Sprinkler irrigation system design model and application
by Usaid Izzat Suliman ElHanbali

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Agricultural Engineering
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Abstract:
Two computer programs were developed to design sprinkler irrigation hand-move systems. They take soil, plant, and climatic data as input and then design the different components of the sprinkler system. The first program, PROGRAM-1, determines the sprinkler head specifications required which are flow and wetted diameter. The second program, PROGRAM-2, designs the lateral and the main line, finds the power requirements, and does an economic analysis. Several sprinkler and lateral spacing combinations can be tested and the one selected is that which gives the most economical solution. The criterion for that selection will be the total annual cost per acre. The two programs are applicable to the areas where sprinkler irrigation is introduced for the first time. The programs are applicable to a hand-move sprinkler system with single size pipe laterals that run parallel to the contour lines and a main line perpendicular to the laterals which runs either up hill or level.

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Date May 25, 1977

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ABSTRACT

Two computer programs were developed to design sprinkler irrigation hand-move systems. They take soil, plant, and climatic data as input and then design the different components of the sprinkler system. The first program, PROGRAM-1, determines the sprinkler head specifications required which are flow and wetted diameter. The second program, PROGRAM-2, designs the lateral and the main line, finds the power requirements, and does an economic analysis. Several sprinkler and lateral spacing combinations can be tested and the one selected is that which gives the most economical solution. The criterion for that selection will be the total annual cost per acre.

The two programs are applicable to the areas where sprinkler irrigation is introduced for the first time. The programs are applicable to a hand-move sprinkler system with single size pipe laterals that run parallel to the contour lines and a main line perpendicular to the laterals which runs either up hill or level.

Chapter 1

INTRODUCTION

"And with water we have made all which is living."
The Holy Koran

Irrigation has been practiced by man for thousands of years, and water had a crucial role in history, not merely as an adjunct of civilization, but as a stimulus to the development of civilization itself. It was no accident that the earliest civilizations arose in arid and semirarid regions, almost simultaneously in several parts of the world. The practice of irrigation was an essential ingredient of those civilizations.

The opinions among archeologists differ on the question whether flood irrigation was first developed in Mesopotamia or in the Nile Valley. The weight of evidence seems to favour Mesopotamia, where flood irrigation was practiced by about 6000 B.C. In the Nile Valley around 4000 B.C., cities became surrounded by flood irrigated fields which were controlled by gates. Basin-type irrigation began a little earlier than 3000 B.C., but by then irrigation was practiced in other parts of the world (Nace, 1975). Ancient irrigation works can be found in Egypt, Iran, Turkey, China, India, Iraq, Spain, England, and the Jordan Valley. In the western hemisphere, the inhabitants of Peru, Mexico, and the southwestern United States practiced irrigation thousands of years ago (Pair, 1975).

It was in early 1900's that pressure water systems of the cities were used to sprinkle lawns. After World War II, quick connecting lightweight steel and aluminum pipe, together with the impact-type sprinkler, made sprinkler irrigation feasible on almost all crops in both arid and humid areas of the world (Pair, 1975).

Sprinkler irrigation provides the essential soil moisture control needed for optimum crop yields. But, unless sprinkler irrigation is accompanied with good soil management, proper fertilization, insect and plant disease control, improved seed strains, and mechanized farming operations, these optimum crop yields cannot be achieved. Moreover, sprinkler irrigation, with its flexibility and efficient control of water application, permits a wide range of soil to be irrigated and has caused changes in land use classification that allows a much greater acreage to be classified as irrigable. Many improvements have been made in sprinkler irrigation equipment and today more information is available on proper operation, sprinkler spacings, pressures, nozzle sizes, weather conditions and system design.

The ultimate goal of a sprinkler-irrigation system design is to obtain a system with optimum nozzle capacity, sprinkler head spacing, lateral spacing, lateral size, main pipe size, and power requirements such that the irrigation system, in addition to meeting the crop and soil requirements, is the most economical one. It is evident that there is a need for a computer program to aid in finding that most economical system. By using a computer, different system parameters can be analyzed rapidly and the optimum solution can be established.

