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New Irrigation System Design for Maximizing Irrigation Efficiency and Increasing Rainfall Utilization

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ABSTRACT

A new concept in irrigation system design, which has the potential of significant savings in both water and energy requirements, has been developed and is under evaluation. The system is characterized by and has been labeled a low energy-precision application (LEPA) system, which rather than spraying water into the air at moderate to high pressures, distributes it directly to the furrow at very low pressure through drop tubes and orifice controlled emitters. This occurs as the system continuously moves through the field in a rectilinear fashion. The system is used in conjunction with micro-basin land preparation which also optimizes the utilization of rainfall. The combined system minimizes the effect of soil and climatic variables which adversely influence furrow and sprinkler irrigation efficiencies. Significant savings of both water and energy resources are indicated from results of the limited testing to date.

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INTRODUCTION

In irrigated agricultural production it is possible that irrigation is the least efficient operation involved in the production of the crop. It is also normally the greatest consumer of energy in the crop production process. It is likewise possible that the low efficiency and excess energy consumption is caused by variables beyond human control using current irrigation system technology.

In furrow or other gravity irrigation methods, variables such as soil intake rate, length of run, slope, capacity of the well, and varying water management skills make precise control of applied water difficult. It is not uncommon in furrow irrigation to apply many times the amount of water necessary to fill the root zone, which means extremely low irrigation application efficiency. This also results in wasted energy for pumping water that does not remain in the root zone. Extremely low distribution efficiencies are also possible with furrow and other gravity systems.

Sprinkler systems, in general, provide greater control over application rates than do furrow or flood irrigation systems. However, the control gained is at the expense of additional energy necessary for the distribution of water at the higher pressures. High pressure center pivots, in some areas, require as much or more energy for pressurization as is expended in the delivery of water to the pivot.

Climatic conditions also have a significant effect on the irrigation efficiencies of a sprinkler system. High wind conditions, such as are common in the Great Plains, cause the distribution efficiency (coefficient of uniformity) to be lowered considerably. Also substantial losses of water are experienced due to spray evaporation. A recent study by Clark (7) revealed significant spray evaporation losses from solid set sprinklers. Wind speeds of 15 mph resulted in evaporation losses of 17 percent. This is about the annual average wind speed in the Texas Panhandle-South Plains area. Spray evaporation losses at wind speeds of 20 mph were greater than 30 percent. In the Texas High Plains where this research was conducted, wind velocities much higher than this can be expected numerous times during the growing season and especially during the spring preplant irrigation period. Thus, the application efficiency of sprinkler systems can be quite low in semi-arid areas.

The problem of inefficient irrigation application systems can, therefore, be attributed primarily to a lack of control over the quantity of water delivered to, and its distribution in, the soil root zone. The lack of control is many times due to variables, such as climatic factors and changing soil intake rates, which cannot always be compensated for with present irrigation system technology.

Background Information

Low pressure sprinkler and drip irrigation methods are essentially in their infancy as compared to other existing irrigation methods. Thus, research on mobile drip type systems has been very limited. Wilke (29) designed a tractor mounted frame which was capable of moving a single drip lateral over either one or two 40-inch rows in cotton. The system required about 30 minutes moving time per acre irrigated. However, the system was adapted only to very low capacity wells and to low growing crops.

One report only has been found involving a mobile wheel type drip system. Rawlings (21) and associates used a small pilot model involving a traveling trickle system. Trickle sources were 18-inch sections of 1/2-inch PVC pipe. Flow into each pipe was controlled by 1/6-inch nylon tubing spaced 18 inches apart, each having a flow rate of 0.17 gallons per minute. They visualized a field scale system design for a center pivot system.

The importance of controlling or retaining rainfall for enhancing dryland crop production has long been recognized and the benefits well documented (5, 6, 18). Numerous methods have been employed to accomplish this; often the one being chosen depending on factors such as topography, soil profile, intended cropping pattern, and economic resources required for the establishment of the practice. These practices which have been employed singularly or in combination include contouring, terracing, conservation and level benching, and various deep tillage methods. Basin tillage has also been used to some extent in the past. However, the practice was used primarily on dryland production during the fallow period. Also, most basin tillage equipment that can be found was designed with technology of the 1930's. Recorded use of basin tillage in conjunction with irrigation is extremely limited. Aarstad (1) reduced runoff from about 40 percent to one percent under center pivot sprinklers by using small basins between crop rows. Increased yields of sugarbeets and potatoes were also reported.

Research Objective

The primary objective of this reported research is the enhancement of total water utilization in irrigated agricultural production and the reduction of energy requirements for irrigation. The term total water utilization used herein includes the utilization of water derived from rainfall in addition to other water sources which are applied through irrigation systems.

The approach taken in this project to enhance total water utilization involves the development and evaluation of a new concept in irrigation application systems along with auxillary equipment designed to increase the retention and utilization of rainfall. The two were designed to be complimentary by providing high irrigation efficiencies with low energy requirements, while at the same time, decreasing irrigation demand due to greater soil rainfall storage.

PROCEDURES

The alleviation of problems mentioned in the previous section was approached by the development and evaluation of an irrigation system whose application and distribution efficiencies are not significantly affected by soil, climate, and other uncontrollable variables. The system was designed for precise control of application amounts with uniform distribution and to accomplish this at a much lower energy requirement than that of current non-gravity systems. The approach to the overall water utilization problem also included development of methods to obtain greater rainfall retention so that the amount of irrigation water required may be reduced.

In initial stages of development, the system was designated a mobile trickle system in which a large number of small stationary orifices of a conventional trickle system were replaced with a small number of large moving orifices. The high emitter flow rate, however, could hardly be construed as trickle irrigation and the concept has since been labeled a low energy precision application (LEPA) system.

Mechanical Design

The following criteria were followed in the design of the LEPA system:

(1) Adaptable to wide range of flow rates (100 to 1,000 gpm) in order to utilize both low and high capacity wells;

(2) Adaptable to all soil types (requires variable travel speed but is less critical when combined with basin tillage);

(3) Low pressure operation (5 to 20 psi, for energy conservation and use with existing pipe);

(4) Capable of continuous linear movement;

(5) Capable of utilizing low pressure underground pipe systems already installed on many farms; and

(6) Adaptable to and requiring minimum alterations of present production systems.

The system was broken down into numerous components for design and development. Many of these are shown in the schematic diagram given in Figure 1. These components are as follows:

(1) System hydraulic design for uniform water distribution.

The prototype system was designed to incorporate a manifold distribution system. Water was taken out of the main pipeline by a 2 1/2-inch hose where it entered the manifold distribution pipe by either a manually operated flow control valve or an automatic pressure regulating valve as shown in Figure 2. The pressure regulating valve to each manifold served to eliminate pressure differentials between manifolds due to friction loss in the main line and to elevation changes in the field. Each manifold was suspended from the main pipe with a track and trolly arrangement which allowed a 35-inch horizontal adjustment in the drop tube location. The emitters could, therefore, be centered over the furrow or bed as desired. A portion of a manifold system is shown in Figure 3.

(2) Emitter source or outlet design.

The design allows each 40-inch furrow to be served by a drop tube and outlet. The outlets have been designed for an omnidirectional discharge of water over a 12 to 14 square-inch area. They simulate gentle rainfall when operated at a height of 3 to 4 inches above the furrow. The outlets are designed to operate in the 1 to 5 psi range with discharge controlled by orifices. The size of orifices along each manifold may be regulated to compensate for friction losses within the manifold. Figure 4 depicts a discharging emitter.

(3) Variable speed drive and alignment system.

Compressed air and an air hydraulic drive system propels the system. Variable flow dividers and flow control valves are incorporated for speed

