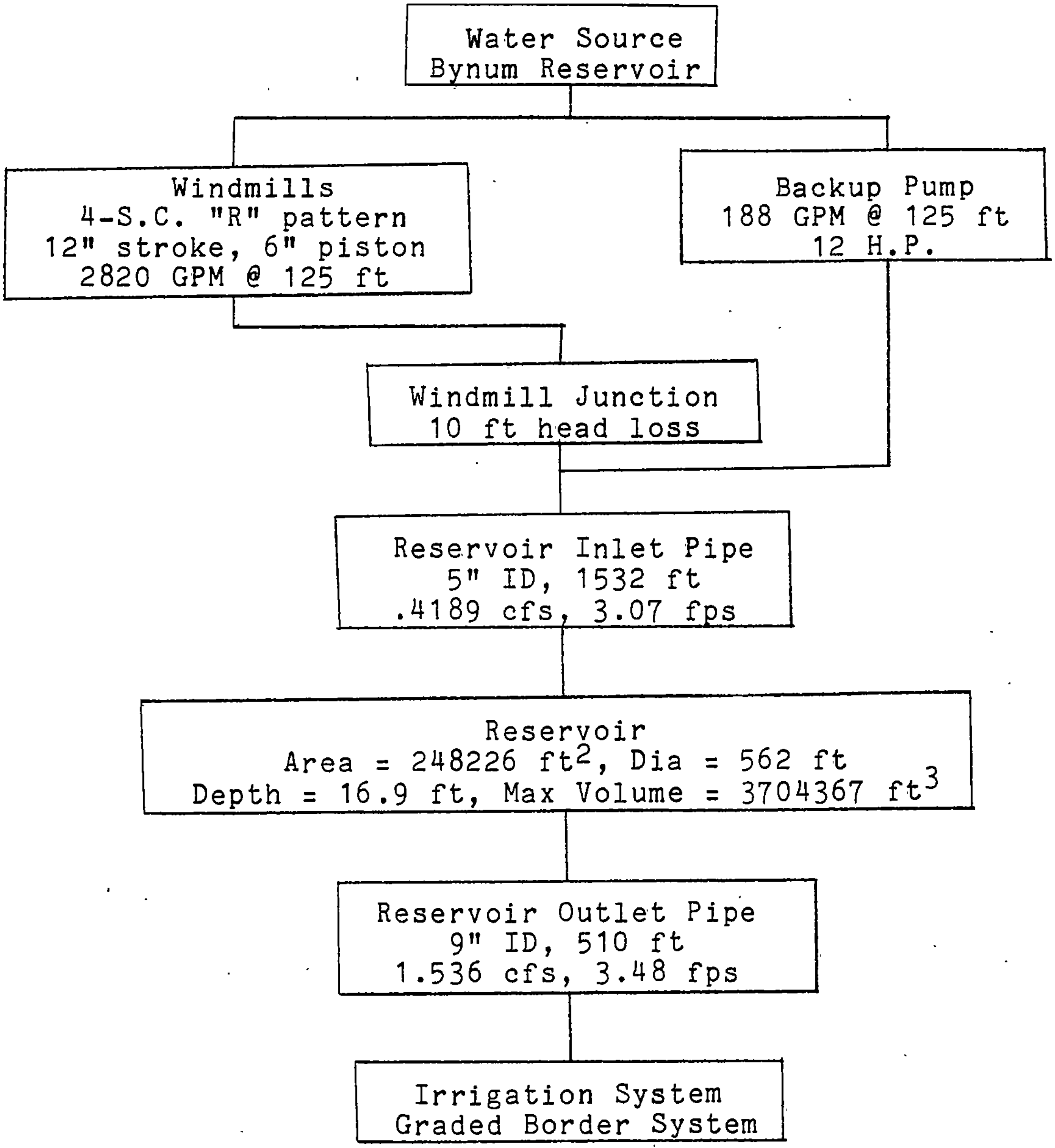


Figure 19. Major system components, Bynum Reservoir site.



Crop Independent Costs

The following is a bill of materials for the wind powered irrigation system. These are the costs that are independent of the enterprise cost associated with crop production.

Table 12. Wind powered irrigation system capital costs, Bynum Reservoir site.

Qty	Description	Unit$	Tot$	% of P
	Irrigation and Wind System			
4	Windmills, S.C. "R" 25' dia 12" str. 6" dia	6514	26056	26
4	Windmill towers 40'	1297	5188	5
1532 ft	Class 150 pvc pipe 4" dia	3.11	4764	5
1830 ft	Irrigation pipe 9"	1.98	3623	4
2640 ft	Irrigation pipe 10"	2.20	5808	6
880 ft	Irrigation pipe 7"	1.54	1355	1
33	Alfalfa valves 9"	67.50	2228	2
66	Alfalfa valves 10"	75	4950	5
1	Backup pump 12 hp	1450	1450	1
1	water funnel and trash hood	50	50	~
1	9" gate valve	180	180	~
1	9.5" gate valve	190	190	~
	Miscellaneous	2000	2000	2
	Installation exp. @ 25 %		14113	14
	Reservoir			
32269 yd	Earth moving	.70	22588	22
124 ton	Bentonite (1lb/ft sq)	58	7198	7
	P = Total system cost =		102088	

Assuming that the capital above would be financed for 15 years at 10% interest rate:

Yearly payment:

Yp = P(.1315) = $13425/yr = $335.6/acre-yr

Economic Analysis

The economic analysis spreadsheet inputs for this site are:

Alfalfa:	Yield = 5 tons/acre Market value = $60/ton
Spring grain:	Yield = 56.5 bu/acre Market value = $3.38/bu
Fixed cost:	$335.6/ac-yr

The spreadsheet outputs the net profit per acre for each crop. The output from the program on a yearly basis for 40 acres is presented in Table 13. (Greiman, 1986)

The system cost are now determined assuming a non-renewable energy source is to be used. A 40 horsepower diesel pump is required. The average fuel cost based on the number of hours that the pump must be run to satisfy the net irrigation requirements is $45.62/ac-yr. The estimated cost of the pumping plant is $4600. The new yearly payment using the diesel pump is $109/ac-yr. This translates into a benefit of $180/ac-yr if the diesel pump is used instead of the wind powered system. Using the same methodology, an electric pump would save $186/ac-yr.

Table 13. Economic analysis spreadsheet output for the Bynum Reservoir site.

	Profit (loss)	Break even price @ yield	Break even yield @ price
Sp. Grain	$(268)/ac	$8.57/bu	126.4 bu/ac
Alfalfa	$(199)/ac	$100/ton	8.3 ton/ac

Results

All the crops at this site show a negative net yearly return. The use of a traditional pumping system would save a considerable amount of money over the wind powered system. In either case, the net return would be negative as the system is designed, but the traditional pumping plants are still more desirable.

CHAPTER 6

OFFSETTING ELECTRICAL IRRIGATION LOADS

Many irrigation units are supplied with electrical power to drive pumping units. A possible alternative to this condition would be to offset some of the electrical grid load with wind derived electricity.

Load offsetting with wind energy is accomplished by one of two methods. The electricity generated by the wind turbine may be directly used by the irrigation plant, with no interconnection to the utility grid. This method is termed the stand alone wind assist mode. In contrast, the wind turbine may be tied to the utility grid, providing wind assist with utility buy-back. An over-running clutch may be used to couple the wind machine directly to the pump, but interconnection with the utility grid is usually more economical. (Clark, 1980)

When the utility buy-back mode is used, the wind turbine produces power when there is adequate wind. While the irrigation plant is in use electricity is supplied directly to the pump motor. The turbine produced electricity that is used by the pump is worth the utility purchase cost. When the pump is not in use the turbine produced electricity is worth the buy-back value established by the utility.

In both the direct wind assist and buy-back modes it may be desirable to use the surplus electricity to offset some other farmstead load, such as winter heating. When the turbine generated electricity is used anywhere on the farm, it can be assumed to be worth the rate at which electricity is bought from the utility grid.

Site Evaluation

The first step in a site evaluation involves the preliminary analysis of wind data from the nearest established wind data recording site. This process will probably not provide a very accurate measure of the wind regime at the site, but it will give the designer some idea of the amount of wind that could be expected. If the preliminary analysis shows some promise that the wind regime will satisfy the power requirements of the irrigation system, the site should have an anemometer installed to collect wind speed and direction data for at least one full year. This anemometer data should then be analyzed to determine the feasibility of offsetting some of the electrical load with a wind turbine.

Electrical load data is also required in the analysis. For existing irrigation plants, the load data may be generated from previous electric bills. For proposed irrigation systems, this data must be developed from irrigation schedules and the type and size of the irrigation equipment.

Having obtained and organized the electrical load data and power output estimates, the problem becomes one of economics. The turbine produced electricity must be cheaper than the weighted average of the electricity purchased from the utility and electricity sold to the utility. The electrical loads provide the weighting factor. The cost of turbine produced power is based on the turbines expected power output and the annualized cost of the wind turbine system plus installation and maintenance costs.

Site 5, Lane Ranch, Park County

The Lane Ranch borders the Yellowstone river 5 miles Northeast of Livingston, MT. The irrigated regions of the ranch are found on the Mission, Elton and Springdale quadrangles on the 7.5 minute series U.S.G.S. topographic maps. The irrigated regions generally follow the Yellowstone river frontage. The ranch is currently owned and operated by Tom Lane and his family.

The irrigated crops currently grown are small grains and alfalfa/grass hay. Sprinkler irrigation is used on 855 acres. Four pumps supply water for center pivots and two pumps operate wheel line systems. All the irrigation pumps are electric and range from 40 to 134 horsepower by nameplate rating. There are also several residences and one machine shop within the irrigated regions of the ranch. There are 14 electric meters on the Lane Ranch. Two are for remote stock watering pumps and have not been included in this analysis. (Lane, 1986)

The Lane Ranch was chosen for this study because of Mr Lanes interest in wind energy, and the desireable characteristics and power usage of the Lane Ranch.

