Main line efficiency of sprinkler irrigation systems
by Robert Goldthwaite Arrington

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Agricultural Engineering
Montana State University

Abstract:
During the summer of 1979, tests were conducted on sprinkler irrigation systems in the state of Montana. Measurements were made to determine if the energy requirements of the main line delivery system were excessive, which could result in high pumping costs for the farmer. Energy is lost as water is transported along the main line from the pump to the distribution unit. An energy equation was used to determine if the total energy loss was above an acceptable level.

The total energy loss that occurs due to friction was divided into four terms which were: (1) head loss due to friction along the walls of straight pipe (hf), (2) energy losses due to fittings which are referred to as minor losses (hm), (3) transition losses, which are those occurring from contractions or expansions in pipe size (ht), (4) head losses due to a partially closed gate valve (hgv). From the field data gathered the energy loss from each of these four parts was determined.

The data showed that many farmers have irrigation systems which have management and design problems. This was indicated by high friction losses (hf) and by systems operating with a partially closed gate valve (hgV). Minor and transition losses resulted in a small percentage of the total energy loss.

Three different power calculations were made for each system, all representing power to the pump. Two of these calculations were made to show the increased power required to pump water through a partially closed gate valve. The third power calculation determined the maximum "good design" power and only had meaning for those systems which had pumping units that were eighty percent efficient.

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Date July 9, 1980

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ABSTRACT

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The total energy loss that occurs due to friction was divided into four terms which were: (1) head loss due to friction along the walls of straight pipe (h_f), (2) energy losses due to fittings which are referred to as minor losses (h_m), (3) transition losses, which are those occurring from contractions or expansions in pipe size (h_t), (4) head losses due to a partially closed gate valve (h_{gv}). From the field data gathered the energy loss from each of these four parts was determined.

The data showed that many farmers have irrigation systems which have management and design problems. This was indicated by high friction losses (h_f) and by systems operating with a partially closed gate valve (h_{gv}). Minor and transition losses resulted in a small percentage of the total energy loss.

Three different power calculations were made for each system, all representing power to the pump. Two of these calculations were made to show the increased power required to pump water through a partially closed gate valve. The third power calculation determined the maximum "good design" power and only had meaning for those systems which had pumping units that were eighty percent efficient.

NOMENCLATURE

Symbol	Description
A	Cross sectional area
C_h	Hazen-Williams roughness coefficient
D	Pipe diameter
g	Acceleration due to gravity
h_L	Total friction loss
h_p	Head on pump
h_f	Friction loss
h_t	Transition losses
h_m	Minor losses
h_{gv}	Gate valve loss
K	Resistance coefficient
L	Pipe length
P	Pressure
Q	Flow rate
V	Velocity
V_{lam}	Velocity of laminar flow
V_{turb}	Velocity of turbulent flow
Z	Elevation
γ	Specific weight of water

Chapter 1

BASIS OF INVESTIGATION

As energy, in the form of electricity and fossil fuels, becomes more and more scarce, the nation as a whole has become increasingly aware of the need to conserve its energy supplies. It is important that all segments of our economy, including agriculture, make the most efficient use of available energy sources. The first developed method of irrigation in the West was that of uncontrolled flooding, which is now often replaced by sprinkler irrigation systems which can apply the water more efficiently with less management and less labor. As sprinkler irrigation becomes more prevalent, irrigators are beginning to understand the need to manage their systems efficiently due to the rising cost of operation.

Irrigating has the ultimate purpose to produce a profit for the farmer, thus the effect of the system's design and operation is directly related to the economic output, which is the crop. If the design and operation of the system is optimum, then maximum economic output is earned from the crop.

Sprinkler irrigation systems always have room for improvement. One of the problems encountered in effectively evaluating their performance is the difficulty in distinguishing inadequacies in the management of the system from those defects inherent in the physical design. Improvement through better management practices and design can conserve valuable energy supplies and reduce the irrigator's fixed and annual operating costs. How can this be accomplished? What can the irrigator do to increase the overall efficiency of his system?

To answer these questions an examination of operating sprinkler systems in Montana has been conducted. This thesis will attempt to answer these questions by evaluating some systems in the state as to proper design and operating effectiveness.