Electronic computers with high speeds, large memory capacities and sophisticated monitor systems have been used extensively in engineering design. This study makes use of the computer in the field of irrigation design. One of the characteristics of the computer that makes it unique among technical achievements is that it has forced men to think about what they are doing with clarity and precision.

Though the computer program developed in this study is in general form, it is oriented to be used in the design of sprinkler systems for the newly irrigated areas in the Jordan Valley, Jordan. The hand-move sprinkler systems have been recommended for those areas in a previous feasibility study (Nedeco, 1974). Based on the annual cost analysis the study showed that sprinkler irrigation is more economical than surface irrigation, especially since labor cost has risen sharply in recent years. However, the developed computer program takes into consideration that research studies to determine crop consumptive use and the distribution patterns of sprinklers with respect to local wind conditions are not available for these areas.

It is hoped that using a computer in sprinkler design and operation will make the design of sprinkler system components more efficient and the operation more precise, resulting in a more profitable irrigation system.

Chapter 2

REVIEW OF SELECTED LITERATURE

A review of the literature indicates that there have been no published studies which have the same objectives as this study. However, several studies have been similar in that they involve computer modeling to design solid set sprinkler irrigation systems, to determine the agriculture crop water requirements or to determine irrigation scheduling.

An early study made by Bruhn (1938) proposed a method for designing sprinkler irrigation systems based on cost analysis which included the initial cost but excluded water cost. Schaenzer (1938) used 50 feet as lateral spacing in a similar sprinkler irrigation study.

The total equipment costs of sprinkler irrigation were studied again in the late forties by Peikert (1947) and Lewis (1949). They found an average cost of $75 per acre for light-weight portable pipe and a semi-portable system. The design of these systems was usually supplied by dealers. In the fifties, Jacobson (1952) found the average initial cost of sprinkler irrigation was about $4.00 per acre-in. Howland (1957) developed methods of selecting economical irrigation pipe by evaluating energy loss in the pipe and the cost of installation. The cost of water as a function of system-design variables was not included in their studies.

The use of uniformity of water distribution as criterion for evaluating efficiency of water application was studied by McCulloch (1949). His study indicated that for a good design, the type of sprinkler nozzle, its operating pressure, and main-line and lateral spacings, should be so selected as to limit variation in moisture distribution to 20 percent or less (uniformity 80 percent or more). The ASAE recommendations (1954) suggested that a sprinkler irrigation system should be designed to achieve a good uniformity of water application by selecting proper spacing, etc. It also recommended that the desirable operating pressures, spacing of sprinklers and nozzle size should be obtained from the sprinkler manufacturer. Various ways of describing uniformity were derived. The statistical parameters of collected sprinkler readings such as mean value, mean deviations and standard deviation are the ones commonly used. The most common and frequently used equations were those derived by Christiansen (1941), Wilcox (1955), Hart and Reynolds (1965). The use of computers in the sprinkler irrigation studies started in the early 60's. Hart (1963) used a digital computer to analyze the sprinkler distribution pattern. The program accepts observations from a single sprinkler and overlaps them to generate a rectangular pattern for the spacing desired. The generated patterns are then statistically analyzed for distribution characteristics by two procedures using uniformity coefficient principle.

Work on determining economical sprinkler spacings and lateral spacings are scarce in reference literature. Several studies looked at various components of a sprinkler irrigation system. Labor cost analysis was studied by Shull (1966). Korven (1965) studied initial equipment and labor cost. Keller (1965) investigated the most economical pipe-size combination which gives the minimum total fixed operation cost. ASAE recommendation (ASAE S262[T], Sprinkler Irrigation Technical Sheet) suggested a procedure for doing an economic analysis of sprinkler irrigation systems. The objectives of past sprinkler irrigation studies were either to develop methods to describe uniformity or to analyze equipment cost, both of which are used separately as criterion in evaluating and selecting sprinkler systems. But in a study by T. Liang and Wu, I-pai (1970), a computer program was developed to aid in the design of solid set sprinkler irrigation systems. In that study the criterion for a system design is the cost of the entire irrigation system (including equipment as well as water but excluding the pump), subject to crop, soil, and other restraints on the system. Also in that study it is necessary to test the sprinkler under field and wind conditions and the resulting precipitation data will be used in the program to evaluate the entire sprinkler system. The size of lateral and main line was determined by using the "slide rule" from the "Rain Bird Company," and by restraining the pressure loss to less than

10 percent of the operating pressure. The selection of an irrigation system criterion is the overall cost, in dollars per acre-inch, for delivering useful water to the root zone.