Methodology

Four general steps were followed in this project; the estimation of the monthly electricity loads, the estimation of the power output from a wind machine given the projected wind conditions of the location, the determination of a dollar value of savings resulting from the use of the wind turbine, and the determination of the maximum amount of initial investment that may be applied to a complete wind energy system.

The above steps may be considered generic for any load offsetting application, but the process by which the steps are carried out will vary with each site.

Load Estimation

The monthly load for each meter in question was determined by reviewing past electric bills. Each months electricity use for each meter was logged for the years of 1981 through 1986. The average monthly electricity use was then determined. For the residences, the deviation from this average should be fairly low. The deviation from the average for the pumping plants will depend on the future cropping patterns and irrigation scheduling practices. A summary of the electrical load data is shown in Table 24, Appendix 2.

Power Output from a Wind Machine

The estimation of the expected power output from a wind turbine is basically a problem of accurately describing the wind regime in which the turbine is to be used. The problem on the Lane Ranch is that the wind regime is largely unmeasured. Estimating the wind regime on the Lane Ranch required the major assumption of the analysis at this site. This assumption is that the wind regime on the Lane Ranch is similar to that on the Livingston Bench, and can be predicted from linear correlations using currently generated Bench data as the dependent variable and any parameter having appropriate units and showing the seasonal variation of wind speeds on the Bench as the independent variable.

The Weibull parameters are commonly used in evaluating wind regimes. From these parameters the probability of occurrence of any wind speed may be predicted. (Barnett, 1985) Since the Weibull parameters are the most complete indication of the quality of a wind regime, they are the parameters that were predicted to describe the wind regime at the Lane Ranch.

The dependent variables are the Weibull parameters for three sites on the Livingston Bench that are currently being developed by GeoResearch Inc., in conjunction with the Montana DNRC. This data is presented in the second columns of Tables 22 ,23 and 25, Appendix 2. If this data were available for the entire year, then a correlation would not be required. The GeoResearch data is available only for November 1985 through April 1986. For this reason it is necessary to use the correlation routine to predict the Geo Research Weibull parameters for the remaining six months of the year. The independent variables used are not considered accurate except as an indicator of the seasonal variation of the wind speed, and therefore cannot by used to directly assess the quality of the wind regime.

The first task was to find a parameter that had the best linear curve fit with the dependent variables. After reviewing nearly all the available wind data for the Livingston Bench, three sets of data were singled out as having the appropriate units, and as accurately describing the seasonal variation of the wind speeds. The three data sets are:

1. Weibull parameters, Livingston Candidate Wind Turbine Site, "Montana Wind Energy Atlas"

2. Weibull parameters, Livingston FAA Airport, "Montana Wind Energy Atlas"

3. Average monthly wind speed, Livingston Bench Area, "Review of Available Wind Data for Watson/Meyers land near Livingston, Montana" prepared by OTECH Engineering for Farrell Seiler

The above data is presented in Tables 22, 23 and 25, Appendix 2.

The correlation with the lowest standard error of estimate, a measure of the accuracy of a linear curve fit, was with the data from the OTECH study as the independent variable. The standard error of estimate was determined via the MSUSTAT program, a statistics software package, available through the Montana State University Computer Services. With this correlation the Weibull scale parameters for the site were predicted, and are presented in the right hand column of Table 25, Appendix 2.

The Weibull shape parameter is assumed to be a constant equal to the average of the reported values given by GeoResearch for the six months of data recovery. This average value is equal to 1.8995. Essentially this yields a modified Rayleigh distribution instead of a Weibull distribution. A standard Rayleigh distribution is a Weibull distribution with the shape parameter held constant at a value of 2.0. (Johnson, 1985) This modified Rayleigh distribution provides an adequate description of the wind regime as the scale parameters are estimates based on several assumptions.

Knowing the monthly scale and shape parameters for the wind frequency distribution, the monthly power output can be determined by multiplying the frequency for each wind speed increment by the number of hours per month and then by the power output at that windspeed as read from a power curve for a given wind machine. The machine that was chosen for this analysis is the Bonus 65/13, manufactured by Danregn Vindkraft A/S. The power curve was adjusted for the Livingston elevation and presented by OTECH Engineering.

Estimation of Savings with Wind Turbine

The dollar value of the savings that would result from the use of the wind energy system was calculated as follows:

1. A weighted energy cost was established for each month, with the percent type of load as the weighting factor. The unit electricity costs used in the weighting process are shown in Table 20, Appendix 2.

2. The cost of power bought from the utility grid with no wind energy was calculated on a monthly basis.

3. The net cost paid for power with the wind turbine operating was calculated. This step is carried out for the situations in which 50% and 75% of the wind derived energy is produced at a usable time. Excess wind derived energy is assumed to be sold back to the utility at a rate of $.013 per kWhr, as established by the Public Service Commission of Montana.

4. The sum of the monthly costs determined in step 2 is subtracted from the sum of the monthly costs in step 3. This is the yearly savings with the use of wind energy.

Maximum Initial Investment

The maximum initial investment for the entire wind energy system was determined by assuming that the maximum yearly payment that could be made on a loan was equal to the yearly savings due to the use of wind energy. In this calculation there are several assumptions:

1. The economic inflation rate is 0.0%.
2. The fuel cost escalation rate is 0.0%.
3. The system life is 10 years.
4. The loan is to be financed for 10 years, at 10% interest.

With these assumptions, the following equation is valid:

$$P = A \frac{(1+i)^n - 1}{i(1+i)^n}$$

Where P is the maximum actual purchase price of the entire wind energy system, A is the yearly savings due to the wind assist system, i is the interest rate, and n is the number of years for which the system is financed.

Discussion

The inherent inaccuracies in the methodology used lie in the assumptions made in the process. The final results would be much more accurate if some of these assumptions could be eliminated by actual site data generated through testing. Site specific data that should be generated to provide more accurate results are:

1. Actual measurement of the wind regime at the site.
2. A realistic relationship concerning the timing of electricity use and generation.

These types of studies are costly, and it is suggested that the results of this study using assumptions and approximations should be used to help determine if the cost of these more accurate studies and expensive methods is warranted.

This study entailed the use of only one wind machine manufacturers product. The machine in question was chosen purely by the availability of data, and it is not the intent of this report to recommend one machine over another. The use of a power curve from a different wind turbine in this analysis could alter the results slightly. It is unlikely that the use of a different machine will yield substantially more optimistic results.

Computer Calculations

The heart of the calculations for this project are accomplished via the BASIC computer program shown in Figure 25, Appendix 1. The input variables that are written into the program are:

1. The month and the number of days in each month.
2. The Weibull scale and shape parameters.
3. The total monthly average electricity loads.
4. The weighted unit cost of electricity for each month.
5. Data points read from the power curve for the particular wind machine. (OTECH)

The program caries out the general calculations as previously outlined on a monthly basis, and sums these to provide a yearly analysis. The computer program was written specifically for this site and must be altered significantly for a change in the input variables.

Results

The computer program was run with several combinations of inputs. The program was run with the estimated energy production from the turbine, and 125% and 75% of this value. The program was also run with 75% and 50% of the energy produced being usable due to load-production timing conflicts. The program was also run for the following 2 cases:

Case 1. Electricity being provided for the entire ranch via a two way meter at some central location. Over-production is sold to the utility grid, which also makes up the difference during times of under-production. This case would require a substantial revamping of the grid network on the ranch. This would require the installation of over 5 miles of new power transmission lines.

Case 2. Electricity being provided for 2 center pivot pumps near Springdale. Over-production is sold to the utility grid, which also makes up the difference during times of under-production.

The output for cases 1 and 2, and different combinations of the amount of energy produced and the percent of produced energy used are shown in Table 21, Appendix 2.

If all the assumptions and approximations in this analysis are valid, and the most desirable situation of case 1 is considered, it it highly unlikely that a complete wind system could be purchased for less than $53,988. (Brittan, 1986) This is because the scenario of case 1 would require installation of new power lines to connect all the loads to one common meter. These power lines alone could run in excess of $75,000.

If case 2, with the most desirable production and timing situation considered, it is highly unlikely that a 60 kW wind energy conversion system could be purchased and installed for less than $ 21,721. It may be possible to purchase a used system for less than this amount. (Seiler, 1986) In this case the decision is up to the purchaser. A used machine comes with no guarantee or manufacturers support, and must be erected and installed by the purchaser.

There are several events that could make the scenario of either case more feasible in the future:

1. A rise in electricity costs.
2. A rise in the buyback rate for electricity.
3. A drop in the cost of wind machines.

Until one or more of these events occur, it seems that offsetting the electrical load with wind derived energy on the Lane Ranch is not economically feasible. It is recommended that further studies concerning the feasibility of offsetting the electrical load on the Lane Ranch be discontinued. At some later date, given the changing atmosphere of the wind industry, utility rate structures, and economic conditions, it may be advisable to undertake another feasibility study.

CHAPTER 7

WINDMILL STAND ALONE SYSTEMS

The wind powered irrigation system discussed in this scenario consists of a windmill directly coupled to the irrigation system. An orchard crop is used as the crop for the model. The orchard crop is selected because most orchard crops can withstand the variations in irrigation schedule that will occur as a result of the variation in the wind energy available.

The site is completely hypothetical. It is assumed that a mature orchard crop is currently being irrigated by a drip/trickle irrigation system and the water is supplied by an electric pump. This scenario analyzes the cost benefit of replacing the electric motor with a windmill.

Methodology

The computer programs shown in Figures 26 and 27 in Appendix 1 are used to calculate the cost benefit of replacing the small electric irrigation pump with a windmill. The program in Figure 26 provides the energy output from each diameter of windmill. The input to the program is the technical data provided by Southern Cross Ltd., as shown in Table 27 of Appendix 4. The energy output in ft-lb/sec is relatively constant for each windmill diameter.