STATEMENT OF PROBLEM

It was the purpose of this study to investigate the energy requirements of sprinkler irrigation pipeline delivery systems and to determine if these energy requirements are excessive. The pipeline delivery system is meant to include the irrigation pump and main line up to, but not including, the actual irrigation unit. In evaluating such systems, the objective was to determine if too much energy was being used to pump water from the source to the irrigation distribution unit.

Design Criteria

The delivery system, depending on the amount of water the farmer is attempting to apply, could be inadequately designed in a number of ways, which are as follows

1) Both the pump and main line could be too large for the

irrigation system or the land irrigated. In this situation, the gate valve at the pump would be partially closed to reduce line pressure and discharge, resulting in energy waste.

2) Both pump and main line could be too small for the irrigation system. No energy is wasted but insufficient water is supplied to the crop, resulting in reduced yields.

3) a. The pump could be too large for the correct size main line.

b. The main line could be too small for the correct size pump. In either case excessive friction occurs, resulting in energy waste.

4) a. The pump could be too small for the correct size main line.

b. The main line could be too large for the correct size pump. In the first case, no energy waste occurs but insufficient water is supplied to the crop, resulting in reduced yields. In the second case, the system would function properly but the initial investment for the main line is larger than necessary; although, as power costs increase the pipe may become the right size economically.

Results of Design Criteria

From the operating sprinkler systems tested, it was possible to positively evaluate parts 1 and 3 of the design criteria, while part 4b was evaluated indirectly. Parts 2 and 4a were not evaluated in this project.

Chapter 2

REVIEW OF SELECTED LITERATURE

A sprinkler irrigation system is fairly complicated in that it is composed of many different kinds of mechanical and hydraulic equipment. The system as a whole must be so designed that it will operate efficiently. The design of an irrigation system requires careful planning in order to fit properly to the fields on which it is to be operated, and to be able to supply sufficient water for the various crops.

The part of the sprinkler system of interest in this report is the delivery system or main line. The function of the main line is to convey the quantities of water required to operate each sprinkler lateral at the needed operating pressure (Pair, 1975). The main line is designed so that the greatest economic return is achieved by balancing the initial cost of the system and the total operating cost due to pumping.

Hydraulics of Closed Conduit Flow

A review of the literature indicates that considerable research has been done in the area of pipe flow. By definition pipe flow refers only to pipes which flow completely full. In designing a main line for pipe flow, relatively few equations are used. These are the continuity equation, the energy equation, and the equations of fluid resistance.

The equation of continuity can best be understood by visualizing a horizontal pipe of fixed diameter carrying a fluid at a constant velocity. Assuming the fluid is incompressible and the density is constant regardless of pressure, then the flow at different sections along the pipe will be equal. This means that the flow rate into one end of the pipe must equal the rate of flow out the other end. The continuity equation reduces to

$$Q_1 = Q_2 = Q = A_1V_1 = A_2V_2 \tag{2.1}$$

where the subscripts $_1$ and $_2$ denote any two arbitrary sections along pipeline. Thus for fluids moving at constant velocity in a fixed diameter pipe, the product of velocity and cross-sectional area will be constant. This value, Q, is designated as flowrate and has dimensions of cubic feet per second or gallons per minute (Vennard, 1975).

The velocity distribution of a flowing fluid through a cross section is not constant as depicted by the dotted line in Figure 1. Flowing water within a pipe may be either laminar or turbulent. Roberson (1975) defines laminar flow as that flow which is void of eddies. King (1963) gives a different definition for laminar flow as that in which the fluid moves in parallel layers with no cross currents. The reason for the parabolic shape of the laminar profile as depicted in Figure 1 is due to friction along the walls of the pipe. Turbulent flow states Roberson (1975) has eddies or vortices throughout the entire field of flow. King (1963) reports turbulent flow as characterized by pulsatory cross current velocities. The velocity profile of turbulent flow is more rounded than that of laminar flow.