It is understood that some irrigation companies have developed their own programs to aid them in the design of sprinkler systems. These programs are not published nor available to the public. On the other hand, several studies have been made to determine the evapotranspiration and the consumptive use of crops, but these studies were primarily to schedule irrigation and not for determining the peak consumptive use as a basis for the design of irrigation systems. A computer program for the extensive computations that are required to evaluate the various estimating methods of evapotranspiration was prepared by R. D. Burman (Jensen, 1973). In a study by Nimer and Bubenzer (1972), a computer model was developed to determine the irrigation potential of selected land areas. A data bank containing crop, soil, and probable well yield data was developed for the state of Wisconsin. This data plus information furnished by the prospective irrigator is used to evaluate the potential irrigation of the selected area.

USDA has developed a computer program for irrigation scheduling (Jensen, 1972). The computer program requires limited input data and uses simple, basic equations so that each can be replaced as more accurate relationships are developed. The U. S.

Bureau of Reclamation has modified the program to provide general irrigation forecasts for the major crops in an area.

Chapter 3

GENERAL PROCEDURE

In the design of sprinkler irrigation systems, the selection of a sprinkler and lateral spacing combination is one of the most difficult parts of the design. Usually the selection of the spacing combination is based on judgment and/or local experience. Thus, this selection does not take into consideration the effect of spacing combination on the overall cost of the sprinkler system and on the total annual cost per acre for that system. Moreover, for a newly irrigated area without background or experience in sprinkler irrigation, the selection of a specific spacing combination will be only a matter of judgment which may not give the most efficient design and the least cost system.

The two computer programs developed in this study, PROGRAM-1 and PROGRAM-2 are to design a hand-move sprinkler irrigation system with laterals running parallel to the contour lines and the main line running perpendicular to the laterals, uphill or level. Different spacings of sprinklers on the lateral and of the laterals on the main line are tested and the optimum solution can be then established.

PROGRAM-1 is to determine the sprinkler head specifications in order to select the appropriate sprinkler heads. In the procedure described afterwards, the adjustment of the soil intake rate and the calculation of the wetted diameter are based on the material in "Sprinkler Irrigation Handbook" by Fry and Gray (1971). PROGRAM-1 has one subroutine, SOIL SUBROUTINE, in which soil information is read and it will also be used in PROGRAM-2. This subroutine will be useful to read the soil data if there is more than one type of soil, or if coding of the different types of soil is desired. An illustrative flow chart for PROGRAM-1 is presented in Appendix A Figure 7, a variable glossary in Appendix B, a listing of the program in Appendix C, and an example output of the program in Appendix D.

PROGRAM-2 is to calculate crop peak daily use, irrigation interval, lateral operating hours, number of lateral sets per day and number of laterals. It is also to size the laterals, the main line and the valves. Then power requirements and economics are analyzed. Sizing of laterals and main line, calculating the power requirements and doing the economic analysis are processed as described in "Sprinkler Irrigation" by C. H. Pair (1975). PROGRAM-2 has five subroutines: SOIL SUBROUTINE to input soil data, PLANT SUBROUTINE to input plant data, CLIMATE SUBROUTINE to input climatic data and to calculate the crop peak daily consumptive use as described in Jensen-Haise method (1963, 1966), SPRINKLER SUBROUTINE to input the selected sprinkler head specifications, and INPUT SUBROUTINE to write the input data needed to run this program. By using subroutines it is possible to reduce the total program size and the amount of branching which must be done in the program. It is usually simpler for a programmer to handle subroutines which are separated physically, rather than attempting to integrate them in the program by branching. Illustrative flow charts for PROGRAM-2 and SUBROUTINE CLIMATE are presented in Appendix E, Figure 8, and Figure 9 respectively. A variable glossary is provided in Appendix F, a listing of the program in Appendix G, and an example output of the program in Appendix H.