The program in Figure 27 calculates the diameter of windmill needed for a given total dynamic head, pump flow rate, and total crop acreage. The choice is based on the energy required to pump the water, and how this energy requirement compares with the energy output of the different diameter machines. The flowrate is calculated by dividing the peak monthly net crop water requirement by the number of seconds in the month. The total yearly crop water requirement for orchard crops in Montana is roughly 18 inches, and the peak monthly requirement is about 6 inches. (SCS Irrigation Guide, 1974)

Given the above information, the program determines the yearly cost per acre of the electric pumping unit and the total installation cost of the required diameter windmill. The windmill system cost is annualized based on a 15 year loan at a 10% interest rate. The annual windmill system cost is subtracted from the annual electricity cost to determine the net cost benefit of replacing the electrical motor with the windmill.

The output from both the programs is provided in Tables 18 and 19 in Appendix 2.

Results

The program is designed to provide output for sites of 1 to 10 acres, with the total dynamic head varied from 0 to 200 feet. In running the program it was determined that with all possible combinations of input, the electrical motor system was always substantially more economical. Under the most optimistic set of input variables (25 ft TDH, 1 acre) the net savings was ($-114.85)/yr for the required windmill diameter of 6 feet. With the worst case (100 ft TDH, 10 acres) the net savings achieved by substituting the windmill was ($-1220.72)/yr for the 25 foot diameter windmill required. Thus, stand-alone windmill systems are not recommended on small acreages of orchard crops.

CHAPTER 8

CONCLUSION

Literature was reviewed concerning the concepts that were proposed as energy saving techniques to boost the feasibility of wind powered irrigation systems. The parameters that affect the technical and economical feasibility of wind powered irrigation systems were examined. Six models of wind powered irrigation systems were developed.

Based on the literature reviewed concerning the energy conserving concepts, several conclusions can be drawn. Crop production functions and the alternative crops suggested should not be used at this time to lessen the energy requirements of an irrigation system. Of the alternative irrigation systems proposed, drip/trickle systems are the most promising. Many conservation tillage practices are already in use in Montana's farming community. Off season pumped water storage reservoirs are likely to be a necessary component of a wind powered irrigation system that uses mechanical water pumping windmills.

Based on literature concerning wind powered irrigation and the results of the system models, wind power for irrigation, in any configuration, is not recommended as a concept that will boost on-farm economics in Montana.

There are several major factors that influence this recommendation. Wind power is free, but the machines used to convert wind power into usable energy are costly. Electricity costs for irrigation pumping units are low in Montana, especially when compared to other agricultural areas of the country. Wind powered irrigation systems are largely untested, thus the risks involved in using such systems are high. These factors lead to the recommendation that wind powered irrigation units not be considered as part of an actual farm production operation. There may be a few select sites where, due to the actual conditions of the location, wind powered irrigation systems may be a reasonable consideration. The probability of existence of such sites is low.

Wind powered irrigation is a relatively new concept. In the future configurations may be developed that are technically and economically feasible. Further research on the energy conservation measures considered in this project may lead to the common use of these practices at some later date. Since this is a new concept there is room for innovative ideas and designs. Economic conditions in Montana may change with time. These changes may also enhance the feasibility of wind powered irrigation.

LITERATURE CITED

Baldridge D., Extension Agronomist, Montana State University, Personal Communication, (Feb. 1986).

Barnett K., Proffesor Emeritus, Mechanical Engineering Dept, New Mexico State University, Class Notes, Wind Energy Systems Design, (1985).

Bauder J., Cooperative Extension Service, MSU, Personal Communication, (1986).

Bradey,N.C., The Nature and Properties of Soils, 8th edition, Macmillan Publishing Co. Inc., New York (1974).

Brittan G., Brittan Ranch, Livingston, MT; Personal Communication (1986).

Brown M.J., Effect of Grain Straw and Furrow Irrigation Stream Size on Soil Erosion and Infiltration, Snake River Conservation Research Center, ARS/USDA Kimberly Idaho (1985).

Bruce D., BNP Lentil Company, Personal Communication, RT. 1, Box 146, Farmington, WA, 99128 208-268-2371, (1981).

Chapman S., and Carter L., Crop Production W.H. Freeman and Co., Publ. San Francisco, (1976).

Clark R.N., "Wind Assisted Deep Well Pumping," Agricultural Energy: Selected papers and abstracts from the 1980 ASAE National Energy Symposium, Vol. 2 (1980).

Clark R.N., "Irrigation Pumping With Wind Energy Only," Agricultural Engineering 64, no. 12 (Dec. 1983).

Clark, R.N., "Wind-Diesel Hybrid System for Water Pumping" USDA/ARS Bushland, TX; AWEA-1985.

Dalton J., SCS Irrigation Engineer, Personal Communication, (1986).

DeBoer D.W. and Beck D.L., "Field Evaluation of Reduced Pressure Sprinklers," ASAE Paper No. 83-2024 (1983).

English B.C. and Dvoskin D., National and Regional Water Production Functions Reflecting Weather Conditions, Miscellaneous Report (1977), The Center for Rural and Ag. Development, Iowa State University, Ames, Iowa 50011.

GeoResearch Inc., "Livingston Bench Wind Energy Study", Submitted to Dave Dysinger, Montana DNRC, (1985).

Gipe, P., Wind Energy, How to Use It, Publ. Stackpole Books, P.O. Box 1831, Harrisburg PA, 17105 (1983).

Greiman B., LYCDDC, Personal Communication, (1986).

Hansen V.E. et al., Irrigation Principles and Practices, 4th ed., John Wiley & Sons Publ. (1979).

Hexam R.W. and Heady E.O., Water Production Functions for Irrigated Agriculture, Iowa State University Press (1978).

Hulsman, R., Assistant Proffesor of Agricultural Engineering, New Mexico State University, Class Notes, Irrigation systems Design, (1985).

Jensen M.C. and Middleton J.E., Scheduling Irrigation from Pan Evaporation, Washington Ag. Exp. Station Circular 527 (1970).

Johnson, G.L., Wind Energy Systems, Publ. Pintace Hall, Inc., Englewood Cliffs NJ. (1985).

Lane T., P.O. Box 1238, Livingston MT, 59047, Personal Communication, (1986).

Lansford R., et al., "Economics of Wind Energy for Irrigation Pumping," Report No. DOE/SEA-7315-20741/81/2 (1980).

Lockerman R. et al., Growing Fababean in Montana, Montana Ag. Exp. Sta. MSU, Bozeman, MT, Bull. 743, (1982).

Lyle W. and Bordovsky J., LEPA Irrigation Systems Evaluation, ASAE Paper no. 82-2536.

Otech Engineering, "Review of Available Wind Data for Watson/Meyers Land Near Livingston Montana" Prepared for Farrell Seiler, (1985).

Paterson B.A., Head, Drainage Branch, Alberta Agriculture, Lethbridge, Alberta Canada, Personal Communication, (1986).

Pair C.H. et al., Irrigation 5th edition, Publ. The Irrigation Institute (1983).

Sammis T.W., "Comparison of Sprinkler, Trickle, Subsurface, and Furrow Irrigation Methods for Row Crops," Agronomy Journal 72, No. 5 (Sep-Oct 1980).

Seiler F., P.O. Box 1376, Livingston MT, Personal Communication, (1986).

Southern Cross Ltd., Towoomba Queensland, Australia; Product Information, (1985).

Vaux H.J. Jr. and Pruitt W.O., "Crop Water Production Functions," Advances in Irrigation, Vol. 2. (1983).

Viessman W. Jr. et al.,Introduction to Hydrology, 2nd edition, Harper and Row Publ. (1972).

Welty L.E. et al., Growing the Garbonzo Bean in Montana MSU Ag. Exp. Sta, Bozeman MT, Bulletin 746, (1982).

Westesen G.L., Professor of Ag. Engr., Montana State University, Personal Communication, 1985-1986.

Irrigation Guide for Montana, United States Department of Agriculture, Soil Conservation Service, (1972).

Irrigation Water Requirements, Technical Release #21, USDA-SCS Engineering Div. (Revised Sept. 1970).

Montana Wind Energy Atlas, Prepared by GeoResearch Inc. for the Energy Division, DNRC Montana (1984).

National Sunflower Association, Market Information Hotline, (1986).

SCS National Engineering Manual, Section 15, Ch. 3., (1983).

ADDITIONAL LITERATURE REVIEWED

Bauder J., *Irrigating with Limited Water Supplies*, Cooperative Extension Service, Montana State University, Circular 1262, (1985).

Blair R., "Fababeans, An Improved Crop for Animal Feeding," *Feedstuffs* 49, no. 29, pp. 15-21, (1977).

Braud H.J. and Amin M.S., "Trickle Irrigation Lateral Design on Sloping Fields," ASAE Paper No. 79-2571.

Bresler E., "Analysis of Trickle Irrigation with Application to Design Problems," *Irrigation Science* 1, pp. 3-17 (1978).

Brosz D. and Jacobs J., *Pump Irrigation Efficiencies and Costs*, Agricultural Extension Service, University of Wyoming, Bul. 740R, (1984).

Buerskens H.J.M. et al., *Low Speed Water Pumping Windmills: Rotor Tests and Overall Performance*, Eindhoven University of Technology, The Netherlands.

Chowdry et al., "Performance of a Low Cost Sail-Wing Windmill," *Ag. Mech. in Asia, Africa, and Latin America* 12, no. 1 (1981), pp. 66-68.

Clark, R.N., "Irrigation Pumping with Wind Energy- Electrical vs. Mechanical," ASAE Paper NO. 81-2560.

Clark R.N. et al., "Wind Turbines for Irrigation Pumping," *Journal of Energy* 5, no. 2 (Mar/Apr 1981), pp. 104-108.