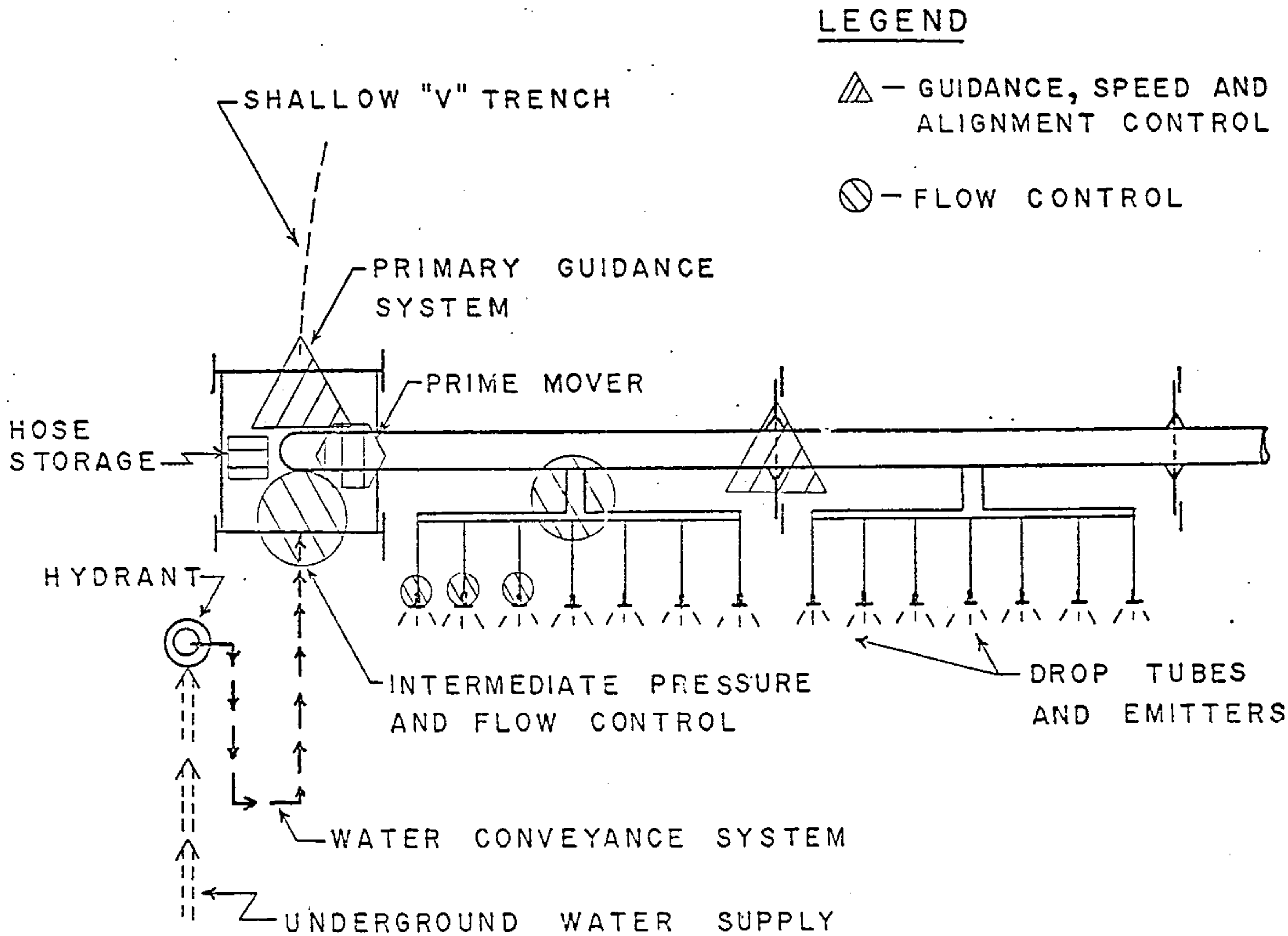


FIG. I. SCHEMATIC DIAGRAM OF LOW ENERGY PRECISION APPLICATION SYSTEM

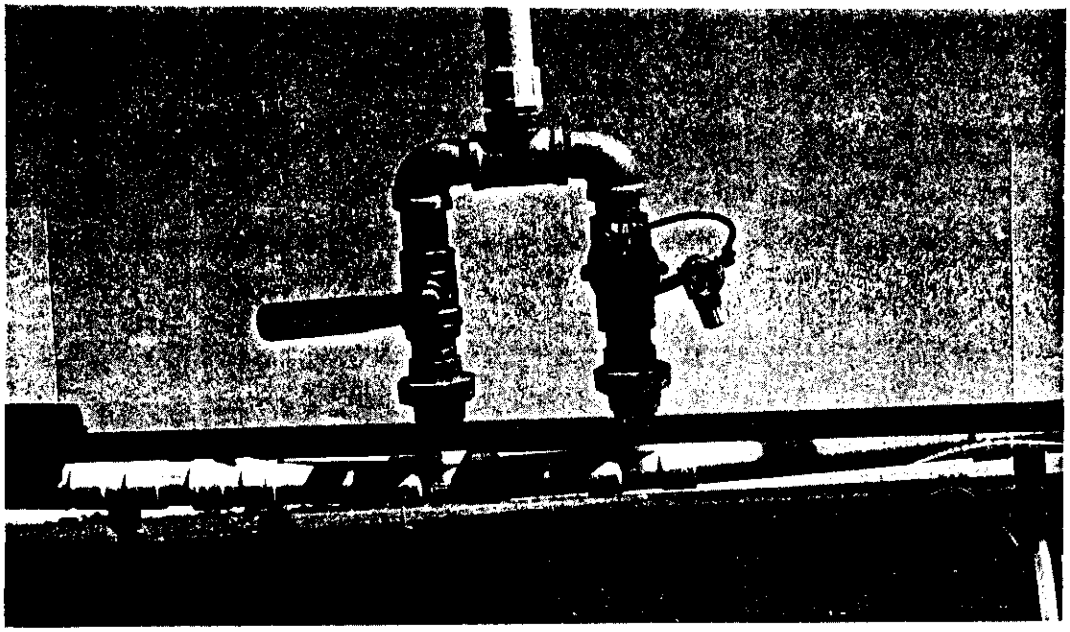


Figure 2. Manual flow control and automatic pressure regulating valves.

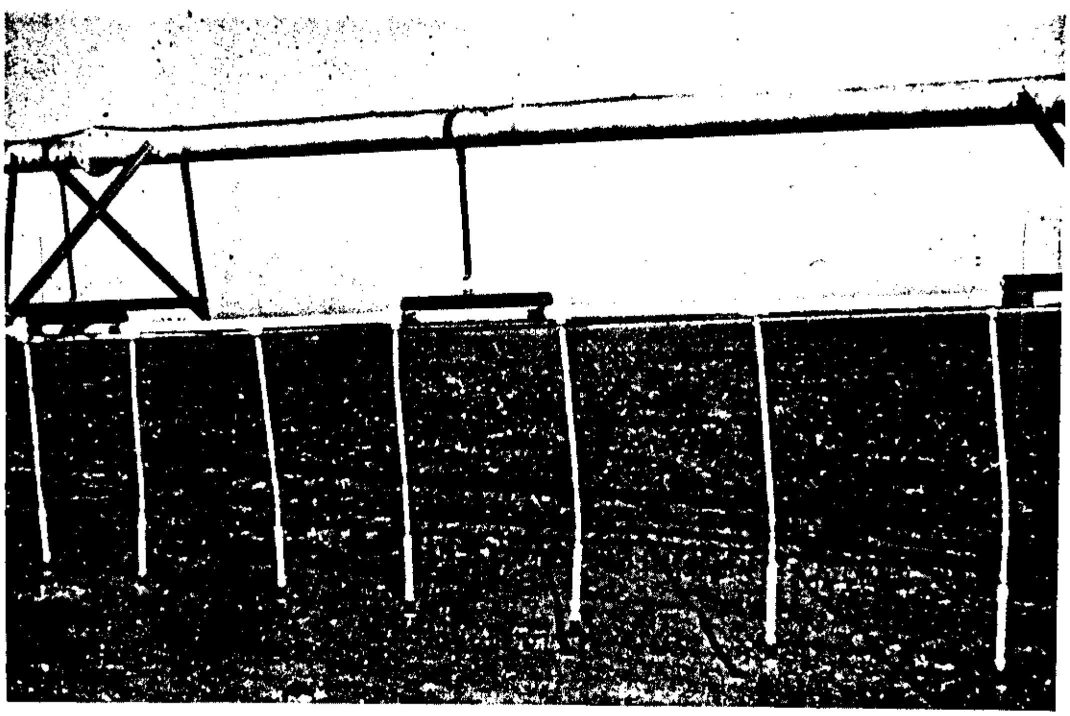


Figure 3. Manifold drop tube distribution system.

Figure 4. Discharging emitter.

control of the command platform and alignment of the pipe system. A mechanical torsion arm and cam arrangement is located at the pivot pad which is responsible for keeping the main pipeline and towers perpendicular to the direction of travel of the pivot pad and command platform. A change in the angle between the command platform and the main pipeline controls the movement of the end tower. The middle towers then align themselves between the command platform and the end tower by other cam actuated valves controlling the hydraulic cylinders.

The prime mover is an 18-horsepower gasoline engine. Figure 5 shows a portion of the air hydraulic system.

(4) Guidance system.

The guidance system combines a mechanical sensing element which actuates a pneumatic direction control circuit. A double disc guide, which is

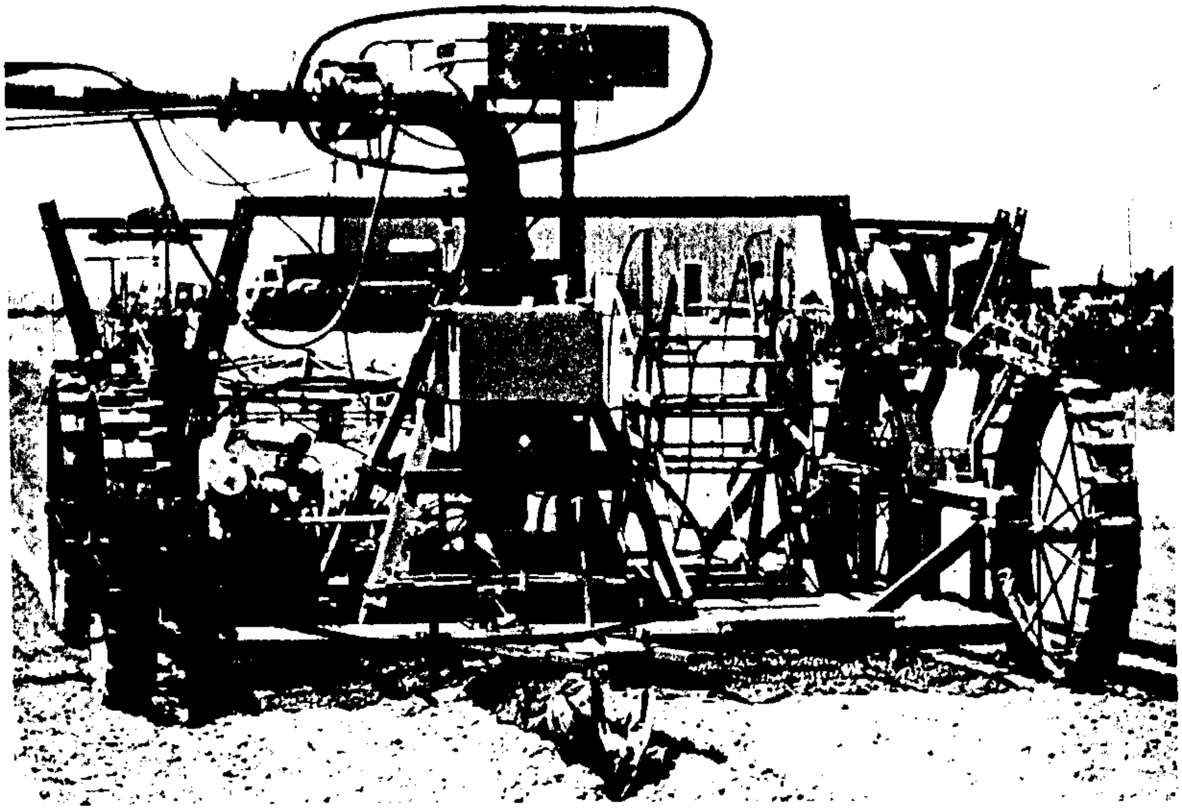


Figure 5. Command platform and portions of air hydraulic system.

designed to follow a shallow trench or furrow is attached to a direction sensing arm. The movement of the sensing arm triggers a 4-way air valve which then directs compressed air to the appropriate wheels. Direction is maintained by application of differential power. The direction sensing arm and double disc guide are depicted in Figure 6 and shown following a trench in Figure 7.

(5) Conveyance system for transporting water from underground pipe risers to the system while allowing system mobility.

Flexible lay-flat irrigation hose is used to convey water to the mobile system. The hose operates at lower than normal design pressure (<10 psi). Therefore, hose carts have been designed that maintain an adequate bend radius and aid in maintaining the internal diameter of the hose at low pressure. The hose and hose cart are illustrated in Figure 8.