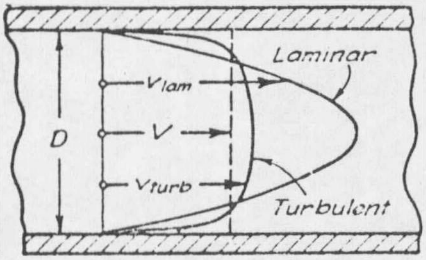

Figure 1 Comparison of Average Velocity, Laminar Velocity and Turbulent Velocity Profiles

For steady, incompressible flowing fluid which can be either laminar or turbulent, Equation 2.1 still applies; however, the velocity in the equation is the average velocity. Vennard (1975) states that the average velocity is a fictitious uniform velocity that will transport the same amount of mass through the cross section as will the actual velocity distribution. The dotted line in Figure 1 represents the average or mean velocity.

In 1750, Leonhard Euler first applied Newton's second law to the motion of fluid particles. For incompressible flow with uniform density the Euler equation is written as

$$d\left(\frac{P}{\gamma} + \frac{V^2}{2g} + Z\right) = 0 \qquad (2.2)$$

The Euler equation can be integrated between any two sections along a pipeline to obtain

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 \tag{2.3}$$

Thus the quantity

$$\frac{P}{\gamma} + \frac{V^2}{2g} + Z = \text{constant} \tag{2.4}$$

applies to all sections along a pipeline. Equation 2.4 is known as the Bernoulli equation; named after Daniel Bernoulli, an eighteenth century mathematician (Rouse, 1957). The Bernoulli equation, which only applies to an ideal fluid where no energy is being lost to friction, provides a useful relationship between pressure, velocity and elevation above some datum for all sections along a pipeline.

A real fluid flowing through a pipe contains four forms of energy which are of interest. Due to the movement of water it contains kinetic energy. Two forms of potential energy are present; one by virtue of its elevation and the other by virtue of its pressure. The fourth energy form is that due to friction. The total of the kinetic, potential, and frictional energies is constant even though the values of the individual portions may change.

The flow of a real fluid is much more complex than an ideal fluid due to the existence of viscosity. The viscosity of a substance is defined as a measure of its internal resistance to flow. Viscosity introduces resistance to motion by causing shear or friction forces between fluid particles and between these and boundary walls (Vennard, 1975). This friction changes some of the useful flow energy into heat which is lost to the system. This energy loss to friction is designated by h_L. The Bernoulli equation now becomes the energy equation which is

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + h_{L_{1,2}} \qquad (2.5)$$

Energy can be defined as the ability to do work. Work from a moving fluid results from force moving through some distance, and therefore energy per unit weight of fluid in the English system has the units of foot pounds per pound which reduces to feet.

A pump may exist in conjunction with a pipeline and its purpose is to supply positive energy to the fluid. The pump energy is represented by h_p. Thus the energy equation becomes

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 + h_p = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + h_{L_{1,2}} \qquad (2.6)$$

The energy equation can be applied between any two sections along the main line and merely represents an accounting of the various energy changes that take place. Therefore the pump may or may not be included in Equation 2.6.

The energy loss due to friction, $h_{L_{1,2}}$ has been divided into four terms which were of interest to this project. These four terms are head loss due to friction along the walls of straight pipe (h_f), energy losses due to fittings which are referred to as minor losses (h_m), transition losses which are those occurring from contractions or expansions in pipe size (h_t), and head losses due to a partially closed gate valve (h_{gv}). If these four energy loss terms are combined, it is seen that

$$h_{L_{1,2}} = h_f + h_m + h_t + h_{gv} \qquad (2.7)$$

Equation 2.7 can be substituted into Equation 2.6 to become the final form of the energy equation used to analyse a pipeline system. It might be noted that energy losses and head losses are used interchangeably and merely represent energy lost as heat.

<u>Head Losses Due To Friction</u> (h_f)

Whenever fluid flow passes a fixed wall or boundary, fluid friction exists. This fluid friction causes a loss of pressure along the pipeline due to flow energy being changed into heat that is lost via conduction. The amount of friction losses in pipelines depends principally upon the inside roughness of the pipe, the size of the pipe, and the velocity of the fluid. Morris (1955) reports that energy loss over rough conduit surfaces is largely attributable to the formation of wakes behind each roughness element. Harris (1950) found that roughness does not appreciably change the resistance in laminar flow because in the parabolic distribution there is no velocity at the surface of contact. If turbulent velocity exists, then pipe roughness has a direct effect on the moving fluid causing energy loss.