Clark R.N. and Schneider A.D. "Irrigation Pumping with Wind Energy," *Transactions of the ASAE* 3, no.4 (1978), pp. 850-853, ASAE Paper No. 78-2549.

Clark R.N., "Wind Power Research for Agriculture," *Ag Information Bulletin* no. 446, USDA ARS.

Coates W., "Comparison of Equipment for the Installation and Retrieval of Drip Irrigation Laterals," *ASAE Transactions* 28 no. 4, (1985 July-August).

Curly Robert et al., "California Energy Commission; Wind Energy for Irrigation Pumping," *Final Report Contract no. 50082047*, University of California at Davis, March 30,1985.

Doorenbos J. and Pruitt W.O., "Crop Water Requirements," Irrigation and Drainage Paper-24, Food and Agriculture Organizations of the United Nations.

Enochian R., "Solar and Wind Powered Irrigation Systems," USDA Agricultural economic Report, no. 482, Economic Research Service.

Evans L.E. et al., Growing and Using Fababeans, Ag. Canada Publ. No. 1540 (1980).

Evans N., Water Requirements of Crops, ASAE Soil and Water Division, St. Joseph Mich. (1962).

Frost K.R., "Plant and Irrigation Water Requirements," Irrigation Journal, (Nov.-Dec. 1973).

Gerard C.J. and Bardovsky D.G., "Conservation Tillage Studies in the Rolling Plains," Proceedings of the Great Plains Conservation Tillage Symposium, (1984) pp. 201-216.

Gilbert R.G. et al., "Trickle Irrigation: Prevention of Clogging," ASAE Paper No. 77-2011.

Gillespie V.A. et al., "Drip Irrigation Design Equations," ASCE Irrigation and Drainage Division Journal, (1979).

Gilly J.R et al., "Potential Use of Wind Power for Irrigation Pumping," Energy Agriculture 4, pp. 133-146.

Gilly J.R. and Supulla R.J., "Economic Analysis of Energy Saving Practices in Irrigation," ASAE Paper No. 82-2005.

Goldberg D. et al., Drip Irrigation Publ. Drip Irrigation Scientific Publications (1976).

Hagen L.J. and Sharif M., "Darrieus Wind Turbine and Pump Performance for Low Lift Irrigation Pumping," Report no. DOE/ARS-3707-20741/81/1.

Hagen L.J. and Sharif M., "Wind Powered Irrigation Tailwater System: Sizing the Wind Turbine and Storage Pit," ASAE Transactions 24, no. 11 (1981), pp. 103-106.

Hane D.C. and Pumphry F.V., Crop Water Use Curves for Irrigation Scheduling, Agricultural Experiment Station, Oregon State University, Special Report 706 (1984).

Hardin T.C. and Lacewell R.D., "Break-Even Investment in a Wind Energy Conversion System for an Irrigated Farm on the Texas High Plains," Technical Report no. 116, Texas A&M, Texas Water Resources Institute.

Hargreaves G.H., "Estimation of Potential and Crop Evapotranspiration," ASAE Paper No. 73-4537 (1974).

Hargreaves G.H. and Samani Z.A., "Economic Considerations of Deficit Irrigation," Journal of Drainage and Irrigation Engineering 110, no. 4 (Dec. 1984), Paper no. 19367.

Hawtin G. and Webb C., "Faba Bean Improvement," Proceedings of the Faba Bean Conference in Cairo, Egypt, Publ. Martinus Nijhoff Publishers (March 1981).

Hebblethwaite P.D., The Faba Bean, Publ. Butterworths, London (1983).

Howell T.A. et al., "Advances in Trickle Irrigation," Irrigation Challenges of the Eighties ASAE Publ., (1981) pp. 69-94.

Johnson M.D. et al., "Soil Moisture Regimes of Three Conservation Tillage Systems," ASAE Paper No. 82-2019.

Keller J., "Trickle Irrigation Lateral Design," ASAE Paper No. 79-2570.

Kenfield J.A.C., A New Type of Wind Turbine for Water Pumping Applications, Dept. of Mechanical Engineering, University of Calgary, Calgary, Alberta, Canada.

Longley T.S., "Reservoir Tillage for Center Pivot Irrigation," ASAE Paper No. PNR84-209.

Marjon P.L. and Clark R.N., "Evaluation of Pumps for Wind Driven Irrigation," Report no. DOE/ARS-7315-20741/83/1.

Martin D.L. et al., "Model and Production Function for Irrigation Management," Journal of Irrigation and Drainage Engineering 110, no. 2 (1984), Paper No. 18949.

McKenzie D., "Range Water Pumping Systems: State-of-the-Art-Review," USDA Project Report 8522 1201, ED&T Report No. OE-01D40 (1985).

Modi V., et al., "Optimum Configuration Studies and Prototype Design of a Wind Energy Operated Irrigation System," Journal of Wind Engineering and Industrial Aerodynamics, no. 16 (1984), pp. 85-86.

Modi V.J., and Fernando M.S., "An Approach to Wind Energy Operated Irrigation Systems," Proceedings, Energex '84, The Global Energy Forum Regina Saskatchewan, Canada (1984).

Nelson V. et al., "Wind Power Applications in the United States; Irrigation Pumping," Wind Engineering 6, no. 2 (1982), pp. 95-106.

Phene C.J. et al., "A Traveling Trickle Irrigation System," Advances in Irrigation, Vol.3 (1985).

Pochop L.O. et al., "Elevation- A Bias Error in SCS Blaney-Criddle ET Estimates", ASAE Paper No. 82-2596.

Rowland G.C. et al., Fababean Production in Saskatchewan, University of Saskatchewan Publ. No. 416, Ag Dex No. 142/10 (1985).

Sammis T.W. et al., "Estimating Evapotranspiration with Water Production Functions or the Blaney-Criddle Method," Transactions of the ASAE, (1982) pp. 1656-1661.

Smika D.E., "Soil and Water Conservation with Minimum Tillage in the Semi-Arid Central Great Plains," Proceedings of Symposium, International Congress of Plant Protection, (1979), pp. 70-72.

Thornton J.R., "Importance of Water Treatment in Drip Irrigation," ASAE Paper No. 81-2080.

Turner J.H., Fundamentals of No-Till Farming, Publ., American Association for Vocational Instructional Material, Sponsored by Ortho, (1983).

Vosper F.C. and Clark R.N. "Water Pumping with Autonomous Wind-Generated Electricity," ASAE paper No. 84-2602.

Westesen G.L. et al., How Fababeans Grew and Yielded in Tests with Four Soil Moisture Levels, Montana Ag Research, Summer 1985, pp. 6-7.

Westesen G.L., Choosing the Proper Irrigation Method, Cooperative Extension Service Circular No. 1199 (1977), MSU.

Willet G.S. et al., Estimating Irrigation Pumping and Sprinkler System Costs, Cooperative Extension Service, College of Agriculture, Washington State University, Pullman, Washington Ext. Bulletin #1166, (1982).

"Drip/Trickle Irrigation in Action" Proceedings of the Third International Drip/Trickle Irrigation Congress, ASAE Publ., Vol. I and II (1985).

Estimated Water Requirements of Crops in Irrigated Areas of Montana Montana State College, Ag. Exp. Sta., Bozeman MT, Bul. 494, (1953).

Evaluation of Low Volume Wind Turbines for Pumping Water Alberta Agriculture, Farming for the Future, Alberta/Canada Energy Resources Research Fund.

Methods for Estimating Evapotranspiration, Irrigation and Drainage Specialty Conference ASCE, Las Vegas, Nev., (1966).

Selecting Water Pumping Windmills, New Mexico Energy Institute, P.O. Box 3EI, Las Cruces, New Mexico 88003; 505 646-1745 (1978).

"Trickle Irrigation" National Engineering Handbook, Section 15, Ch. 7, USDA-SCS, (1983).

"Windmills for Small Scale Irrigation," Annual report 1981, International Institute for Land Reclamation and Improvement.

Wind Power and Windmills, USDA Program Aid #1256, (1982).