The language used in these two programs is FORTRAN IV, and the computer machine is Xerox Sigma 7. The computer time needed to run PROGRAM-1 is 1 minute, and PROGRAM-2 is 2 minutes.

Chapter 4

PROGRAM-1

PROGRAM-1 is a computer program to determine sprinkler head specifications taking into account the intake rate of the soil and the average speed of prevailing winds.

INPUT INFORMATION

Since the application rate of a sprinkler should be equal or slightly less than the intake rate of soil, to insure no runoff, the intake rate of the soil should be determined. This intake rate should then be adjusted for slope effect (Pair, 1975). Also in selecting the soil intake rate values for sprinkler system design, it is essential not to use initial rates, but to select a rate which will prevail during the total irrigation (Pair, 1975). The soil input information, in addition to the intake rate in inches per hour, will include: type, texture, depth in feet, and holding capacity of that soil in inches per foot. This information will be read in SUBROUTINE SOIL, and will be used later in PROGRAM-2.

The other input information needed to run this program is the average speed of prevailing winds in MPH during the growing season. Based on this information and on Irrigation Guides or local experience, different spacings between sprinklers on the laterals (SL) in feet, and spacings of laterals on main line (SM) in feet, are read into the program. If field observations for the distribution pattern of sprinklers are available, taking into consideration the wind velocity, wind direction, and risers height, the spacings selected should be based on this information.

CALCULATING PROCEDURE

Once all of the above information is read into the program, the computer is ready to start calculating the sprinkler head flow in GPM and the wetted diameter in feet for the different spacings. First it will adjust the soil intake rate for slope effect as shown in Table 1.

Table 1

Adjustment of Soil Intake Rate for Effect of Land Slope

Slope	Intake Rate Reduction
0- 5% grade	0%
6- 8% grade	20%
9-12% grade	40%
13-20% grade	60%
over 20%	75%

Next it will read the average speed of prevailing winds (AWS) in MPH and the different spacings of sprinklers on laterals (SL) in feet and the different spacings of laterals on the main line (SM) in feet. Then it will calculate the flow of each sprinkler for each combination of (SL) and (SM), as follows:

$$Q = (IRA*SL*SM)/96.3 \quad (1.1)$$

where

Q = Flow of sprinkler in GPM

IRA = Adjusted intake rate of the soil in inches/hour

SL = Spacing of sprinklers on the lateral in feet

SM = Spacing of laterals on the main line in feet

Next it will calculate the wetted diameter of the sprinkler for each combination of (SL) and (SM) as shown in Table 2.

Table 2

Selection of Sprinkler Wetted Diameter With Respect to Average Wind Speed

Average Wind Speed	Spacing
Up to 7 MPH	SL = 40% of wetted dia.
	SM = 65% of wetted dia.
Up to 10 MPH	SL = 40% of wetted dia.
	SM = 60% of wetted dia.
Above 10 MPH	SL = 30% of wetted dia.
	SM = 50% of wetted dia.

OUTPUT

PROGRAM-1 will give the desired flow of the sprinkler in GPM and the wetted diameter of sprinkler in feet, for each combination of (SL) and (SM) spacings. This output will be used to select the available commercial sprinkler heads. The specifications of the selected sprinkler heads will be then read into PROGRAM-2.

Chapter 5

PROGRAM-2

PROGRAM-2 is a computer program to design laterals, main lines, size valves, find power requirements and do an economic analysis. It consists of MAIN PROGRAM-2 and five subroutines, namely SUBROUTINE SOIL, SUBROUTINE PLANT, SUBROUTINE CLIMATE, SUBROUTINE SPRINKLER and SUBROUTINE INPUT.

Before running this program it is assumed that the engineer has determined the layout of the sprinkler system. Thus there will be a good estimate of the length of both the lateral and the main line, and the difference in elevation between the pump and the end lateral. This program is written for systems with the laterals running parallel to the contour lines and the main line perpendicular to the laterals either up hill or level.

INPUT INFORMATION

PROGRAM-2 takes soil, plant and climatic data as input. It also takes as input the specifications of the selected sprinkler heads, as determined by PROGRAM-1 output.