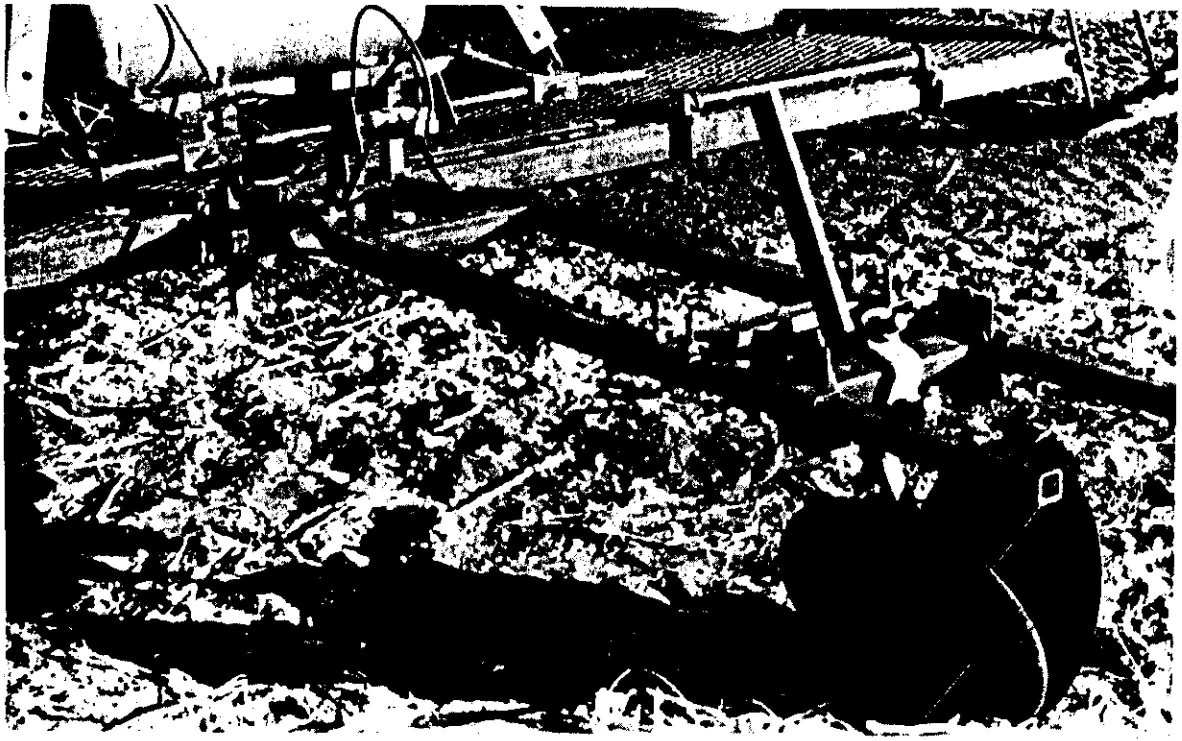


Figure 6. Mechanical double disc guidance sensing component.

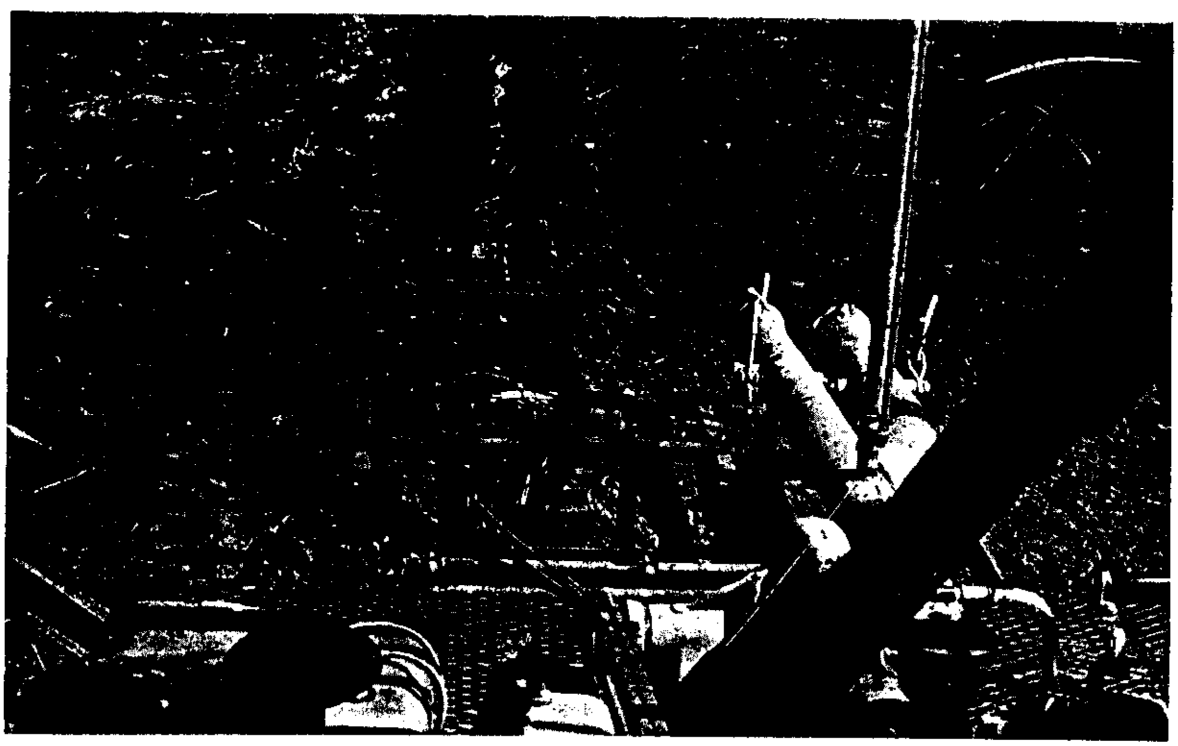


Figure 7. Double disc guide following a shallow trench.

Figure 8. Supply hose and hose cart.

Two hoses are required to prevent pump stoppage when switching from one underground pipe riser to the next. One hose is therefore stored on a hose reel while the other is supplying water. The second hose is wound on the reel by means of a small air motor with a 200 to 1 gear reduction to the reel. Storage of the second hose on the reel is shown in Figure 9.

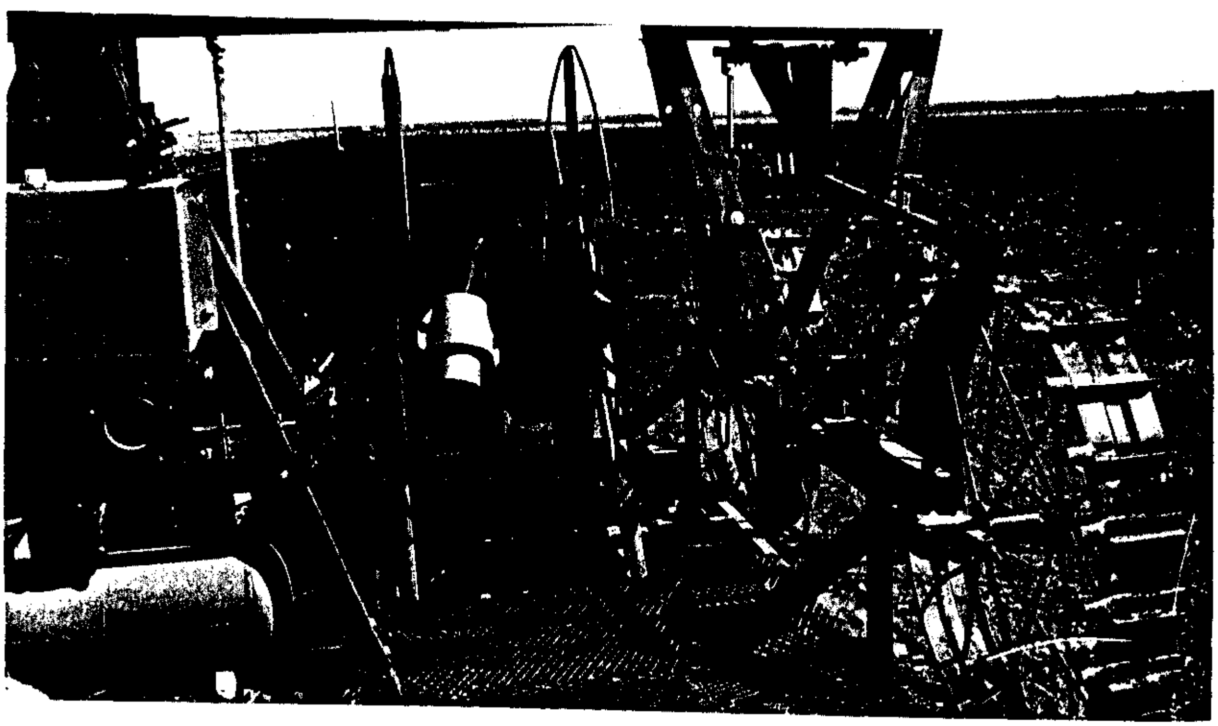


Figure 9. Hose stored on hose reel.

(6) Intermediate pressure system.

The LEPA system is designed to take water from low head underground pipelines which are often open to the atmosphere. This requires an intermediate pressure system to supply the low operating pressure and must balance the flow rate from the pressurization pump to the system with that being supplied by the pipeline. Also negative pressure must be prevented in the hose which would cause its collapse. This pressurization system incorporates a small centrifugal pump, a ball type air relief valve, and a diaphragm actuated surge control valve which is sensitive to entrained air.

Operation requires the RPM of the pressurization pump to be adjusted so that about two feet of head is available on the intake side of the pump. Any circumstance which would cause this head to be reduced below atmospheric will first introduce air into the pump through the air relief valve. The air introduced into the system is trapped in an accumulator where a flap valve opens and actuates a diaphragm controlled butterfly valve. This in turn throttles the flow rate slightly until a positive pressure is again present on the intake side of the pump. The pressure system is shown in Figure 10.

Greater rainfall retention was approached by the development of a basin tillage implement which is adapted to current farming methods and equipment. Criteria followed in the design of this implement were as follows:

(1) Capable of trouble free operation;

(2) Attachable to equipment currently being used in row crop production such as bedders, planters, and cultivators so as not to require a separate operation;

(3) Capable of high speed operation; and

(4) Provide for adjustment of dike spacing and height in order to regulate basin size.

The hydraulically operated basin tillage implement constructed to perform the furrow diking operation is shown in Figure 11. The attachment to plow out dikes in front of the tractor tires is given in Figure 12. Water is shown being applied to the micro-basins by the LEPA system in Figure 13. A close-up view is given in Figure 14.