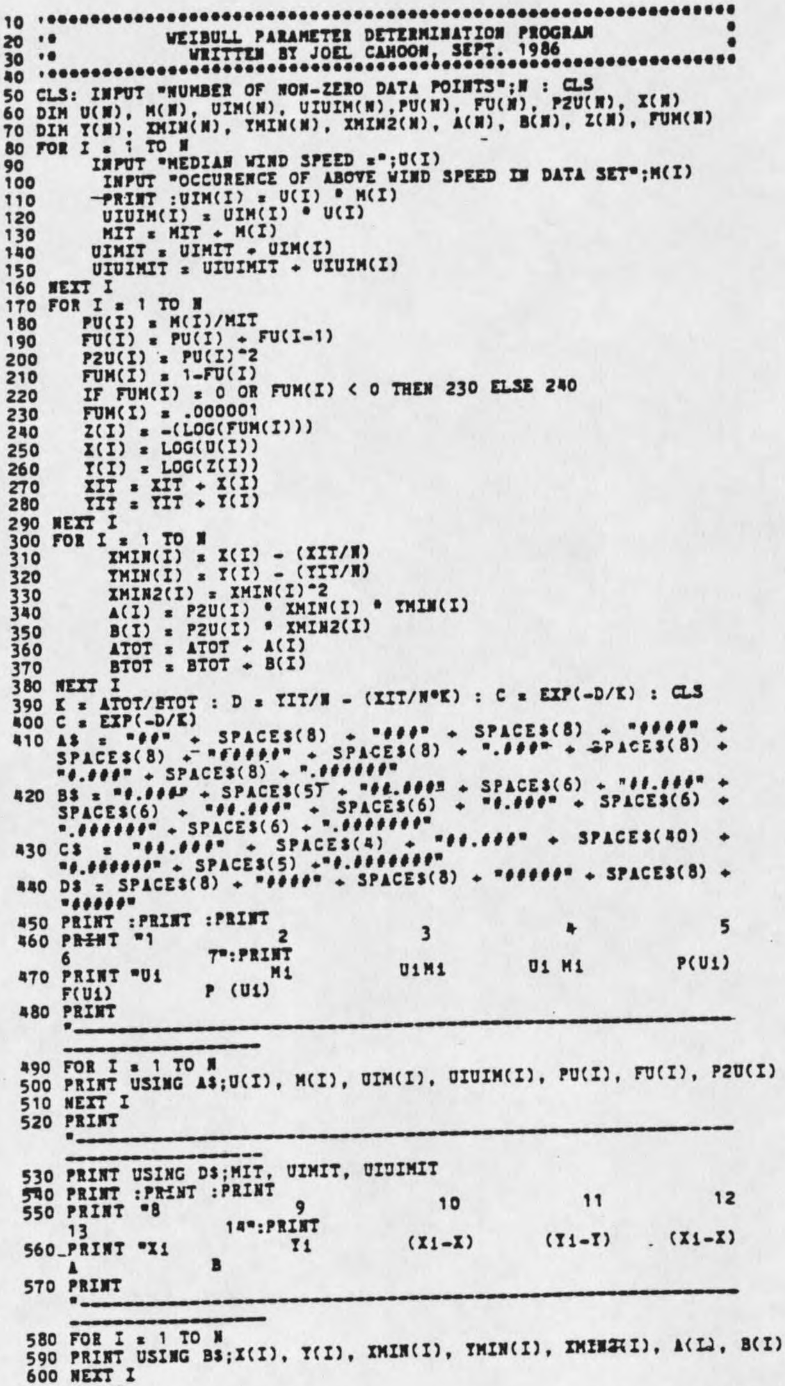
Wind Power for Homes, Energy Information Series, New Mexico Energy Publications Council, Developed by N. Mex. Solar Energy Inst., Las Cruces NM, Box 3 SOL, NMSU, 88003, (1981).

APPENDICES

Appendix 1

Computer Programs

Figure 20. Weibull parameter determination program.



```
10 '*************************************************************
20 '*          WEIBULL PARAMETER DETERMINATION PROGRAM           *
30 '*            WRITTEN BY JOEL CAHOON, SEPT. 1986              *
40 '*************************************************************
50 CLS: INPUT "NUMBER OF NON-ZERO DATA POINTS";N : CLS
60 DIM U(N), M(N), UIM(N), UIUIM(N),PU(N), FU(N), P2U(N), X(N)
70 DIM Y(N), XMIN(N), YMIN(N), XMIN2(N), A(N), B(N), Z(N), FUM(N)
80 FOR I = 1 TO N
90      INPUT "MEDIAN WIND SPEED =";U(I)
100      INPUT "OCCURENCE OF ABOVE WIND SPEED IN DATA SET";M(I)
110     -PRINT :UIM(I) = U(I) * M(I)
120      UIUIM(I) = UIM(I) * U(I)
130      MIT = MIT + M(I)
140     UIMIT = UIMIT + UIM(I)
150     UIUIMIT = UIUIMIT + UIUIM(I)
160 NEXT I
170 FOR I = 1 TO N
180    PU(I) = M(I)/MIT
190    FU(I) = PU(I) + FU(I-1)
200    P2U(I) = PU(I)^2
210    FUM(I) = 1-FU(I)
220    IF FUM(I) = 0 OR FUM(I) < 0 THEN 230 ELSE 240
230    FUM(I) = .000001
240    Z(I) = -(LOG(FUM(I)))
250    X(I) = LOG(U(I))
260    Y(I) = LOG(Z(I))
270    XIT = XIT + X(I)
280    YIT = YIT + Y(I)
290 NEXT I
300 FOR I = 1 TO N
310       XMIN(I) = X(I) - (XIT/N)
320       YMIN(I) = Y(I) - (YIT/N)
330       XMIN2(I) = XMIN(I)^2
340       A(I) = P2U(I) * XMIN(I) * YMIN(I)
350       B(I) = P2U(I) * XMIN2(I)
360       ATOT = ATOT + A(I)
370       BTOT = BTOT + B(I)
380 NEXT I
390 K = ATOT/BTOT : D = YIT/N - (XIT/N*K) : C = EXP(-D/K) : CLS
400 C = EXP(-D/K)
410 A$ = "##" + SPACE$(8) + "###" + SPACE$(8) + "####" +
    SPACE$(8) + "#####" + SPACE$(8) + ".###" + SPACE$(8) +
    "#.###" + SPACE$(8) + ".######"
420 B$ = "#.###" + SPACE$(5) + "##.###" + SPACE$(6) + "##.###" +
    SPACE$(6) + "##.###" + SPACE$(6) + "#.###" + SPACE$(6) +
    ".######" + SPACE$(6) + ".#######"
430 C$ = "##.###" + SPACE$(4) + "##.###" + SPACE$(40) +
    "#.######" + SPACE$(5) +"#.#######"
440 D$ = SPACE$(8) + "####" + SPACE$(8) + "#####" + SPACE$(8) +
    "#####"
450 PRINT :PRINT :PRINT
460 PRINT "1              2                  3                4               5
    6              7":PRINT
470 PRINT "Ui              Mi                UiMi            Ui Mi          P(Ui)
    F(Ui)          P (Ui)
480 PRINT
    "____________________________________________________________________
    __________________
490 FOR I = 1 TO N
500 PRINT USING A$;U(I), M(I), UIM(I), UIUIM(I), PU(I), FU(I), P2U(I)
510 NEXT I
520 PRINT
    "____________________________________________________________________
    __________________
530 PRINT USING D$;MIT, UIMIT, UIUIMIT
540 PRINT :PRINT :PRINT
550 PRINT "8              9                 10               11              12
    13             14":PRINT
560 PRINT "Xi              Yi              (Xi-X)           (Yi-Y)         (Xi-X)
    A              B
570 PRINT
    "____________________________________________________________________
    __________________
580 FOR I = 1 TO N
590 PRINT USING B$;X(I), Y(I), XMIN(I), YMIN(I), XMIN2(I), A(I), B(I)
600 NEXT I
610 PRINT
    "____________________________________________________________________
    __________________
620 PRINT USING C$;XIT, YIT, ATOT, BTOT
630 PRINT :PRINT :PRINT
640 PRINT "SHAPE PARAMETER K = "K
650 PRINT "SCALE PARAMETER C = "C :PRINT :PRINT :PRINT
```

Figure 21. Reservoir sizing program, Jefferson river site.

```
10 CLS:KEY OFF
20 GOSUB 600
30 INPUT "AREA OF RESERVOIR IN square feet";AREA
40 INPUT "ANNENOMETER HEIGHT IN feet";H1
50 INPUT "WINDMILL HUB HEIGHT IN feet";HUB
60 INPUT "FIRST RATED FLOW IN gph";A
70 INPUT "FINAL RATED FLOW IN gph";B
80 INPUT "RATED FLOW STEP IN gph";C
90 CLS
100 DIM MONS$(12), DAYS(12), C(12), K(12), EVAP(12), IRREQ(12), INFLOW(12)
110 DIM EVAPO(12), VOL(12), IRRG(12), RAIN(12), RAINF(12)
120 FOR RFLOW = A TO B STEP C
130 PRINT:PRINT :PRINT
140 PRINT "               INFLOW          EVAP            IRREQ          RAIN          VOLUME
150 PRINT "MONTH           gal             gal             gal            gal            gal
160 PRINT "-----------------------------------------------------------------------------------
170 PRINT
180 RESTORE
190 FOR M = 1 TO 12
200 READ MONS$(M),DAYS(M),C(M),K(M),EVAP(M),IRREQ(M), RAIN(M)
210 C(M) = C(M)*((HUB/H1)^(1/7))
220 VOLUMT = 0
230 FOR U = 7.5 TO 23.5 STEP 1
240 AHOURS = DAYS(M)*24*(K(M)/C(M))*((U/C(M))^(K(M)-1))
250 BHOURS = EXP(-(U/C(M))^K(M))
260 HOURS = AHOURS * BHOURS
270 IF U<18 THEN 280 ELSE 300
280 FLOW = RFLOW*( -1.512112 + .272218*U - 7.461564E-03*U^2)
290 GOTO 310
300 FLOW = RFLOW
310 VOLUM = FLOW*HOURS
320 VOLUMT = VOLUMT + VOLUM
330 NEXT U
340 INFLOW(M) = VOLUMT
350 EVAPO(M) = EVAP(M) * AREA/(12*.1337)
360 RAINF(M) = RAIN(M) * AREA/(12*.1337)
370 IRRG(M) = IRREQ(M) * 1086013!
380 VOL(M) = INFLOW(M) - EVAPO(M) - IRRG(M) + VOL(M-1) + RAINF(M)
390 IF VOL(M)<0 THEN 430 ELSE 400
400 PRINT USING A$; MONS$(M), INFLOW(M), EVAPO(M), IRRG(M), RAINF(M), VOL(M)
410 IF M = 12 THEN 560
420 NEXT M
430 CLS:NEXT RFLOW
440 DATA OCT, 31,   9.7184,  1.7159,  1.65,  0.00,  0.70
450 DATA NOV, 30,   9.2849,  1.9824,  0.00,  0.00,  0.49
460 DATA DEC, 31,   9.3819,  1.7057,  0.00,  0.00,  0.33
470 DATA JAN, 31,  12.0335,  1.7752,  0.00,  0.00,  0.38
480 DATA FEB, 28,  10.2853,  2.0567,  0.00,  0.00,  0.26
490 DATA MAR, 31,  10.7508,  1.7221,  0.00,  0.00,  0.60
500 DATA APR, 30,  11.0400,  1.8757,  2.68,  0.00,  1.04
510 DATA MAY, 31,   9.6473,  1.5579,  4.44,  1.72,  1.95
520 DATA JUN, 30,   7.1149,  1.6632,  5.90,  6.16,  2.58
530 DATA JUL, 31,  10.0365,  1.9073,  9.54,  8.91,  1.05
540 DATA AUG, 31,   8.1084,  1.6818,  9.00,  7.18,  1.16
550 DATA SEP, 30,   8.3692,  1.7032,  1.14,  1.28,  1.01
560 PRINT
570 PRINT "RESERVOIR AREA = "AREA" FEET SQUARED"
580 PRINT "NECESSARY RATED FLOW = "RFLOW" GPH"
590 END
600 A$ = "\   \" + SPACE$(9) + "########" + SPACE$(4) + "#########"
    + SPACE$(4) +             "#########"  + SPACE$(4) + "##########"
    + SPACE$(4) + "##########"
610 RETURN
```