Many formulas, both rational and empirical, have been proposed to express the relationship between the principal factors that cause friction loss. A common and basic expression for the pressure drop that occurs during the flow of fluids under turbulent conditions was proposed by Chezy in 1775, which has come to be known as the Darcy-Weisbach equation (Nolte, 1978). While the Darcy-Weisbach equation is a fundamentally proven method for determining head loss in closed conduit flow, empirical equations are often used. The most widely used equation, according to Jeppson (1977), is the Hazen-Williams equation which was developed in 1920. The equation is

$$h_f = \left(\frac{2.31}{C_h}\right)^{1.852} \left(\frac{Q^{1.852}}{D^{4.87}}\right) (L) \tag{2.8}$$

in which Q is flowrate in cubic feet per second, D is pipe diameter in feet, and L is pipe length in feet. The Hazen-Williams roughness coefficient, C_h, varies with the type of pipe material and its smoothness with a range of about 70 for rough pipes to about 150 for very smooth pipes.

It has been found that pipes carrying water exhibit increasing pressure losses with the passage of time. This is due to the influence of corrosion. The surface roughens and incrustations of scales may form on the inside walls of the pipe. Pigott (1933) found that the effect of age in steel and uncoated cast-iron pipe is largely that of reduction in diameter and increase of roughness. Karaki (1971) substantiated these findings that age may reduce the conduit capacity.

One other empirical formula that is worth mentioning is the Scobey formula. This formula was selected by the irrigation industry for computing the various charts and tables now being used in design, although irrigation design slide rules are now using the Hazen-Williams formula. Gray (1954) conducted tests using three inch aluminum pipe and found that the existing charts and tables for aluminum pipe, which are based on the Scobey formula, have higher friction losses than actually exist.

Minor Losses (h_m)

There are many different types of pipe fittings that are used in connecting straight sections of pipe; such as bends, elbows, tees, check valves, couplers, flow meters, strainers and other fittings. These different types of fittings alter the flow pattern in the pipe creating additional turbulence which results in energy loss in excess of the normal friction losses in the pipe. These additional head losses are termed minor losses. Minor losses that occur in a pipe system can be evaluated by

$$h_m = K \frac{V^2}{2g} \qquad (2.9)$$

From experimental results charts are readily available listing values for the resistance coefficient, K, for the different fittings. The magnitude of the loss coefficient is determined mainly by the size and shape of the different fittings.

Head losses in pipe bends are caused by combined effects of separation, wall friction, and the twin-eddy secondary flow (Vennard, 1962). Extensive work in clarifying the losses caused by bends has been done by Ito (1973). Haugh (1962) has updated K values to handle pressure losses in plastic tubing and fittings.

In the design of irrigation systems with quick couplers it has become accepted practice to account for the additional loss due to couplers by using the Scobey formula for friction loss in the pipe and applying a greater friction coefficient than the value obtained experimentally for straight pipe without couplers. Gray (1954) suggests still using the Scobey formula but using a lower friction factor and equivalent feet of pipe for the energy loss due to the couplers. Lytle (1962) recommends using Equation 2.9 and found that the resistance values varied considerably, depending on the type of coupler, the pipe size, the velocity of the water passing through, the distance between pipe ends in the coupler, and the angle of inclination between successive tubings. Benami (1968) supports Lytle's findings and found that an average value for K equal to 0.12 appears suitable for all couplers currently being used.

Commercial pipe fittings are built more for structural properties, ease of handling, and economics rather than for head loss considerations. Vennard (1962) states that the energy loss caused by these fittings is due to the rough and irregular shapes of the fittings, which produces large scale turbulence.

Although the sum of energy losses are often small in comparison to friction losses, Villemonte (1977) emphasizes the importance of including the minor losses in the analysis of a pipeline.

Transition Losses (h_t)

The objective of a transition, states Vennard (1975), is to provide an expanding or contracting passage of proper shape and minimum length which will yield minimum head loss. When there is a change in size, shape, or direction of flow, there must be a corresponding change imposed on the flow velocity. When abrupt expansions in pipe size occur, they are accompanied by large scale turbulence producing loss of head. The energy loss for gradual expansions is generally less than that for abrupt expansions and is dependent on both the cone angle and the area ratio of the connecting pipes. It has been shown that the optimum angle for a gradual expansion is between six and eight degrees. Generally, Vennard states (1962), when the cone angle becomes greater than sixty degrees it is better to go with an abrupt expansion. Gradual and abrupt contractions also create head loss but in much smaller proportions. The transition loss from either a contraction or an expansion can be expressed by

$$h_t = K \frac{V^2}{2g} \qquad (2.10)$$

where the velocity is that of the smaller pipe. The loss coefficient, K, has been determined experimentially and is presented in numerous tables.