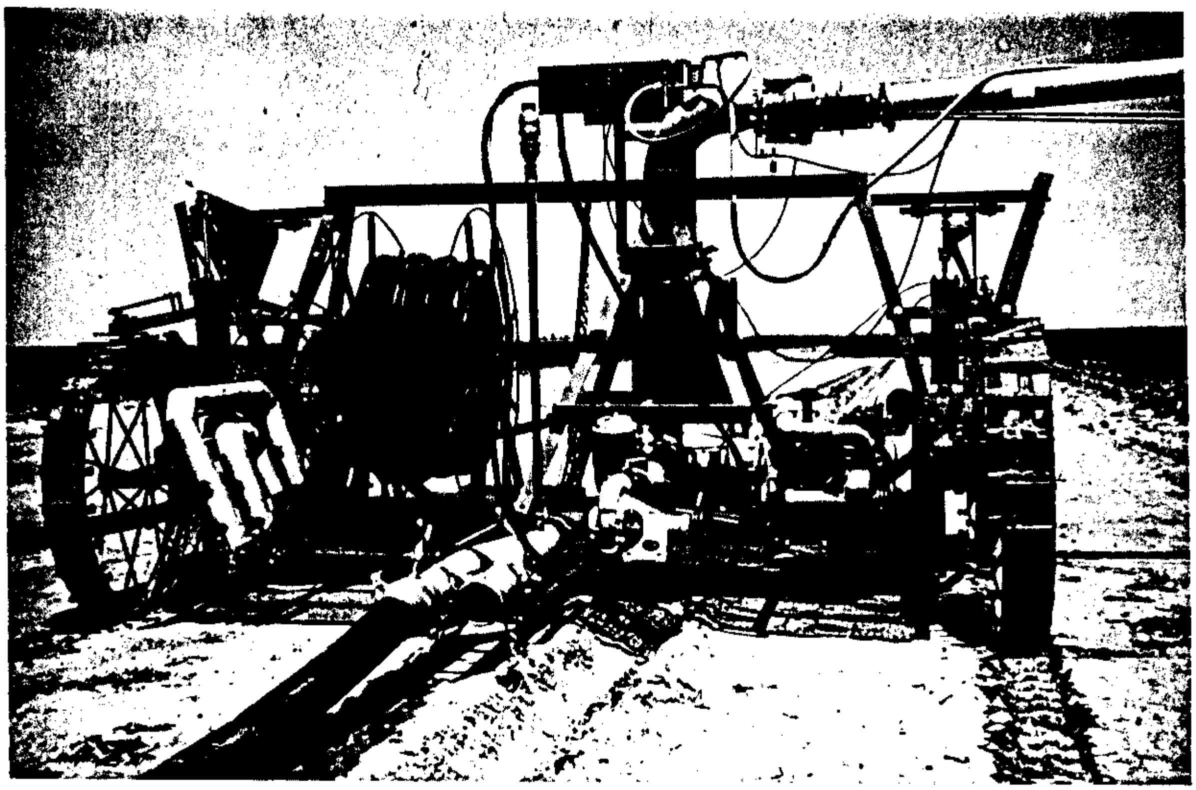


Figure 10. Water pressurization system.

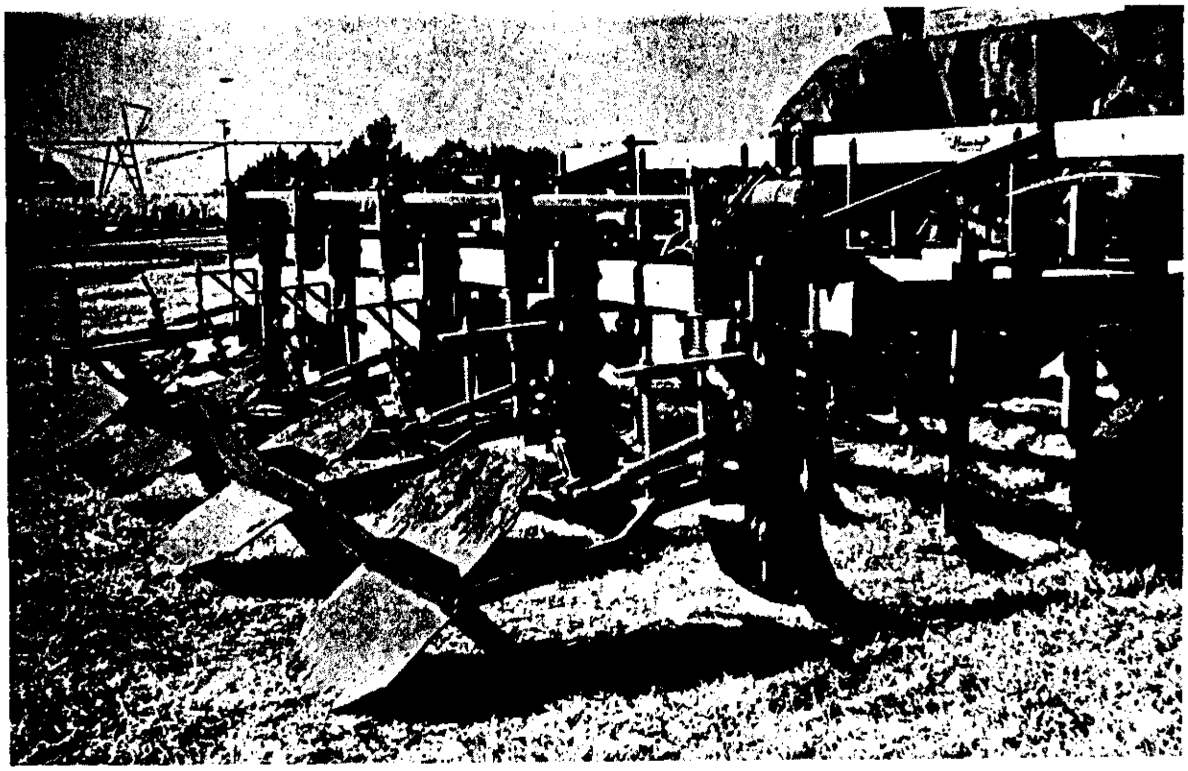


Figure 11. Hydraulically operated basin tillage implement.

Figure 12. Attachment for plowing out dikes in front of tractor tires.

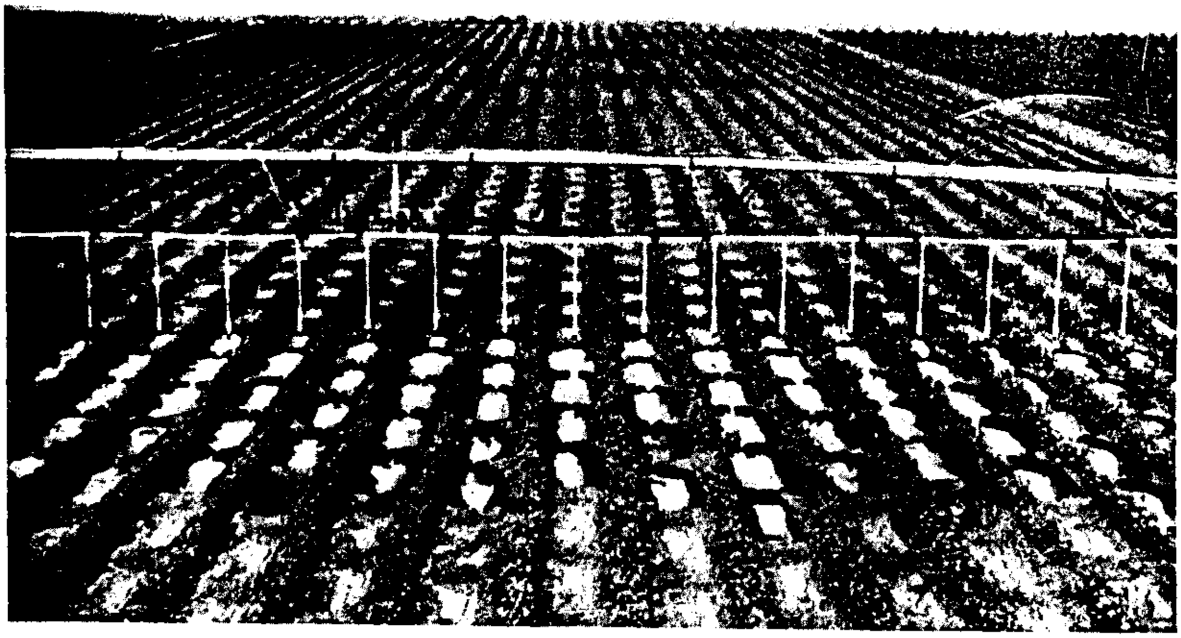


Figure 13. Water applied to micro-basins by LEPA system.

Figure 14. Close-up of micro-basin irrigation.

Test Plan

A number of factors were analyzed in order to establish a basis for comparing the LEPA system and the concept of micro-basin irrigation with other established irrigation methods. High pressure impact sprinklers were installed along the main pipeline for the sprinkler tests. The sprinkler heads are shown operating on the LEPA system in Figure 15. The factors analyzed in the evaluation were chosen to provide a sound basis for acceptance or rejection of the new irrigation concept based on performance in terms of water use efficiency, energy conservation and economic feasibility.

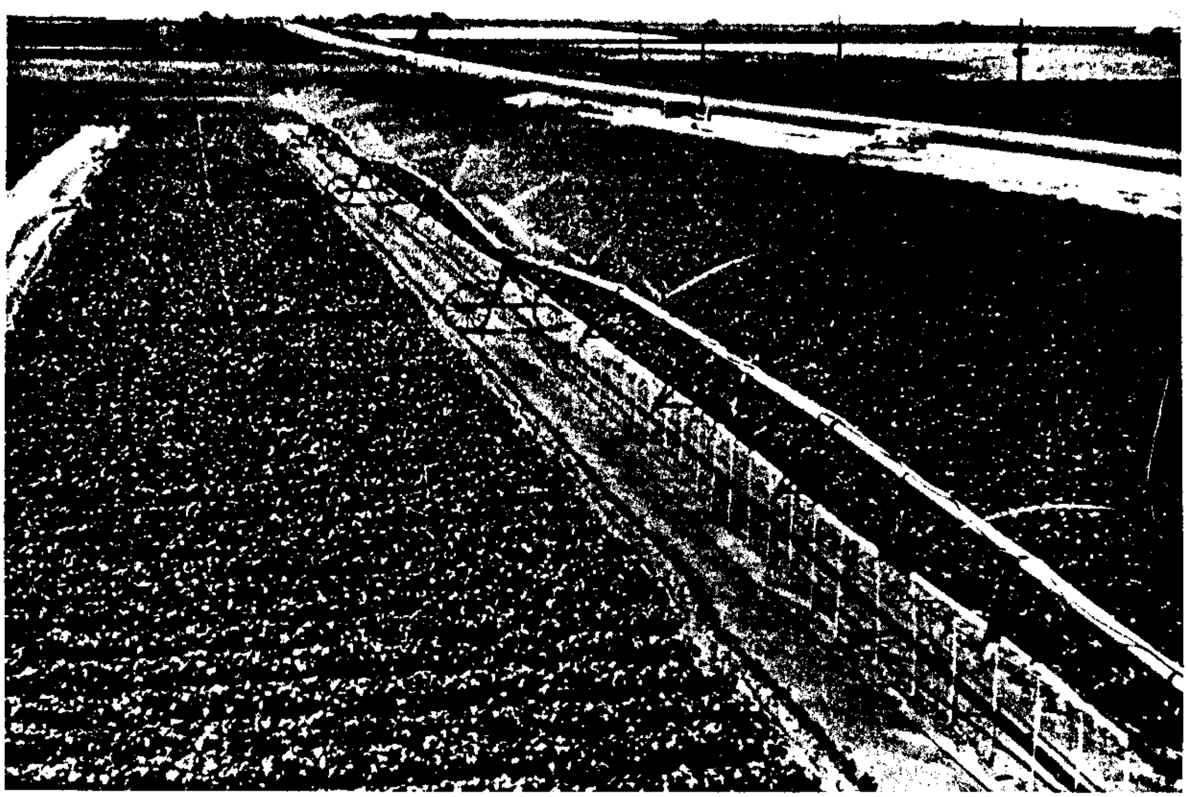


Figure 15. Sprinkler heads in operation on LEPA system.

The major factors analyzed were:

(1) Irrigation application and distribution efficiencies.