Figure 22. Reservoir sizing program, Milk River site.

```
10 CLS:KEY OFF
20 GOSUB 600
30 INPUT "AREA OF RESERVOIR IN square feet";AREA
40 INPUT "ANNENOMETER HEIGHT IN feet";H1
50 INPUT "WINDMILL HUB HEIGHT IN feet";HUB
60 INPUT "FIRST RATED FLOW IN gph";A
70 INPUT "FINAL RATED FLOW IN gph";B
80 INPUT "RATED FLOW STEP IN gph";C
90 CLS
100 DIM MON$(12), DAYS(12), C(12), K(12), EVAP(12), IRREQ(12), INFLOW(12)
110 DIM EVAPO(12), VOL(12), IRRG(12), RAIN(12), RAINF(12)
120 FOR RFLOW = A TO B STEP C
130 PRINT:PRINT :PRINT
140 PRINT "                 INFLOW          EVAP            IRREQ          RAIN          VOLUME
150 PRINT "MONTH             gal             gal             gal            gal            gal
160 PRINT "----------------------------------------------------------------------------------
170 PRINT
180 RESTORE
190 FOR M = 1 TO 12
200 READ MON$(M),DAYS(M),C(M),K(M),EVAP(M),IRREQ(M), RAIN(M)
210 C(M) = 2.237*C(M)*((HUB/H1)^(1/7))
220 VOLUMT = 0
230 FOR U = 7.5 TO 23.5 STEP 1
240 AHOURS = DAYS(M)*24*(K(M)/C(M))*((U/C(M))^(K(M)-1))
250 BHOURS = EXP(-(U/C(M))^K(M))
260 HOURS = AHOURS * BHOURS
270 IF U<18 THEN 280 ELSE 300
280 FLOW = RFLOW*( -1.512112 + .272218*U - 7.461564E-03*U^2)
290 GOTO 310
300 FLOW = RFLOW
310 VOLUM = FLOW*HOURS
320 VOLUMT = VOLUMT + VOLUM
330 NEXT U
340 INFLOW(M) = VOLUMT
350 EVAPO(M) = EVAP(M) * AREA/(12*.1337)
360 RAINF(M) = RAIN(M) * AREA/(12*.1337)
370 IRRG(M) = IRREQ(M) * 1086000!
380 VOL(M) = INFLOW(M) - EVAPO(M) - IRRG(M) + VOL(M-1) + RAINF(M)
390 IF VOL(M)<0 THEN 430 ELSE 400
400 PRINT USING A$; MON$(M), INFLOW(M), EVAPO(M), IRRG(M), RAINF(M), VOL(M)
410 IF M = 12 THEN 560
420 NEXT M
430 CLS:NEXT RFLOW
440 DATA OCT, 31,   6.7230,  3.0130,  0.28,  0.00,  0.45
450 DATA NOV, 30,   6.3180,  2.6950,  0.00,  0.00,  0.35
460 DATA DEC, 31,   6.1650,  2.8210,  0.00,  0.00,  0.30
470 DATA JAN, 31,   5.6660,  1.9680,  0.00,  0.00,  0.32
480 DATA FEB, 28,   6.6380,  2.6350,  0.00,  0.00,  0.30
490 DATA MAR, 31,   6.2470,  2.1430,  0.00,  0.00,  0.33
500 DATA APR, 30,   6.9250,  2.3220,  0.88,  0.00,  0.70
510 DATA MAY, 31,   6.4370,  2.2040,  2.56,  0.72,  1.61
520 DATA JUN, 30,   6.6400,  3.0260,  5.61,  8.13,  2.73
530 DATA JUL, 31,   6.5940,  3.1830,  7.96, 11.31,  1.46
540 DATA AUG, 31,   6.3260,  3.2680,  7.11,  9.53,  1.12
550 DATA SEP, 30,   6.6630,  3.1570,  4.33,  0.40,  0.95
560 PRINT
570 PRINT "RESERVOIR AREA = "AREA" FEET SQUARED"
580 PRINT "NECESSARY RATED FLOW = "RFLOW" GPH"
590 END
600 A$ = "\   \" + SPACE$(9) + "########" + SPACE$(4) + "########"
    + SPACE$(4) +             "#########"  + SPACE$(4) + "##########"
    + SPACE$(4) + "##########"
610 RETURN
```

Figure 23. Reservoir sizing program, Yellowstone River site.

```
10 CLS:KEY OFF
20 GOSUB 600
30 INPUT "AREA OF RESERVOIR IN square feet";AREA
40 INPUT "ANNENOMETER HEIGHT IN feet";H1
50 INPUT "WINDMILL HUB HEIGHT IN feet";HUB
60 INPUT "FIRST RATED FLOW IN gph";A
70 INPUT "FINAL RATED FLOW IN gph";B
80 INPUT "RATED FLOW STEP IN gph";C
90 CLS
100 DIM MON$(12), DAYS(12), C(12), K(12), EVAP(12), IRREQ(12), INFLOW(12)
110 DIM EVAPO(12), VOL(12), IRRG(12), RAIN(12), RAINF(12)
120 FOR RFLOW = A TO B STEP C
130 PRINT:PRINT :PRINT
140 PRINT "                INFLOW           EVAP            IRREQ          RAIN          VOLUME
150 PRINT "MONTH            gal              gal             gal            gal            gal
160 PRINT "-------------------------------------------------------------------------------------
170 PRINT
180 RESTORE
190 FOR M = 1 TO 12
200 READ MON$(M),DAYS(M),C(M),K(M),EVAP(M),IRREQ(M), RAIN(M)
210 C(M) = 2.237*C(M)*((HUB/H1)^(1/7))
220 VOLUMT = 0
230 FOR U = 7.5 TO 23.5 STEP 1
240 AHOURS = DAYS(M)*24*(K(M)/C(M))*((U/C(M))^(K(M)-1))
250 BHOURS = EXP(-(U/C(M))^K(M))
260 HOURS = AHOURS * BHOURS
270 IF U<18 THEN 280 ELSE 300
280 FLOW = RFLOW*( -1.512112 + .272218*U - 7.461564E-03*U^2)
290 GOTO 310
300 FLOW = RFLOW
310 VOLUM = FLOW*HOURS
320 VOLUMT = VOLUMT + VOLUM
330 NEXT U
340 INFLOW(M) = VOLUMT
350 EVAPO(M) = EVAP(M) * AREA/(12*.1337)
360 RAINF(M) = RAIN(M) * AREA/(12*.1337)
370 IRRG(M) = IRREQ(M) * 1086000!
380 VOL(M) = INFLOW(M) - EVAPO(M) - IRRG(M) + VOL(M-1) + RAINF(M)
390 IF VOL(M)<0 THEN 430 ELSE 400
400 PRINT USING A$; MON$(M), INFLOW(M), EVAPO(M), IRRG(M), RAINF(M), VOL(M)
410 IF M = 12 THEN 560
420 NEXT M
430 CLS:NEXT RFLOW
440 DATA OCT, 31,   5.4475,  1.5784,  1.15,  0.00,  0.71
450 DATA NOV, 30,   5.4908,  1.5013,  0.00,  0.00,  0.51
460 DATA DEC, 31,   5.5355,  1.5660,  0.00,  0.00,  0.48
470 DATA JAN, 31,   5.5802,  1.5902,  0.00,  0.00,  0.49
480 DATA FEB, 28,   5.5938,  1.6024,  0.00,  0.00,  0.51
490 DATA MAR, 31,   6.0120,  1.6027,  0.00,  0.00,  0.65
500 DATA APR, 30,   6.4164,  1.7234,  4.92,  0.00,  1.26
510 DATA MAY, 31,   6.2187,  1.7748,  6.07,  0.00,  2.06
520 DATA JUN, 30,   5.6613,  1.7021,  7.14,  3.26,  3.32
530 DATA JUL, 31,   5.9878,  1.5525,  9.02,  7.89,  1.55
540 DATA AUG, 31,   5.4299,  1.5167,  8.24,  7.77,  1.20
550 DATA SEP, 30,   5.6097,  1.5684,  6.40,  2.87,  1.19
560 PRINT
570 PRINT "RESERVOIR AREA = "AREA" FEET SQUARED"
580 PRINT "NECESSARY RATED FLOW = "RFLOW" GPH"
590 END
600 A$ = "\    \" + SPACE$(9) + "########" + SPACE$(4) + "########"
+ SPACE$(4) +                "#########"  + SPACE$(4) + "###########" +
SPACE$(4) + "##########"
610 RETURN
```