The soil data includes type, texture, holding capacity in inches per foot, depth in feet, intake rate in inches per hour and slope as a percentage. This information will be read into the SUBROUTINE SOIL. The plant data includes name of crop and its root zone depth in feet. This information will be read into the SUBROUTINE PLANT. The climatic data includes maximum and minimum daily temperatures in ^{o}F, daily solar radiation in cal cm^{-2} or langleys, and effective daily precipitation in inches. Since this data will be used in calculating the peak daily consumptive use, which occurs about July 15 to July 25 in the northern hemisphere (Jensen, 1972), the data read in this program will be the average daily data of July. This information will be read into the SUBROUTINE CLIMATE. The other information that is read into this subroutine is the average elevation of irrigated area (E) in feet, crop factor (KC) and Jensen-Haise constant C2.

The sprinkler head specifications will be read into the SUBROUTINE SPRINKLER. The selection of these specifications will be according to the output of PROGRAM-1. These specifications include type, flow in GPM, wetted diameter in feet, pressure in psi and nozzle diameter in inches. Also the different spacings of sprinklers on the laterals (SL) in feet, and those of laterals on the main line (SM) in feet and the cost of sprinkler heads in dollars, will be read into the same subroutine.

The other information needed to run this program will be read into the MAIN PROGRAM-2 and will include:

Leaching requirements in inches

Efficiency of sprinkler system in decimal form

Area to be irrigated in square feet

Length of lateral in feet

Length of main line in feet

Hazen-Williams coefficient (C)

Exponent (M) in Hazen-Williams equation for head loss in pipes

Elevation at the center line of the pump in feet

Suction head on the pump in feet (assuming centrifugal pump)

Pump efficiency in decimal form

Net seasonal irrigation requirements in inches

Cost per kwh in dollars

Demand cost in dollars

Efficiency of the motor in decimal form

Note that the cost of the different diameters of aluminum and steel pipes and the cost of main line risers used in the main program should be changed to meet local current prices.

CALCULATING PROCEDURE

PROGRAM-2 consists of MAIN PROGRAM-2 and of five subroutines. The calculating procedure of the MAIN PROGRAM-2 and the subroutines are as follows.

MAIN PROGRAM-2

After reading the input information, the calculating procedure will be:

1. Calling the SUBROUTINES: SOIL, PLANT, CLIMATE, SPRINKLER, and INPUT.

2. Calculate the peak daily use of crop:

Peak Daily Use = Average Peak + Leaching Requirements (1.5)

where the average peak of the crop daily consumptive use has been calculated in SUBROUTINE CLIMATE.

3. Calculate net and gross moisture to be replaced each irrigation. This is based on root zone depth of crop and on soil depth. If soil depth is less than root zone depth, the root zone depth is limited to the value of soil depth. The available moisture content of the soil is equal to:

AMC = (Holding Capacity/ft)* Root Zone Depth (2.5)

The allowable percentage of soil moisture depletion before irrigating is a function of crop, its root zone depth, soil type and texture, irrigation policy and economics. However, in this program, the criterion for determining this percentage and calculating the net moisture to be replaced each irrigation is arbitrary and based on the following assumptions:

High value shallow rooted crops(RZ≤3ft) maintain 67% available moisture

For lower value deeper rooted crops (RZ≤5ft) maintain 50% available moisture

For low value deep rooted crops (RZ>5ft) maintain 33% available moisture

These assumptions can be altered depending on the availability of local data and on the engineer's experience, i.e., in a study on when to irrigate alfalfa (Hanson, 1972), little difference in yield or the amount of water used per unit of hay produced was found when irrigations were made within the range of 20 to 75 percent of the available soil moisture remaining.