Application efficiency may be defined as the ratio of the water stored in the soil root zone to the water delivered to the field. The distribution efficiency is a numerical expression of the extent that individual measurements of stored soil water differ from the mean on an areal extent. Application and distribution efficiencies were obtained on LEPA, sprinkler and furrow irrigation for comparative figures.

(2) The interaction of basin tillage with LEPA, sprinkler and furrow irrigation.

The effect of basin tillage was determined as it related to enhancing total water utilization. This included rainfall retention as well as the effect it had on application and distribution efficiencies of LEPA and sprinkler irrigation. The experimental design was such that the effect of rainfall on the soil moisture status and yield response could be separated from the effect of the irrigation water applied.

(3) Crop yield response.

Crop yield response for each irrigation treatment was obtained. Cotton was the test crop in 1979. The yield was to be used in calculating water use efficiency (lbs yield/acre-inch) and energy use efficiency (lbs yield/total energy expended) However, unique climatic conditions prevented a meaningful evaluation using these values as explained later.

(4) Economic analysis.

A economic analysis was made, comparing the LEPA with sprinkler and furrow irrigation methods.

Testing Methodology

The performance data necessary to adequately analyze the above mentioned factors were obtained by the following methods. They will be expanded somewhat in the Data Description and Analysis Chapter.

(1) Irrigation application and distribution efficiencies.

Two flow meters with totalizing capabilities were used to measure the quantity of water delivered to the field. These were periodically calibrated with a free discharging, precision machined orifice plate. Volumetric catchments were also made from the sprinkler nozzles to confirm the quantity of water being delivered by the system. A field water meter attached to a hydrant is depicted in Figure 16. Volumetric catchments from the sprinkler nozzles are shown in Figure 17. The quantity of water reaching the soil surface from the LEPA system was determined also by timed volumetric catchments of water applied to each furrow.

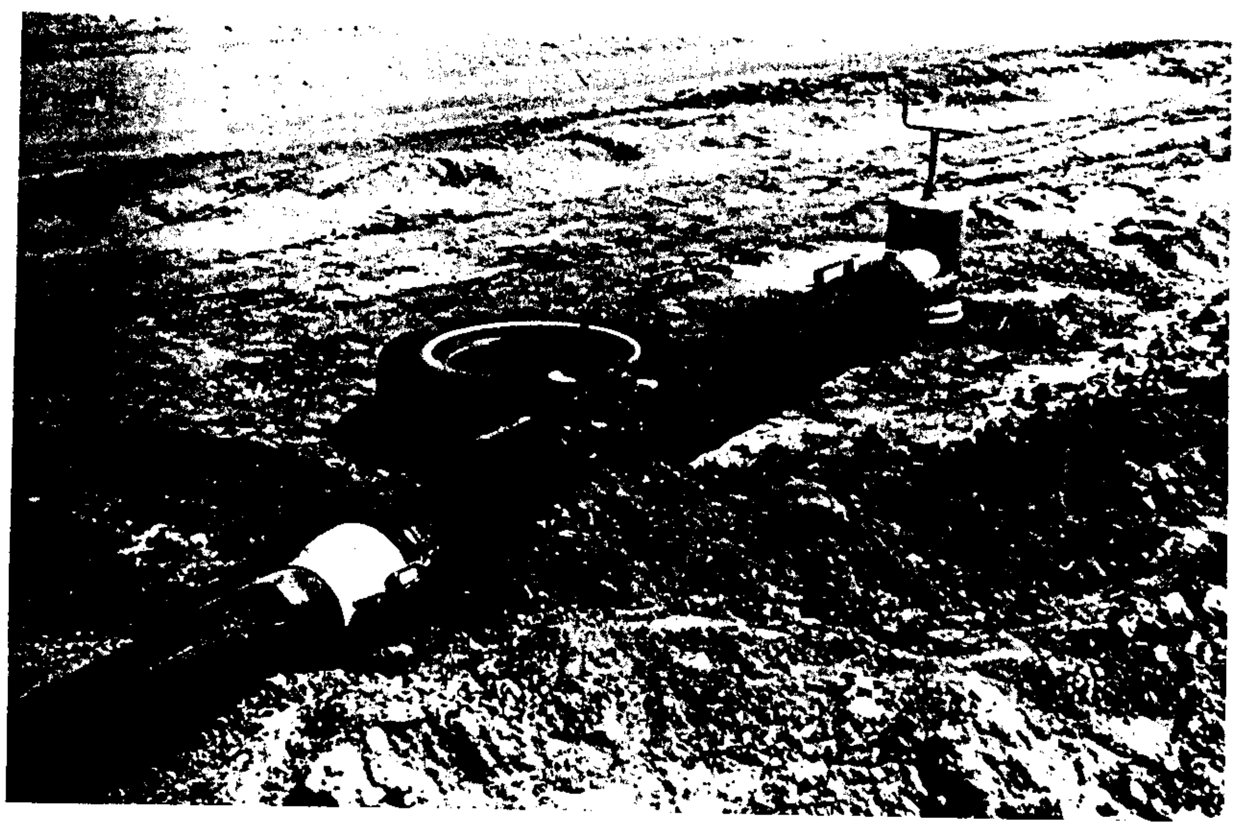


Figure 16. One of two water meters used to measure the flow rate for each test.

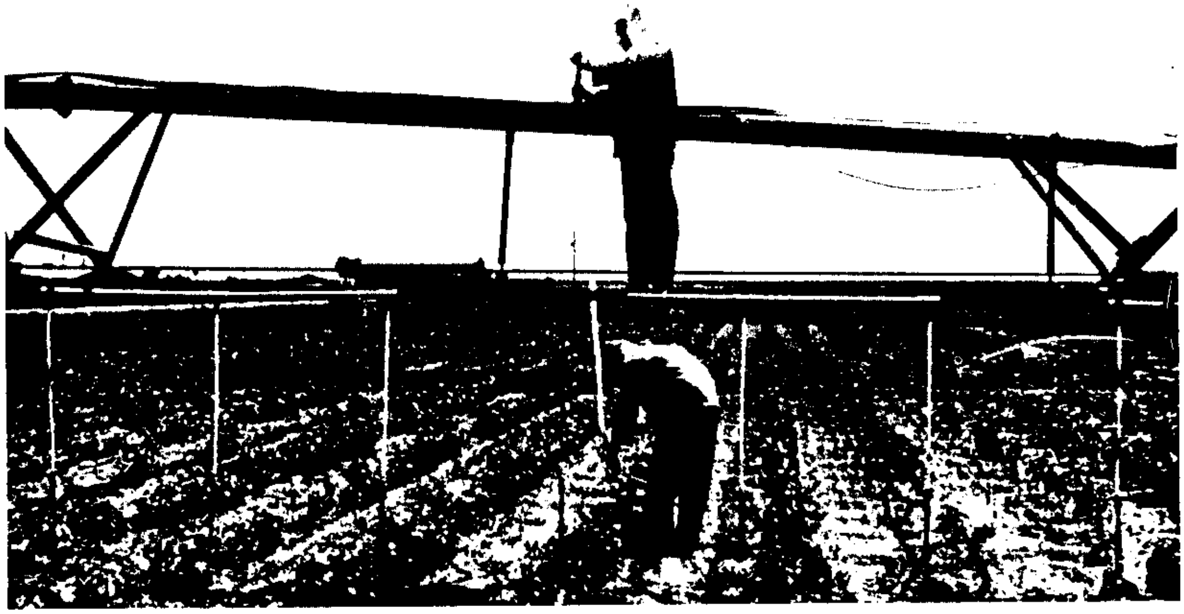


Figure 17. Timed volumetric check of water being delivered by sprinkler heads.

Water quantities reaching the surface from the sprinkler treatments were obtained by gravimetric measurements of the water caught in precipitation bottles and then converted to volumetric values. The precipitation bottles were placed at 6.6 ft intervals along the span of system. Precipitation bottles are shown aligned in Figure 18.

An equal gross volume of water per acre was delivered to the furrow, LEPA, and sprinkler treatments. LEPA and sprinkler plots received water at an equal gross rate whereas furrow application rate was limited by the non-erosive furrow stream size. Irrigation and rainfall runoff from each plot was measured with trapezoidal flumes equipped with water level recorders as shown in Figure 19. Net irrigation application amounts were determined by subtracting the runoff from the amount of water reaching the soil surface. Soil moisture accounting in the root zone was accomplished by nuclear measurement methods. Also matric potential in the top two feet of the soil profile was monitored with tensiometers.

Figure 18. Precipitation bottles for sprinkler application measurements.

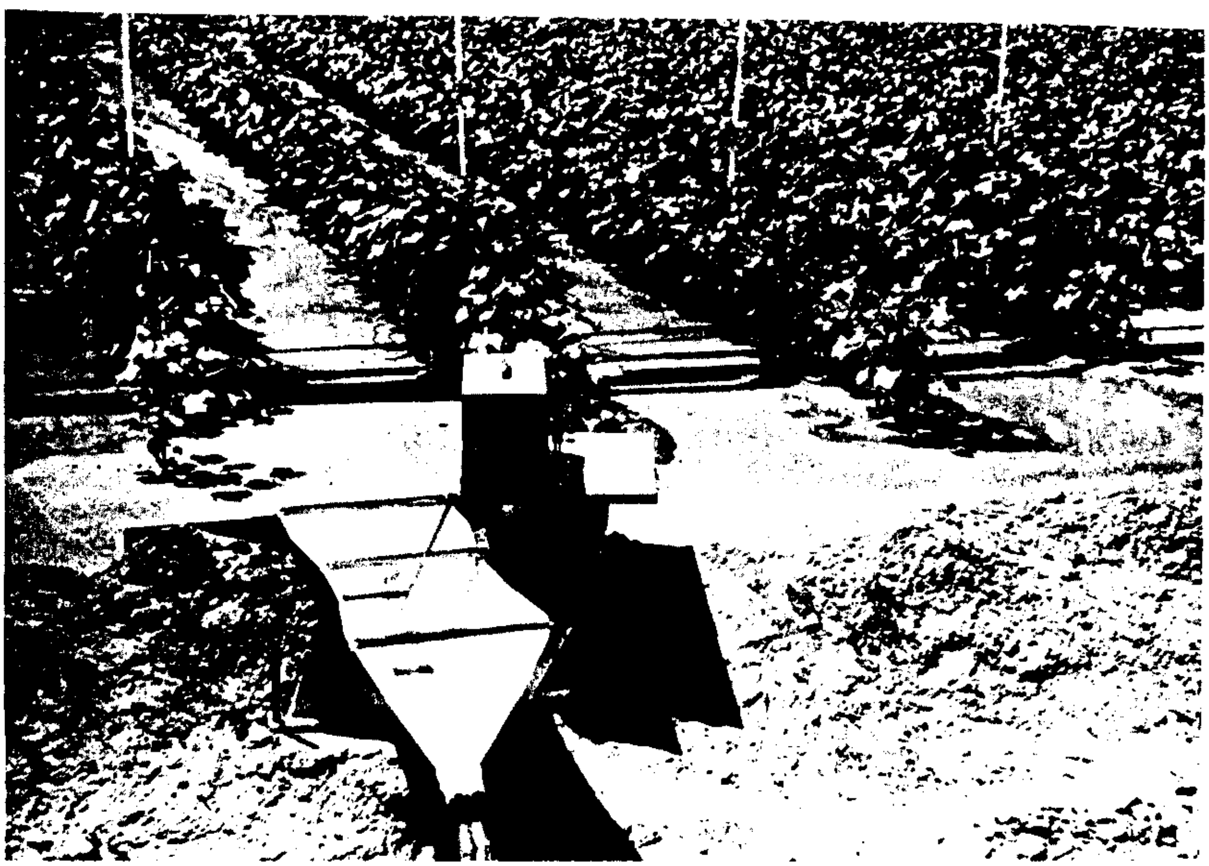


Figure 19. Trapezoidal flume and recorder for runoff determinations.