Figure 24. Reservoir sizing program, Bynum Reservoir site.

```
10 CLS:KEY OFF
20 GOSUB 600
30 INPUT "AREA OF RESERVOIR IN square feet";AREA
40 INPUT "ANNENOMETER HEIGHT IN feet";H1
50 INPUT "WINDMILL HUB HEIGHT IN feet";HUB
60 INPUT "FIRST RATED FLOW IN gph";A
70 INPUT "FINAL RATED FLOW IN gph";B
80 INPUT "RATED FLOW STEP IN gph";C
90 CLS
100 DIM MONS$(12), DAYS(12), C(12), K(12), EVAP(12), IRREQ(12), INFLOW(12)
110 DIM EVAPO(12), VOL(12), IRRG(12), RAIN(12), RAINF(12)
120 FOR RFLOW = A TO B STEP C
130 PRINT:PRINT :PRINT
140 PRINT "                 INFLOW          EVAP            IRREQ         RAIN        VOLUME
150 PRINT "MONTH             gal             gal             gal           gal           gal
160 PRINT "-----------------------------------------------------------------------------------
170 PRINT
180 RESTORE
190 FOR M = 1 TO 12
200 READ MONS$(M),DAYS(M),C(M),K(M),EVAP(M),IRREQ(M), RAIN(M)
210 C(M) = 2.237*C(M)*((HUB/H1)^(1/7))
220 VOLUMT = 0
230 FOR U = 7.5 TO 23.5 STEP 1
240 AHOURS = DAYS(M)*24*(K(M)/C(M))*((U/C(M))^(K(M)-1))
250 BHOURS = EXP(-(U/C(M))^K(M))
260 HOURS = AHOURS * BHOURS
270 IF U<18 THEN 280 ELSE 300
280 FLOW = RFLOW*( -1.512112 + .272218*U - 7.461564E-03*U^2)
290 GOTO 310
300 FLOW = RFLOW
310 VOLUM = FLOW*HOURS
320 VOLUMT = VOLUMT + VOLUM
330 NEXT U
340 INFLOW(M) = VOLUMT
350 EVAPO(M) = EVAP(M) * AREA/(12*.1337)
360 RAINF(M) = RAIN(M) * AREA/(12*.1337)
370 IRRG(M) = IRREQ(M) * 1086000!
380 VOL(M) = INFLOW(M) - EVAPO(M) - IRRG(M) + VOL(M-1) + RAINF(M)
390 IF VOL(M)<0 THEN 430 ELSE 400
400 PRINT USING A$; MONS$(M), INFLOW(M), EVAPO(M), IRRG(M), RAINF(M), VOL(M)
410 IF M = 12 THEN 560
420 NEXT M
430 CLS:NEXT RFLOW
440 DATA OCT, 31,   6.0758,  1.9157,  2.36,  0.00,  0.44
450 DATA NOV, 30,   5.5697,  1.9847,  0.00,  0.00,  0.43
460 DATA DEC, 31,   5.8277,  1.4221,  0.00,  0.00,  0.38
470 DATA JAN, 31,   5.5000,  1.2500,  0.00,  0.00,  0.35
480 DATA FEB, 28,   5.4916,  1.2504,  0.00,  0.00,  0.38
490 DATA MAR, 31,   5.9406,  1.6256,  0.00,  0.00,  0.47
500 DATA APR, 30,   6.0806,  2.2936,  1.47,  0.00,  0.87
510 DATA MAY, 31,   5.8950,  1.7790,  2.94,  0.52,  1.91
520 DATA JUN, 30,   4.7379,  1.7467,  5.88,  7.25,  3.28
530 DATA JUL, 31,   4.8661,  1.8147,  8.14, 11.00,  1.77
540 DATA AUG, 31,   4.3276,  1.7681,  7.90,  8.82,  1.18
550 DATA SEP, 30,   4.9832,  1.8542,  4.73,  1.25,  0.98
560 PRINT
570 PRINT "RESERVOIR AREA = "AREA" FEET SQUARED"
580 PRINT "NECESSARY RATED FLOW = "RFLOW" GPH"
590 END
600 A$ = "\   \" + SPACE$(9) + "########" + SPACE$(4) + "########"
    + SPACE$(4) +            "#########"  + SPACE$(4) + "##########"
    + SPACE$(4) + "##########"
610 RETURN
```

Figure 25. Energy balance program, Lane Ranch site.

```
10 '*********************************************************************
20 '*                                                                   *
30 '*       YEARLY VALUE OF ENERGY SAVED DUE TO WIND ENERGY OFFSETTING  *
40 '*                 WRITTEN BY JOEL CAHOON, SUMMER 1986               *
50 '*                                                                   *
60 '*                     READ DOCUMENTATION BEFORE USE                 *
70 '*                                                                   *
80 '*********************************************************************
90 CLS
100 INPUT "DECIMAL PERCENT OF ENERGY PRODUCED";PP
110 INPUT "DECIMAL PERCENT OF ENERGY USED";PU
120    PRINT "MONTH               LOAD           PROD          SAVINGS
130    PRINT "                    kWhr           kWhr             $"
140    PRINT "-------------------------------------------------------------":PRINT
150 DIM KW(30),MO$(12),DAYS(12),C(12),HOURS(12),F(30),FREQ(30),KWHR(30)
160 DIM LOD(12),BUY(12),SELL(12),USE(12),COST(12),WIND(12),NOWIND(12),SAV(12)
170 GOTO 520
180    FOR I = 1 TO 12
190       J = J+1
200      RESTORE
210      K = 1.8995
220      HOURS(I) = DAYS(I)*24
230      KWHT = 0
240        FOR U = 2 TO 60 STEP 2
250           UC = U*.447
260           F(I)=(K/C(I))*((UC/C(I))^(K-1))*EXP(-(UC/C(I))^K)
270           FREQ(I)= F(I)*HOURS(I)
280           READ KW
290           KWHR(I)=FREQ(I)*KW*PP
300           KWHT = KWHT+KWHR(I)
310        NEXT U
320      YKWH = YKWH + KWHT
330      IF LOD(I) > KWHT THEN 340 ELSE 360
340      USE(I) = PU*KWHT:BUY(I) = LOD(I) - USE(I):SELL(I) = (1-PU)*KWHT
350      GOTO 370
360      USE(I) = PU*LOD(I):BUY(I) = (1-PU)*LOD(I):SELL(I) = KWHT - USE(I)
370      NOWIND(I) = COST(I)*LOD(I)
380      WIND(I) = (COST(I) * (BUY(I) - USE(I))) - .015*SELL(I)
390      SAV(I) = NOWIND(I) - WIND(I)
400      SAVT = SAVT+SAV(I)
410      PRINT USING A$;MO$(I),LOD(I),KWHT,SAV(I)
420    NEXT I
430 PRINT :PRINT "YEARLY SAVINGS IN ENERGY = "SAVT" $"
440 PRINT :PRINT "YEARLY ENERGY PRODUCTION = "YKWH " kWhr
450 IF J = 12 THEN 670
460 '------------------------------------------------------------------------
470 '                        DATA AND PRINT FORMAT STATEMENTS
480 '------------------------------------------------------------------------
490 DATA 0,0,0,0,1.1,2.1,3.6,5.9,11.4,18.2,34.3,42.1,48.2,53.2,56.3,59.3,60,62.5
500 DATA 63.6,64.6,65,65.2,66.4,67,67,67,67,67,67,67,67
510 '
520 A$ = "\    \"+SPACE$(8)+"######"+SPACE$(8)+"######"+SPACE$(8)+"####"
530 '
540 MO$(1)="JAN":  DAYS(1)=31:  C(1)=12.78:       LOD(1)=14529:    COST(1)=.04925
550 MO$(2)="FEB":  DAYS(2)=28:  C(2)=11.97:       LOD(2)=13004:    COST(2)=.04925
560 MO$(3)="MAR":  DAYS(3)=31:  C(3)=7.82:        LOD(3)=13957:    COST(3)=.04925
570 MO$(4)="APR":  DAYS(4)=30:  C(4)=7.64:        LOD(4)=11856:    COST(4)=.037885
580 MO$(5)="MAY":  DAYS(5)=31:  C(5)=6.99:        LOD(5)=47819!:   COST(5)=.03268
590 MO$(6)="JUN":  DAYS(6)=30:  C(6)=5.4:         LOD(6)=91159!:   COST(6)=.03185
600 MO$(7)="JUL":  DAYS(7)=31:  C(7)=4.57:        LOD(7)=109258!:  COST(7)=.03174
610 MO$(8)="AUG":  DAYS(8)=31:  C(8)=3.95:        LOD(8)=102757!:  COST(8)=.03181
620 MO$(9)="SEP":  DAYS(9)=30:  C(9)=4.93:        LOD(9)=43205!:   COST(9)=.03281
630 MO$(10)="OCT": DAYS(10)=31: C(10)=8.100001:   LOD(10)=14315:   COST(10)=.03668
640 MO$(11)="NOV": DAYS(11)=30: C(11)=10.44:      LOD(11)=12006:   COST(11)=.03789
650 MO$(12)="DEC": DAYS(12)=31: C(12)=13.59:      LOD(12)=13544:   COST(12)=.04925
660 GOTO 180
670 END
```

Figure 26. Energy output program for Southern Cross windmills.

```
10 CLS : KEY OFF
20 INPUT "windmill diameter";D
25 PRINT
30 INPUT "lift";L
40 INPUT "flow";F
50 A = L*F
60 ATOT = A + ATOT
70 CON = CON + 1
80 AVE = ATOT/CON
90 AVEFPPS = AVE*.00232
100 AREA = (3.14159*D^2)/4
110 CF = (2*AVEFPPS)/(.00023*AREA*49296.3)
120 INPUT "another";A$
130 IF A$ = "y" THEN 30 ELSE 140
140 LPRINT "Average power = "AVEFPPS" ft-lb/sec for a "D" foot diameter machine.
150 LPRINT "The flow factor is "CF" for a "D" foot diameter machine.
160 LPRINT :LPRINT
```