The gross moisture to be replaced each irrigation is equal to:

$$GMR = \frac{\text{Net Moisture Replaced}}{\text{Efficiency of Sprinkler System}} \qquad (3.5)$$

4. Calculate irrigation interval, irrigation period, lateral operating hours, number of sets per lateral per day, and number of laterals:

$$\text{Irrigation Interval} = \frac{\text{Net Moisture Replaced}}{\text{Peak Daily Use}} \qquad (4.5)$$

The irrigation interval should be usually an integer number. This program allows 0.10 day as a maximum before truncating the value of the irrigation interval calculated by equation (4.5).

$$\text{Lateral Operating Hours} = \frac{\text{Gross Moisture Replaced}}{\text{Application Rate}} \quad (5.5)$$

where the application rate is calculated in the SUBROUTINE SPRINKLER. Since the sprinkler system designed by this program is a hand-move semi-portable system, one hour is allowed to move the lateral. So for lateral operating hours less or equal 7, three sets per lateral per day are possible. If lateral operating hours is greater than 7 and less than or equal to 11, two sets are possible; otherwise only one set is possible.

Number of laterals =

$$\frac{\text{Area to be Irrigated (sq. ft)}}{\text{No. of sets/day * SM (ft) * Irrigation Interval (days) * length of lateral (ft)}} \quad (6.5)$$

Irrigation Period =

$$\frac{\text{length on the Main Line Irrigated by One Lateral}}{\text{SM * No. of Sets/lateral/day}} \quad (7.5)$$

where the Length on the Main Line Irrigated by One Lateral =

$$\frac{\text{Area to be Irrigated (sq. ft)}}{\text{Lateral Length (ft) * No. of Laterals}} \quad (8.5)$$

and SM = Spacing of laterals on the main line in feet

5. Design of Lateral: this program is limited to a single size pipe lateral. In order to obtain the high water application efficiencies possible with sprinkler irrigation, it is essential to keep the variation in pressure at a practical minimum. For good

design, the variation should be held to ± 10 percent of average lateral design pressure (ASAE minimum performance for sprinkler systems). On level ground, the case assumed here, this would mean holding the pressure drop due to friction to 20 percent between the first and the distal sprinkler. For practical purposes, allowable friction loss can be computed by multiplying the required average pressure (determined by the sprinkler selected) by 23.4 percent (Pair, 1975).

To simplify the computations of the losses in the laterals, they are assumed mainly as the friction losses in the pipe. Christiansen's procedure (1942) for calculating losses in pipes with multiple outlets is used here:

$$H_f = F\left(\frac{K\ L\ Q^m}{D^{2m+n}}\right) \tag{9.5}$$

in which

H_f = head loss in feet

k = a friction factor based on the friction formula used (here it is Hazen-Williams Eq.)

L = the length of pipe line in feet

Q = the total flow into the lateral in cu.ft./sec

D = the diameter of pipe in ft

F = is a factor for multiple outlets effect on friction losses

The exponent m, velocity exponent, and n, a pipe diameter exponent, are based on the formula used.

The diameter of pipe computed by equation (9.5) is to be rounded to the nearest commercial diameter. This program allows only 0.10 inches as a maximum increase in the pipe diameter before it is rounded to the next diameter.

6. Design of Main Pipe Line: there are a number of varying conditions which may govern the design of main lines (Pair, 1975). The selection of the economical pipe sizes is an engineering consideration of as much importance as the solution of the hydraulic problems involved (Keller, 1965). However, in this program the trial-and-error method is used. By running the program several times, the most economical solution for the whole sprinkler system can be established.

In the first run of this program, the loss of 1 ft head per 100 ft of the pipe length is used as a "rule of thumb" to determine the diameters of the several parts of the main line. In the subsequent runs, these diameters may be increased or decreased to obtain the most economical solution for the whole sprinkler system. The criterion for that is the total annual cost per acre. However, it is also necessary to examine the velocity of flow before increasing or decreasing the diameters of the main line segments, and to keep these values within the allowable limits for each pipe material.

Hazen-Williams equation for head loss in pipes is used to calculate the pipe diameter:

$$D = \left(\frac{10.43\ L\ Q^{1.85}}{C^{1.85}\ H_l}\right)^{1/4.87} \qquad (10.5)$$

in which

D = pipe diameter in inches

L = length of pipe in feet

Q = flow of the pipe in gallon per minute

C = Hazen-Williams coefficient

H_l = head loss in feet

PROGRAM-2 can handle the configurations of laterals on the main line shown in Fig. 1, i.e., from two laterals on the main line up to twelve laterals. For more than twelve laterals, the program can be easily modified. Also PROGRAM-2 is applicable to buried main lines which run uphill or on level ground. For downhill main lines, special consideration must be given to the elevation difference if the average slope gradient exceeds the friction-head gradient.