Climatic parameters measured include solar radiation, temperature, relative humidity, and wind speed and direction. These values were used to calculate the evaporative demand by energy balance-mass transfer methods. Class A evaporation pans were also used for this measurement and to verify evaporation losses from free water surfaces in the micro-basins and furrow irrigation treatments. An evaporation pan in the field is shown in Figure 20. Spray evaporation losses from the sprinkler tests were to be correlated with climatic variables to gain a better understanding of their effect on sprinkler application efficiency. However, limited testing due to excessive rainfall prevented this. Rainfall amounts were measured in four standard USWB rain gauges located in each one-quarter segment of the field.

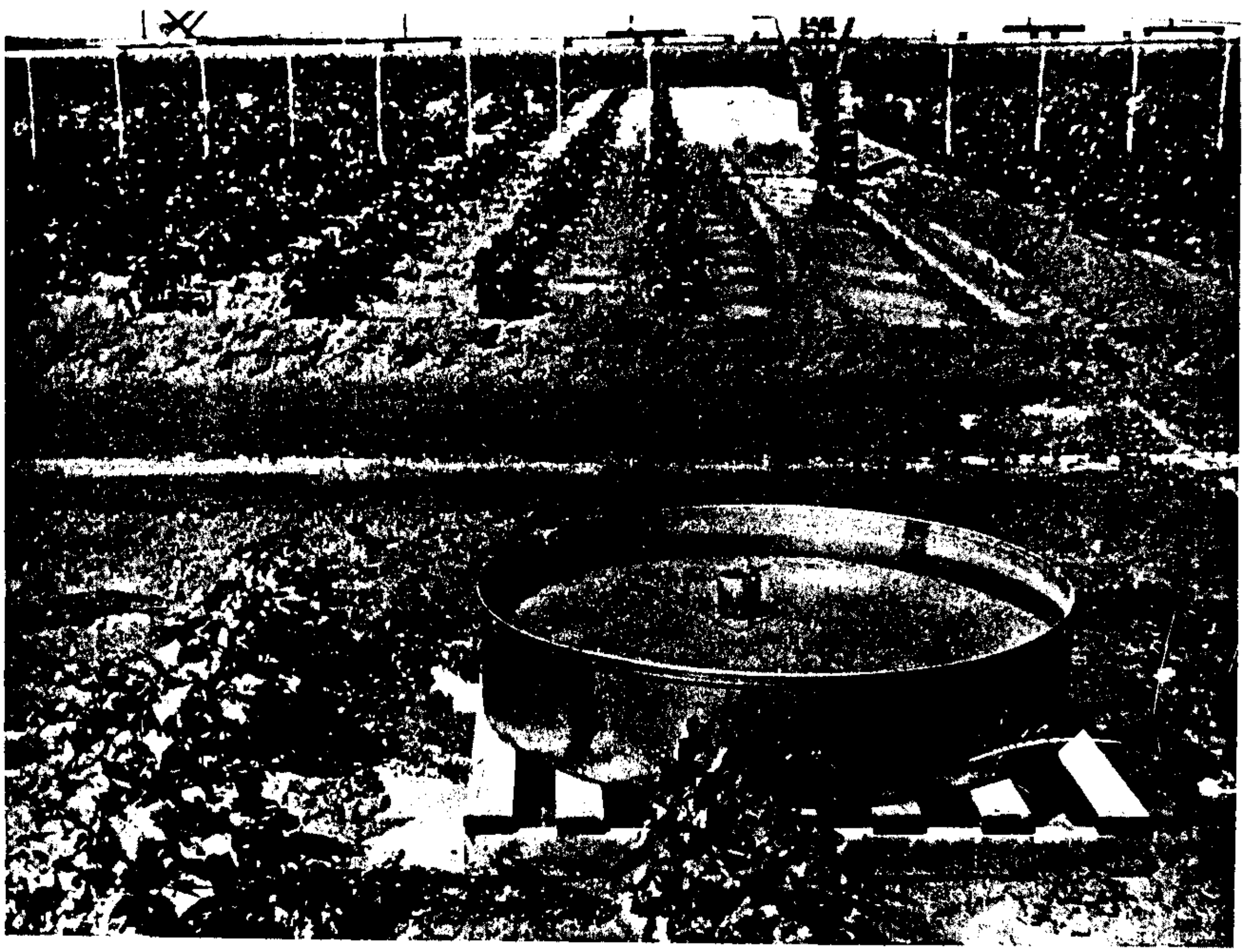


Figure 20. Evaporation pan at test site.

(2) The interaction of basin tillage with LEPA, sprinkler and furrow irrigation.

Furrow dikes were placed in randomized blocks and irrigated by LEPA, sprinkler and furrow methods. Likewise, undiked or conventional plots were irrigated at the same time. Dikes in the furrow irrigated blocks were removed prior to irrigation and replaced at the first cultivation following the irrigation. In addition, diked and undiked dryland treatments were monitored as to the contribution rainfall had on the soil moisture status and crop yield. Soil moisture and matric potential were determined as described previously.

(3) Crop yield response.

Random 1/1000 acre samples were hand harvested from each treatment. Each treatment was also machine harvested separately to obtain a check on the hand harvested values. The hand harvested values were used in the statistical analysis. The gross application of water applied per treatment and its yield was to be used to calculate the water use efficiency for that treatment. Energy use efficiency was likewise to be found by using the yield and gross energy consumption per treatment.

(4) Economic analysis.

Fuel and energy prices, volumes of water pumped, pumping pressures, fuel consumed, and complete logs of tillage and irrigation operations were recorded for purposes of economic analysis.

Experimental Design

The experimental design utilized in comparing the LEPA irrigation system with furrow and sprinkler systems consisted of a 3 x 2 factorial design. The three level factor consisted of irrigation methods, in which identical amounts of water were delivered to the systems. The two level factor was the presence or absence of furrow dikes within each irrigated plot. The plot lay-out consisted of two replicated blocks containing each treatment. Replications were limited because of the excess land area required for the sprinkler tests.

In addition to the irrigated blocks, replicated dryland treatments with both diked and undiked plots helped separate the effect that retained rainfall had on yields and the soil moisture budget.

Analysis of variance was to be used to evaluate the significance of the factorial test results. The main effects of irrigation treatments were to be analyzed along with the main effects of basin tillage as well as the interaction between the two. Data relating to yield, water use efficiency and energy use efficiency were to be analyzed most extensively. However, this was impossible due to negative yield results to applied water, as will be explained later.

DATA DESCRIPTION AND ANALYSIS

The following data have been taken, to date, in order to evaluate the performance of the low energy precision application irrigation system and to facilitate comparison with other irrigation methods and systems. Additional description of procedures and methods are also offered for clarification.

Irrigation Efficiencies

(1) Distribution efficiency

Water distribution efficiency has been defined by Hansen (10) as:

$$E_d = 100 \left[1 - \left(\frac{Y}{D}\right)\right] \qquad [1]$$

in which E_d is distribution efficiency, D is the average depth of water stored during the irrigation and Y is the average numerical deviation from D. This formula is identical to the expression used to determine Christian's uniformity coefficient (C_u) which is a measure of the uniformity with which water is applied by sprinkler irrigation. However, water distribution efficiency refers to the resulting stored soil moisture values and could differ from the coefficient of uniformity if runoff occurs from the water application.

Soil surface modification to form micro-basins is considered an integral part of the LEPA system and effectively eliminates runoff. Basin tillage may also be used with sprinkler irrigation to minimize runoff. When micro-basin tillage is used in conjunction with these systems, the distribution efficiency may confidently be assumed to be numerically equal to the coefficient of uniformity and may be obtained from volumetric catchments of applied water at the soil surface. Also, if uniform forward velocity of the rectlinear system is maintained, the irrigation distribution efficiency for an entire field then becomes equal to the coefficient of uniformity obtained along the span. This can be said only if the influence of wind is negligible, such as the case with the LEPA system. The distribution of water from a sprinkler system will vary in relation to variations in wind direction and velocity during its traverse of the field.

Stationary Tests. Table I gives data taken for distribution efficiency determinations on the LEPA system. Values reported were obtained from stationary timed volumetric catchments from each individual drop tube and emitter along the entire span of the system. Elevation differential along the span was constant for the tests.

The system was designed with optional flow regulation into each manifold. The flow may be pressure regulated by routing through pressure regulating valves or may bypass the valves allowing free flow into each manifold. Data for both operating conditions are reported in Table I.

Pressure regulating valves installed on the system are 1 1/2-inch valves. Specifications on the valves call for friction losses in the valves to range from about 2 psi at flow rates of 50 gpm to 6 psi at 80 gpm. This would correspond to flow rates in a 10-tower system of between 500 and 800 gpm. Test results that are reported in Table I, however, indicate operating pressure increases of 5 to 6 psi were experienced when pressure regulation was used on flow rates between 37 and 75 gpm per manifold. Flow rates above 70 gpm per manifold will require a 2-inch valve to keep the friction loss in the valve to an acceptable value. A 2-inch valve should effectively handle total flow rates up to 1200 gpm on a 10-tower system.

Pressure regulation increased the coefficient of uniformity very little on the 4-tower prototype system with a constant elevation differential. However, at low discharge pressures, pressure regulation will be absolutely

TABLE I
COEFFICIENT OF UNIFORMITY DETERMINATIONS
ON 4-TOWER LEPA SYSTEM

Orifice Size	Flow Rate (gpm)	Pressure Regulation Yes	Pressure Regulation No	Pressure at Pivot	Coefficient of Uniformity, C_u Span A	Span B	Span C	Span D	Total System
5/32	150		X	5.0	97.6	97.3	97.2	96.8	94.2
		X		10.1	97.6	97.3	97.2	96.3	96.9
	200		X	9.2	97.7	97.5	97.2	97.3	96.4
		X		12.4	98.1	97.9	97.5	96.9	97.2
	250		X	15.7	97.4	97.4	97.1	97.1	97.0
		X		20.0	97.5	97.5	97.1	97.6	97.3
3/16	200		X	4.0	96.6	97.2	97.3	97.5	94.9
		X		10.3	97.6	97.5	97.3	97.5	94.2
	250		X	7.9	97.2	97.5	97.5	97.2	96.0
		X		14.1	97.8	97.2	97.6	97.8	96.5
	300		X	12.2	97.4	97.6	97.8	97.8	97.1
		X		18.8	97.3	97.4	97.5	97.9	97.3
7/32	250		X	5.5	97.2	97.0	97.0	96.8	94.8
		X		10.9	97.2	97.2	97.0	97.1	96.1
	300		X	9.8	97.0	97.5	97.1	97.4	96.3
		X		16.0	97.5	97.4	97.0	97.7	96.7
	350		X	12.0	97.4	97.6	97.1	97.2	96.4
		X		21.3	97.4	97.4	97.5	97.4	97.7
1/4	300		X	7.0	96.4	97.1	96.2	96.1	95.1
		X		14.0	96.1	96.8	96.0	96.4	95.6
	350		X	10.0	96.8	97.0	96.8	96.4	96.0
		X		19.5	96.3	96.4	96.3	95.4	95.3
	400		X	13.0	96.5	96.9	96.4	97.0	96.3
		X		24.0	96.4	96.7	96.6	96.4	96.2

essential to maintain a high C_u when significant elevation changes take place in the field.