Figure 27. Energy balance program, small orchard crop.

```
10 CLS
15 FOR ACRES = 1 TO 10 STEP 1
16 PRINT :PRINT "                       "ACRES" ACRES
20  PRINT :PRINT "TDH                 DIAMETER             DOLLARS SAVED
30 PRINT
50 PU = 17.39
60 MPU = 5.64
70 FOR TDH = 25 TO 200 STEP 25
80 Q = .0014*MPU*ACRES
90 FLBS = Q*TDH*62.4/.75
100 E = FLBS/737.6
110 PE = ACRES*PU*E*43560!/(Q*12*3600)
120 DLE = PE*.035/.9
130 IF FLBS < 23.4 THEN 220 ELSE 140
140 IF FLBS > 23.4 AND FLBS < 47.3 THEN 230 ELSE 150
150 IF FLBS > 47.3 AND FLBS < 84 THEN 240 ELSE 160
160 IF FLBS > 84 AND FLBS < 122.3 THEN 250 ELSE 170
170 IF FLBS > 122.3 AND FLBS < 145.6 THEN 260 ELSE 180
180 IF FLBS > 145.6 AND FLBS < 328.6 THEN 270 ELSE 190
190 IF FLBS > 328.6 AND FLBS < 543.6 THEN 280 ELSE 200
200 IF FLBS > 543.6 AND FLBS < 776 THEN 290
210 IF FLBS > 776 THEN 347
220 D = 6: C = 888   :GOTO 300
230 D = 8: C = 1026  :GOTO 300
240 D = 10: C = 1431 :GOTO 300
250 D = 12: C = 1934 :GOTO 300
260 D = 14: C = 2420 :GOTO 300
270 D = 17: C = 5559 :GOTO 300
280 D = 21: C = 9010 :GOTO 300
290 D = 25: C = 9868 :GOTO 300
300 COST = C*.1315
310 GAIN = DLE-COST
320 PRINT USING "###" + SPACE$(20) + "##" + SPACE$(20) + "#####.##";TDH,D,GAIN
330 NEXT TDH
340 NEXT ACRES
345 GOTO 400
347 A$ = "MORE THAN ONE WINDMILL NEEDED"
350 PRINT USING "###" + SPACE$(5) + "\                          \";TDH,A$
360 GOTO 340
400 END
```

Appendix 2

Supplemental Tables

Table 14. Net irrigation requirements and peak daily consumptive use for the Jefferson River Site.

	Green Peas in. (in.)	Potatoes in. (in.)	Sp. Grain in. (in.)	Alfalfa in. (in.)
Apr	0.00	0.00	0.00	0.00
May	0.00	0.00	0.75(0.11)	1.41(0.15)
Jun	2.67(0.17)	2.11(0.13)	5.93(0.26)	5.05(0.23)
Jul	7.35(0.31)	8.02(0.34)	5.35(0.26)	7.31(0.30)
Aug	1.26	7.81(0.34)	0.00	5.89(0.24)
Sep	0.00	0.92	0.00	1.05
Oct	0.00	0.00	0.00	0.00

Parentheses - Peak daily consumptive use.
Open - Monthly net irrigation requirements.

Table 15. Net irrigation requirements and peak daily consumptive use for the Milk River Site.

	Sunflower in. (in.)	Alfalfa in. (in.)	Wint. Grain in. (in.)	Spr. Grain in. (in.)
Apr	0.00	0.00	0.00	0.00
May	0.00	0.43	2.88(0.18)	0.00(0.10)
Jun	1.29(0.13)	4.88(0.22)	3.59(0.25)	5.05(0.24)
Jul	6.49(0.27)	6.79(0.28)	0.00	6.67(0.30)
Aug	3.60(0.20)	5.72(0.23)	0.00	0.00
Sep	0.00	0.24	0.00	0.00
Oct	0.00	0.00	0.00	0.00

Parentheses - Peak daily consumptive use.
Open - Monthly net irrigation requirements.

Table 16. Net irrigation requirements and peak daily consumptive use for the Yellowstone River site.

	Sugar Beets in. (in.)	Silage Corn in. (in.)	Dry Beans in. (in.)
Apr	0.00	0.00	0.00
May	0.00 (0.07)	0.00	0.00
Jun	3.26 (0.18)	1.43 (0.13)	3.95 (0.21)
Jul	7.89 (0.33)	6.81 (0.28)	8.07 (0.34)
Aug	7.77 (0.31)	6.69 (0.27)	1.88
Sep	2.87 (0.16)	1.05	0.00
Oct	0.00	0.00	0.00

Parentheses - Peak daily consumptive use.
Open - Monthly net irrigation requirements.

Table 17. Net irrigation requirements and peak daily consumptive use for the Bynum Reservoir site.

	Alfalfa in. (in.)	Spring Grain in. (in.)
Apr	0.00	0.00
May	0.31	0.00 (0.07)
Jun	4.35 (0.21)	3.81 (0.21)
Jul	6.60 (0.27)	7.36 (0.30)
Aug	5.29 (0.22)	0.21 (0.09)
Sep	0.75	0.00
Oct	0.00	0.00

Parentheses - Peak daily consumptive use.
Open - Monthly net irrigation requirements.

Table 18. Average power output and efficiency as a function of diameter for Southern Cross windmills.

Diameter ft.	Efficiency %	Power ft-lb/sec
6	14.6	23.42
8	16.6	47.28
10	18.9	84.00
12	19.1	122.26
14	16.7	145.57
17	25.5	328.62
21	27.7	543.60
25	27.9	776.26

Table 19. Net savings obtained by replacing an electric pump with a windmill on a small orchard site with a previously installed trickle irrigation system.

	1 Acre		5 Acres		10 Acres	
TDH ft.	Dia. ft.	Savings $/yr	Dia. ft.	Savings $/yr	Dia. ft.	Savings $/yr
25	6	-115	10	-179	17	-712
50	8	-131	17	-712	17	-693
75	10	-182	17	-702	21	-1127
100	10	-181	17	-693	25	-1221
125	10	-179	21	-1137	*	*
150	12	-243	21	-1127	*	*
175	12	-241	25	-1230	*	*
200	14	-303	25	-1221	*	*

* - More than one windmill required.
Dia. indicates the required windmill diameter.

Table 20. Unit electricity costs when purchased from Montana Power Company.

Residential:

Winter: all kWhr, @ .049250 $/kWhr

Summer: all kWhr, @ .037885 $/kWhr

Irrigation:

$23.70 per season plus all kWhr @ .031089 $/kWhr

Commercial:

	First 3000 kWhr	Add. kWhr	First 10 kW	Add. kW
Winter	$.048278	$.029711	N.C.	$4.662
Summer	$.040230	$.024758	N.C.	$2.912

where: Summer- April through November
Winter- December through March

Table 21. Results of computer trials for least and most desirable situations, cases 1 and 2.

Case	% of energy produced	% energy used	max. init. invest.
1	125	75	$ 53,998
1	100	75	$ 48,689
1	75	75	$ 41,433
1	125	50	$ 41,242
1	100	50	$ 36,658
1	75	50	$ 30,771
2	125	75	$ 21,721
2	100	75	$ 17,494
2	75	75	$ 13,260
2	125	50	$ 19,724
2	100	50	$ 15,859
2	75	50	$ 11,988

Table 22. Data from Wind Energy Atlas, Livingston FAA Airport.

Month	Recorded Weibull Scale Parameter m/s	GRI Weibull Scale Parameter m/s	Predicted Weibull Scale Parameter m/s
Jan	11.16	15.22	13.01
Feb	10.90		12.54
Mar	8.66	8.80	8.51
Apr	7.79	7.58	6.95
May	7.02		5.57
Jun	6.95		5.44
Jul	5.87		3.49
Aug	6.32		4.31
Sep	6.49		4.61
Oct	8.11		7.53
Nov	10.29	8.12	11.45
Dec	10.79	12.54	12.35

1. Standard error of estimate is 2.342.
2. Regression equation:

$$Ypred = 1.798Xrep - 7.058$$

Table 23. Data from Wind Energy Atlas, Livingston Candidate Wind Turbine Site.

Month	Recorded Weibull Scale Parameter m/s	GRI Weibull Scale Parameter m/s	Predicted Weibull Scale Parameter m/s
Jan	8.70	15.22	10.27
Feb	13.09		12.40
Mar	6.29	8.80	9.11
Apr	7.74	7.58	9.81
May	5.12		8.54
Jun	5.68		8.82
Jul	5.84		8.88
Aug	4.38		8.18
Sep	5.34		8.65
Oct	7.59		9.74
Nov	10.33	8.12	11.07
Dec	12.26	12.54	12.00

1. Standard error of estimate is 3.582.
2. Regression equation:

$$Ypred = .485Xrep + 6.059$$

Table 24. Monthly average electrical loads for Lane Ranch, 1981-1986.

	Residential kWhr	Irrigation kWhr
Jan	14529	0
Feb	13004	0
Mar	13957	0
Apr	11856	0
May	11215	36604
Jun	10271	80888
Jul	10399	98859
Aug	10936	91821
Sep	10927	33279
Oct	12006	2540
Nov	12006	0
Dec	13544	0

Table 25. Data from OTECH ENGINEERING report prepared for Farrell Seiler.

Month	Monthly Ave. Wind Speed m/s	GRI Weibull Scale Parameter m/s	Predicted Weibull Scale Parameter m/s
Jan	8.76	15.22	12.78
Feb	8.36		11.97
Mar	6.30	8.80	7.82
Apr	6.21	7.58	7.64
May	5.89		6.99
Jun	5.10		5.39
Jul	4.69		4.57
Aug	4.38		3.94
Sep	4.87		4.93
Oct	6.44		8.10
Nov	7.60	8.12	10.44
Dec	9.16	12.54	13.59

1. Average monthly wind speed is from corrected (30 ft) valuesfrom Mission Field, OSU/PNL Summaries and Livingston FAA Airport.
2. Standard error of estimate is 2.114.
3. Regression equation:

$$Ypred = 2.0169Xrep - 4.9009$$

Appendix 3

Maps