7. Calculate Power Requirements: the total dynamic head on the pump may be determined by the following equation:

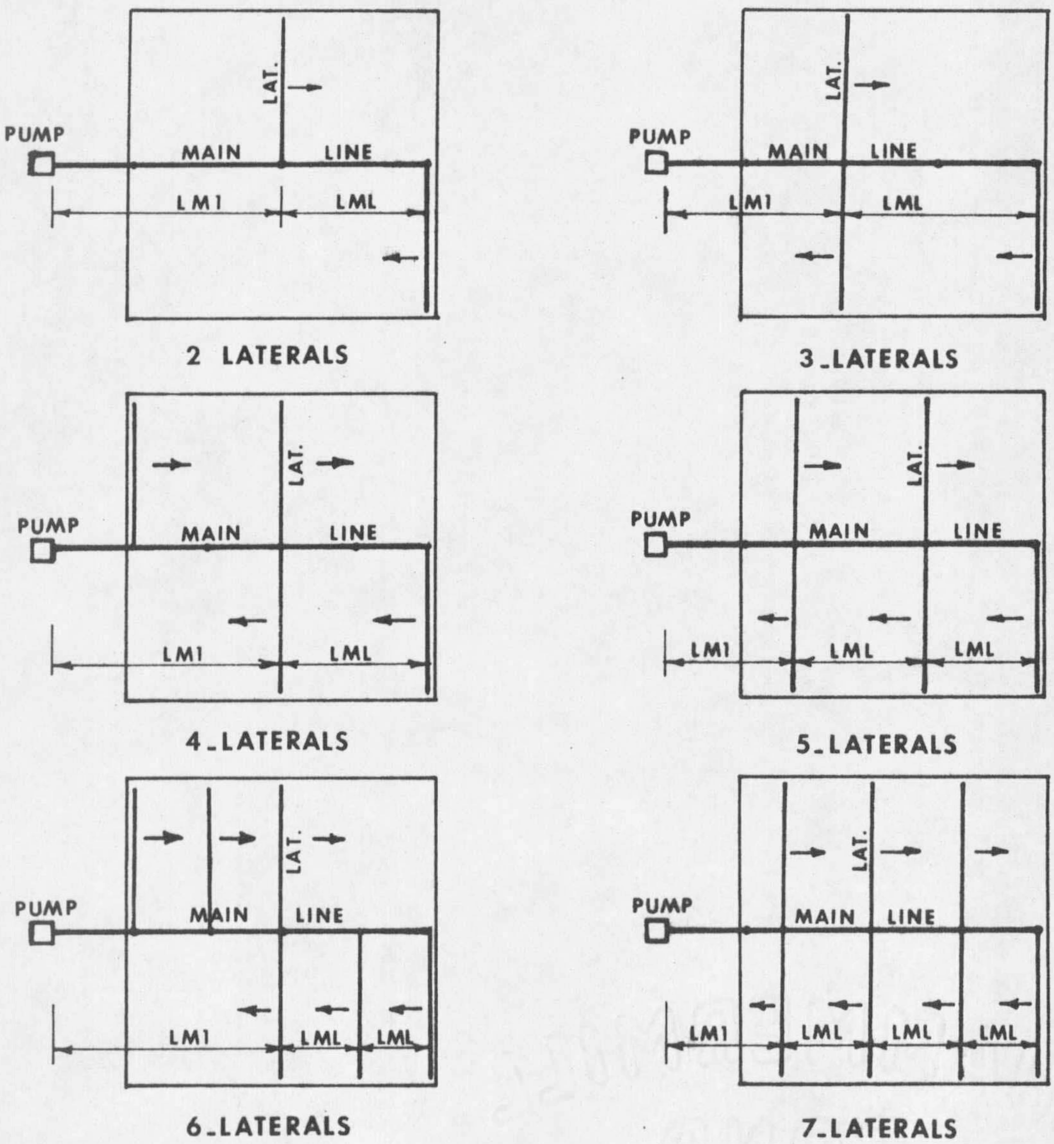

Figure 1. Laterals Configurations