The coefficient of uniformity of 96 or slightly above is probably the maximum that can be expected in the field. Thirty-three random orifices of the same size were laboratory tested with three replications each at the same pressure. These tests yielded a coefficient of uniformity of 98.6 percent, the variation resulting from slight differences in machined orifice size and sampling error.

Performance of longer LEPA systems must be projected from operating data obtained from the 4-tower prototype. To accomplish this, pressure gauges were strategically placed along the main pipe and sub-piping system and were used along with elevation differences to obtain friction losses within each portion of the system. From these values friction factors were calculated with the Darcy formula as

$$f = \frac{2\ h_f\ D\ g}{V^2\ L\ F} \quad [2]$$

where h_f is the head loss due to friction in feet, D is the diameter of pipe in feet, L is the length of pipe segment in feet, V is velocity in feet/second, g is the acceleration of gravity and F is a correction factor based on the number of multiple outlets in the pipe section (19). The friction factor (f) was then used in the Colebrook transistion function

$$\frac{1}{\sqrt{f}} = -0.86\ \ln\left\{\frac{\varepsilon/D}{3.7} + \frac{2.51}{R\sqrt{f}}\right\} \quad [3]$$

to obtain the relative roughness (ε/D); R being the Reynolds number. The relative roughness (ε/D) was used to obtain friction factors for flow rates higher than the 4-tower system was capable of handling. However, the values of (ε/D) obtained were extremely variable with many being in the smooth pipe range. Therefore, the published value of 0.00015 for the absolute roughness (ε) of commercial steel pipe was used for head loss determinations and should result a conservative prediction of the performance of longer systems.

The friction factor (f) was obtained from the explicit form of the Colebrook equation developed by Wood (30) which is in the form of

$$f = a + bR^{-c} \qquad [4]$$

where the coefficients are a power function of ε/D and given as

$$a = 0.094\ (\varepsilon/D)^{0.225} + 0.53\ (\varepsilon/D),$$

$$b = 88\ (\varepsilon/D)^{0.44}, \text{ and}$$

$$c = 1.62\ (\varepsilon/D)^{0.134} \qquad [5]$$

Table II gives predicted operating pressures of LEPA systems based on friction factors obtained as outlined above; operating pressures in the manifold of 3.0 ft which could be maintained in field trials; friction loss at the pivot pad proportional to 6.0 $V^2/2g$ as determined experimentally; and a 5 psi head loss through the pressure regulating valve. Flow rates of 600 gpm and above assume a 7-inch main line.

Field Tests. The coefficient of uniformity for the sprinkler application was measured only when test plots were irrigated in field tests for crop yield and application efficiency determinations. This again consisted of only one irrigation due to adequate rainfall. Therefore the quantity of data obtained was much too small.

LEPA coefficient of uniformity was again determined for direct comparison with the sprinkler values. The high pressure impact sprinklers installed were 3/16-inch x 1/8-inch x 20 degree nozzles placed at 20-foot spacings

TABLE II
PREDICTED PRESSURE REQUIREMENTS
FOR LEPA SYSTEMS

Flow Rate (gpm)	Pressure Regulation Yes	Pressure Regulation No	Orifice Size (in)	Predicted Pressure at Pivot Pad (PSI)[1/] 4 Towers (530 ft)	6 Towers (790 ft)	8 Towers (1060 ft)	10 Towers (1320 ft)
100[2/]	X		3/32	9.3	9.3	9.3	9.4
		X		4.3	4.3	4.3	4.4
200	X		1/8	9.7	9.8	10.0	10.1
		X		4.7	4.8	5.0	5.1
300	X		5/32	10.4	10.6	11.0	11.3
		X		5.4	5.6	6.0	6.3
400	X		11/64	11.4	11.7	12.4	12.9
		X		6.4	6.7	7.4	7.9
500	X		13/64	12.7	13.2	14.2	14.9
		X		7.7	8.2	9.2	9.9
600[3/]	X		7/32	12.4	12.7	13.3	13.7
		X		7.4	7.7	8.3	8.7
700	X		15/64	13.6	13.9	14.8	15.4
		X		8.6	8.9	9.8	10.4
800	X		1/4	--	15.4	16.4	17.2
		X		--	10.4	11.4	12.2
900	X		17/64	--	17.1	18.3	19.3
		X		--	12.1	13.3	14.3
1000	X		9/32	--	18.9	20.5	21.7
		X		--	13.9	15.5	16.7

1/ Assumes level field

2/ 6-inch main line for 100 thru 500 gpm

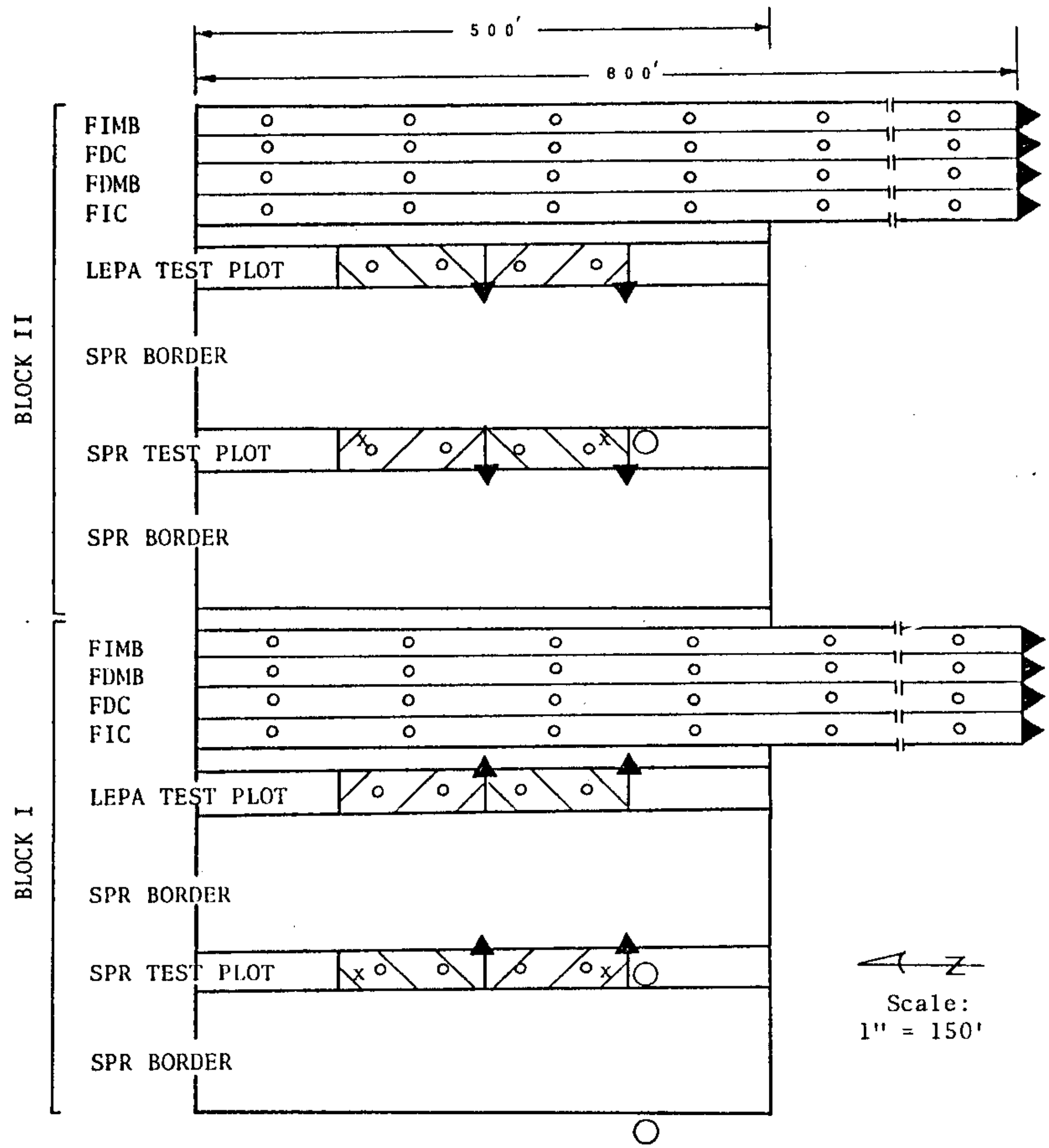
3/ 7-inch main line for 600 thru 1000 gpm along the main pipe for the sprinkler tests. Gate valves were installed in the manifold supply hose to prevent flow into the low pressure manifolds when the sprinklers were in use.

The field in which the tests for both distribution and application efficencies were conducted was divided into two blocks (see Figure 21). Each block had two 30-foot wide instrumented plots, one for the sprinkler distribution test, the other for the LEPA test. The sprinkler plot was instrumented with the flumes, neutron access tubes, tensiometers, official USWB class A evaporation pans, USWB rain gauges, and sprinkler catchment cans. Borders, one hundred twenty (120) feet in width, were located on each side of the sprinkler test plots so that complete sprinkler wetting patterns could cross the 30-feet instrumented plot without applying water to the adjacent test areas. Each test plot was completely enclosed with an earth embarkment which isolated it from any water source other than rainfall and that applied by LEPA or sprinkler irrigation. Runoff from each enclosed plot made its exit through a trapezoidal flume and water level recorder.

The length of each test plot corresponded to the length of the lateral move system span between the wheels. The test area consisted only of the middle two spans, one of which was conventionally tilled and one in which micro-basins were placed. The areas irrigated by the two end spans of the system were considered border areas and were not included in the determination of application or distribution efficiencies.

The LEPA plots contained flumes, neutron access tubes, and tensiometers. Again, only the two middle sections of the plot were instrumented, one having conventional furrows, the other having micro-basins.

Figure 21. Field layout for LEPA, sprinkler, and furrow tests for 1979.