Gate Valve Loss (h_{gv})

Of the many types of valves available, gate valves offer the least resistance to flow and are generally the only type used in conjunction with sprinkler systems. On most irrigation systems a gate valve is installed near the pump to give the farmer control of discharge and pressure. If a gate valve at the pump does exist, it was of interest to determine the energy loss through the valve.

The head loss from a partially closed gate valve can be extremely large. Corp and Ruble in 1922 determined average values for the loss coefficient, K, to be used in the following equation

$$h_{gv} = K \frac{V^2}{2g} \tag{2.11}$$

where the K value depends on the size of the valve and the percent that the valve is open.

The problem in using Equation 2.11 is in obtaining a reliable K value for the percent that the valve is open. A much simpler method that yields a direct solution is found by taking pressure readings on each side of a partially closed gate valve. The pressure difference represents the head loss across the valve.

Other types of valves, such as check, foot, and butterfly valves, are found in irrigation systems and are grouped with the minor losses. Certain types of valves, such as globe and angle valves, are not used with sprinkler systems because of their extremely high head loss.

Selection of Main Line Size

In the design of main lines, the amount of friction allowed is generally a matter of economics. Nolte (1978) suggests that optimum pipe size selection can be based on three parameters which are: (1) the least annual cost, (2) pressure drop available, and (3) the velocity allowable. Most pipeline designs fall into one or more of these categories.

The least annual cost approach is used to balance the cost of operation with the cost of construction to provide a size which results in the lowest annual charge for the system (Nolte, 1978). This approach has its limitations due to the rapidly changing costs of power and materials.

The pressure drop available approach is often used for a gravity type system where pressure loss is required.

Velocity allowable is a logical approach for pipe selection, in that velocity is independent of pipe length as well as the number and style of fittings used. The velocity approach can permit size selection without knowing details about the system. The purpose in using this approach can be to keep the velocity below some upper limit because of water hammer. This method has limiting conditions in that it does not allow for variations in pressure or material to labor ratios and many other conditions; thus this method used strictly by itself may not meet the needs of the system.

The optimum diameter pipe for the main line of an irrigation system is the one that results in the lowest annual cost to the owner for his particular operating conditions. Many methods of selection have been cited in the literature over the years. Howland (1957) suggests a method consisting of fitting the various available sizes of pipe to a generalized curve of diameter for the theoretically most economical tapered pipe. Garton (1960) suggests a method of selection using a graphical approach that relates the number of hours per year of pumping, the fuel cost per horsepower hour, and the pump efficiency.

Bagley (1961) used a set of seven graphs, arranged coaxially, to be entered with eight variables to determine the most economical pipe size. Selection of economic concrete pipeline size for irrigation was suggested by Garton (1962) using a slightly different graphical approach from his previous method. Keller (1965) reported a method that assumed that only the friction loss portion of the total dynamic head is altered by different main line pipe size combinations. Keller concludes that the selection can therefore be based primarily on the water horse power required to overcome the friction losses in the main line under study. Perold (1974) determined a method whereby the most economical pipe sizes in a pumped system is found by determining the flow rates at which pipe sizes should be changed from one size to the next, according to the number of operating hours per year. There seem to be many more methods available and all are essentially based on one or more of the parameters suggested by Nolte.

Statement of Facts

From the previous discussion the selection of the correct size pipe line can be a complicated process. In designing main lines for sprinkler systems the loss of pressure caused by friction is the primary consideration. It should be remembered that the total friction, (h_L), which has been divided into four parts is what causes pressure loss.

There have been some generalized standards set for main line pipe selection. The Agricultural Engineers Yearbook states (1977):

> The allowable pressure loss in the main supply line shall not exceed an economically practical value that shall be determined by the system designer with the approval of the purchaser. This becomes a matter of balancing the capital cost of the pipe against the pumping costs that are incurred by friction. These will vary widely, depending on the location for which the system is being designed.

The yearbook also notes that for thermoplastic irrigation pipelines, the design water velocity when operating at system capacity should not exceed five feet per second.

Since the allowable pressure loss in main lines is essentially left to the designer's discretion, designers have come to rely on generalities that have been developed over the years. Rainbird (1961), a large manufacturer of irrigation equipment, concludes that for average power costs, if the pressure drop in the main line exceeds eight to ten pounds per square inch, then it usually becomes more economical to go to the next larger size of pipe and reduce the energy required to pump against the added head.

Another familiar guideline used by some designers is that the friction loss, h_f, should not exceed one foot of loss per one hundred feet of pipe. A final method that gives an indication of problem areas is to take the total friction loss, h_L, and divide it by the operating pressure and then multiply by one hundred to give a percentage value. This value indicates what percent of the operating pressure is lost to energy dissipation. The general rule is to keep this value below twenty percent for an acceptable operating system. With the data from the project some of the unanswered questions will be satisfied as to how effectively existing sprinkler irrigation systems are operating in Montana.

Chapter 3

SPRINKLER IRRIGATION SYSTEMS TESTED

Before explaining the procedures used to collect the field data, a brief summary of site selection and the physical characteristics of the different irrigation systems is presented.

SELECTION OF SITES

Cooperators in four Montana counties: Broadwater, Lewis and Clark, Park, and Yellowstone, were selected upon the criteria that their irrigation systems had to have a pump and a main line which terminated at either a flood irrigation or a sprinkler distribution unit. From the systems selected, thirty-nine tests were conducted. Of the thirty-nine systems none were of the flood irrigation type; all were sprinkler systems.

IRRIGATION SYSTEMS

The layout of main lines depends on the size and shape of the field, topography, location of the water source and pumping unit, and on the type of sprinkler distribution unit used. The distribution units encountered were center pivots, side rolls, big guns, boom sprinklers, and hand move laterals.

A center pivot system consists of a sprinkler lateral fixed to a pivot point. The lateral continuously rotates around the pivot point and is self propelled either electrically or by water, air, or oil hydraulics. The lateral consists of a pipeline suspended above the ground on individually powered tower units, and can vary in length depending on the field size.

The side roll system is a lateral pipeline, with sprinklers, carried by a series of wheels. The lateral pipeline acts as an axle through which power can be applied to roll the entire system to a new setting. The side roll system is stationary during the sprinkler operation and has to be shut off and automatically drained first before it can be moved.

Big gun and boom sprinklers can be either stationary or traveling systems which are mounted on portable wheeled units. The big gun consists of a high capacity nozzle which operates through a complete or part circle. The boom sprinkler consists of a tower and cable arrangement to hold the two booms in place. The booms are one hundred and eighty degrees apart and move about the center due to the reaction force of the water leaving the nozzles.

Hand move systems are laterals moved by uncoupling, picking up, and physically moving sections of the lateral pipe entirely by hand. Quick-coupling sections of aluminum pipe with rotating-head type sprinklers mounted along the pipe are the most common type of lateral used. The length of the sections is generally based on ease of handling and come in twenty, thirty, and forty foot sections.

IRRIGATION SYSTEM LAYOUTS

Of the thirty-nine systems tested, thirty-six were laid out, as shown in Figure 2, with only one pump and one main line. The system, depicted by Figure 2, consists of an intake pipe, a pumping unit, a main line, a distribution unit, and all the fittings, valves, and bends necessary to complete the system. The gate valve at the pump, which controls pressure and discharge, is optional but was found on most systems. Pressure gauges were found on all the systems tested while flow meters were only found on a few systems.

Only one system was tested with a layout such as that shown in Figure 3 which contains a booster pump in series with the initial pump. Booster pumping units are used where the change in elevation between the water surface and the distribution units is so large that two pumps are more economical than one large unit.

Two systems were tested where the main line flow splits and delivers water to two or more distribution units, such as the four side roll systems shown in Figure 4.

PUMPING UNITS

There were two different types of pumping units tested. These were the vertical turbine pump with multiple stages and the single stage centrifugal pump. All the turbine and most of the centrifugal pumps were electrically driven. Two systems were tested that had centrifugal pumps driven by diesel engines.