(hatched box) = Micro-basin Area		x	= USWB Rain Gage
(hatched box) = Conventional Area		FDMB	= Furrow Dryland Micro-basin
▲ = Flume		FDC	= Furrow Dryland Conventional
○ = Evaporation Pan		FIMB	= Furrow Irrigated Micro-basin
o = Neutron Access Tube		FIC	= Furrow Irrigated Conventional
		SPR	= Sprinkler

Within each block was also four furrow treatments consisting of eight rows per treatment, each with an 800-foot length of run. The furrow treatments consisted of: (1) furrow irrigated-conventional; (2) furrow dryland conventional; (3) furrow irrigated micro-basin; and (4) furrow dryland micro-basin. The furrow dikes were removed for the irrigation and then replaced in the irrigated-basin tillage treatment. Each of the four furrow treatments were likewise instrumented with flumes, neutron access tubes, and tensiometers.

Output from each sprinkler nozzle was determined by 30-second timed catchments immediately after the sprinkler pattern completely passed the test plots. These values were used to check the flow rate recorded by the two water meters as well as to obtain discharge uniformity. The discharge from the LEPA nozzles was likewise determined by 15-second volumetric catchments immediately after the system passed the test plots. Sprinkler nozzle discharge, sprinkler can catchment, and LEPA nozzle discharge, which is also equivalent to the amount reaching the surface, along with coefficient of uniformity (C_u), is given in Figures 22 and 23 for blocks I and II, respectively. It is obvious from the figures that the sprinkler pattern experienced considerable distortion although the wind speed was only 12 and 9 MPH, respectively, and blowing almost parallel to the system in direction.

An equal quantity of water per unit area was applied to the furrow irrigated plots as was applied by LEPA and sprinkler methods. The flow rate was established by the estimated non-erosive furrow stream size according to the rule of thumb

$$Q = \frac{10}{S} \qquad [6]$$

where Q is the non-erosive furrow stream flow rate in gallons per minute and S is the slope of the furrow in percent. Discharge into each furrow

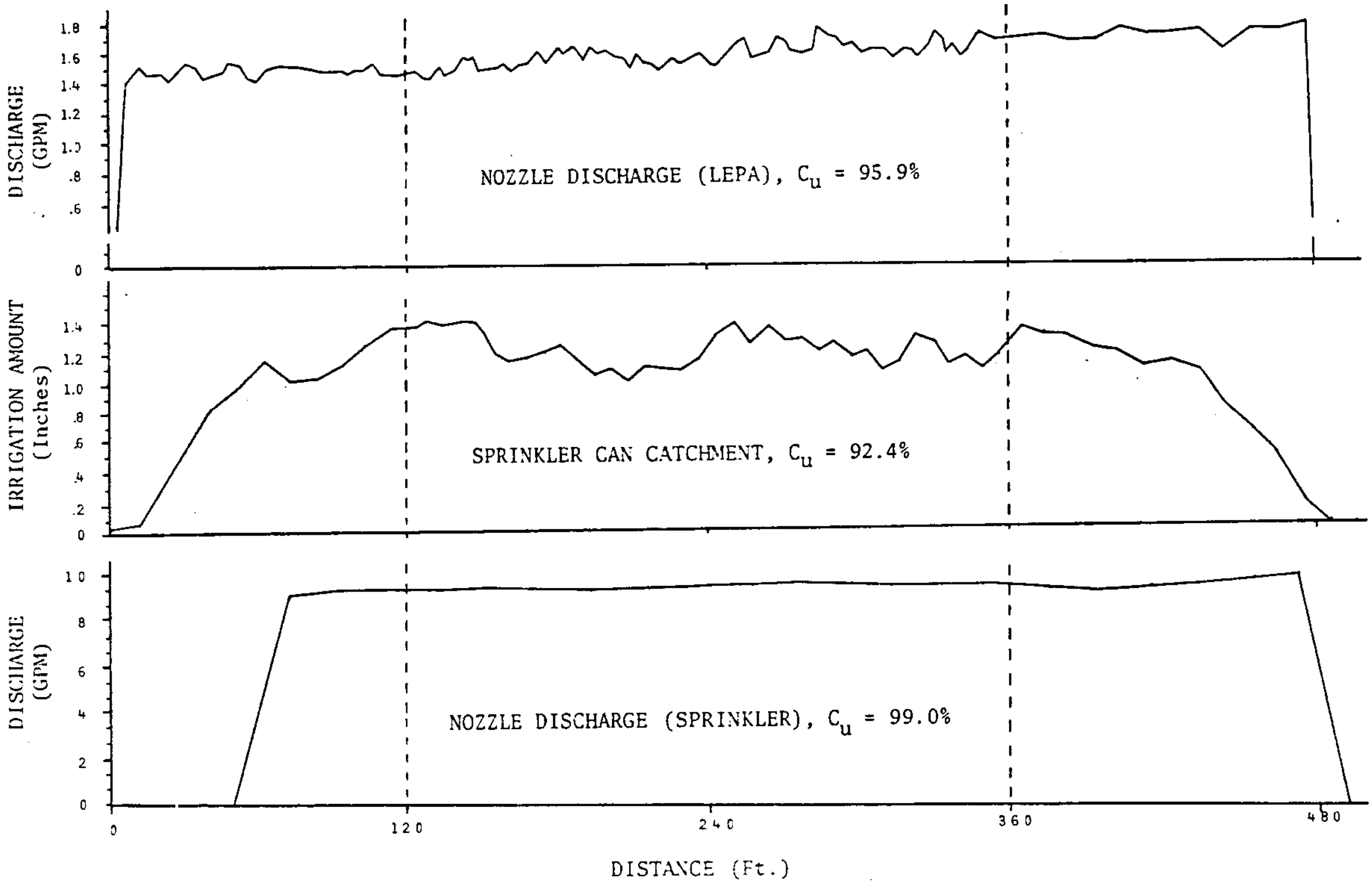


Figure 22. Irrigation test data. Block I, 1979.

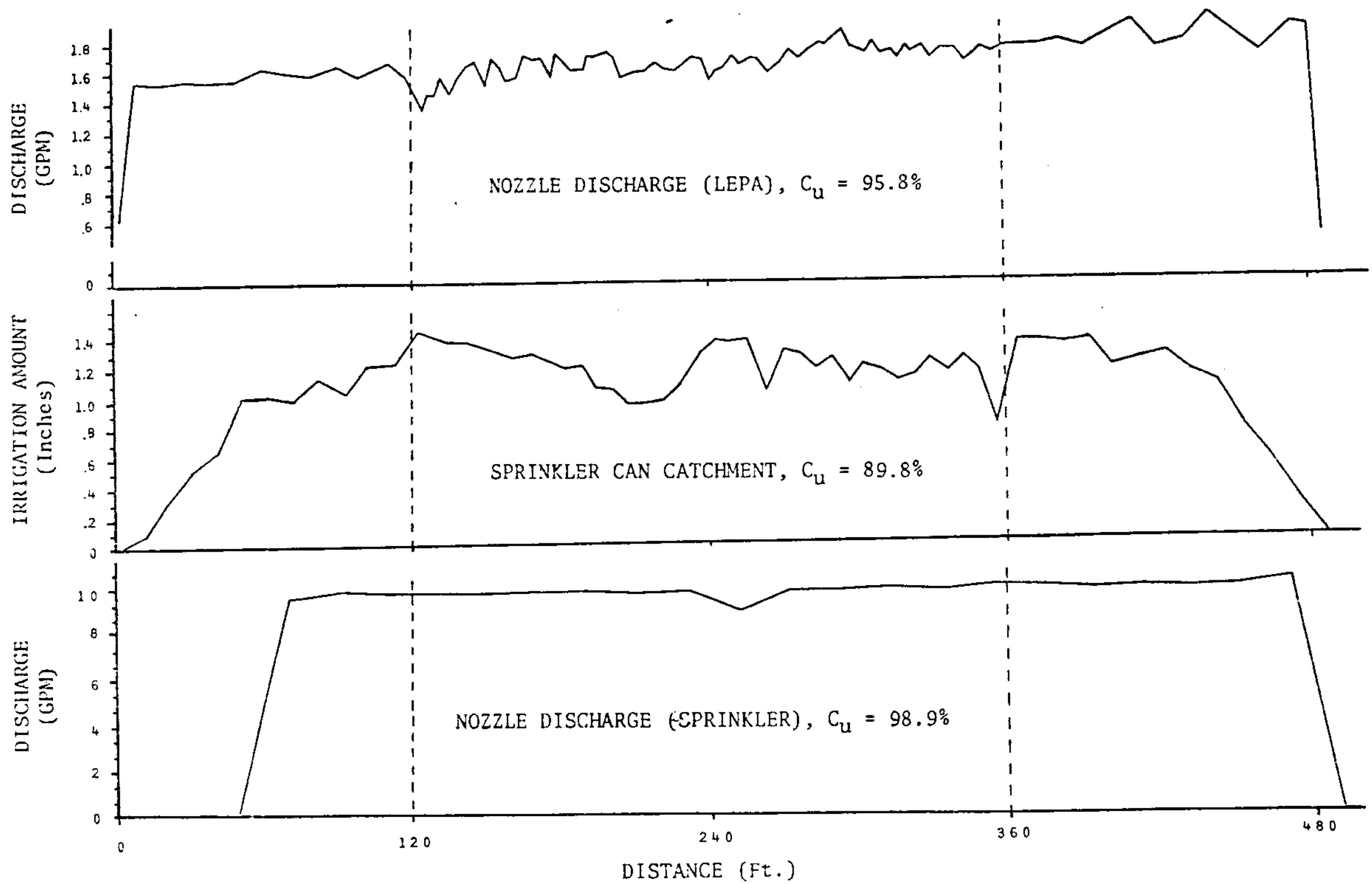


Figure 23. Irrigation test data. Block II, 1979.

was approximately equal but differences in the rate of advance between furrows occurred due to tractor wheel compaction. These differences can be seen graphically in Figure 24. The majority of furrows did not reach the end of the field, with very little runoff from those that did. An indication of the change in soil moisture was given by neutron moisture readings taken the day before and 3 days after the irrigation. The change in moisture is not considered quantitatively accurate, but gives a good indication of relative moisture changes. Changes in soil moisture based on the neutron data are shown in Figure 25. Distribution efficiencies for the furrow irrigated treatments were estimated from the neutron moisture data.

The coefficients of uniformity based on the field data for the sprinkler and LEPA tests are summarized in Table III. Runoff did not occur in the diked plots from sprinker irrigation nor with the LEPA system. Here again the distribution efficiency may be assumed to be numerically equal to the coefficient of uniformity. Both application methods did create runoff in the conventional tilled plots, thus the irrigation distribution efficiency could not be determined from the measurements taken. However, it must be assumed to be less than the basin tilled plots. Furrow distribution efficiencies, estimated from the neutron moisture data, are given in Table IV.

(2) Irrigation application efficiency

Recalling that application efficiency is the ratio of water stored in the soil root zone to the water delivered to the field; application efficiency may be influenced by losses from the following:

(a) evaporation losses from surface flowing water or in the air from sprinkler nozzle spray,

(b) deep percolation below the root zone,

(c) runoff from the field, or

(d) soil surface evaporation during the irrigation.

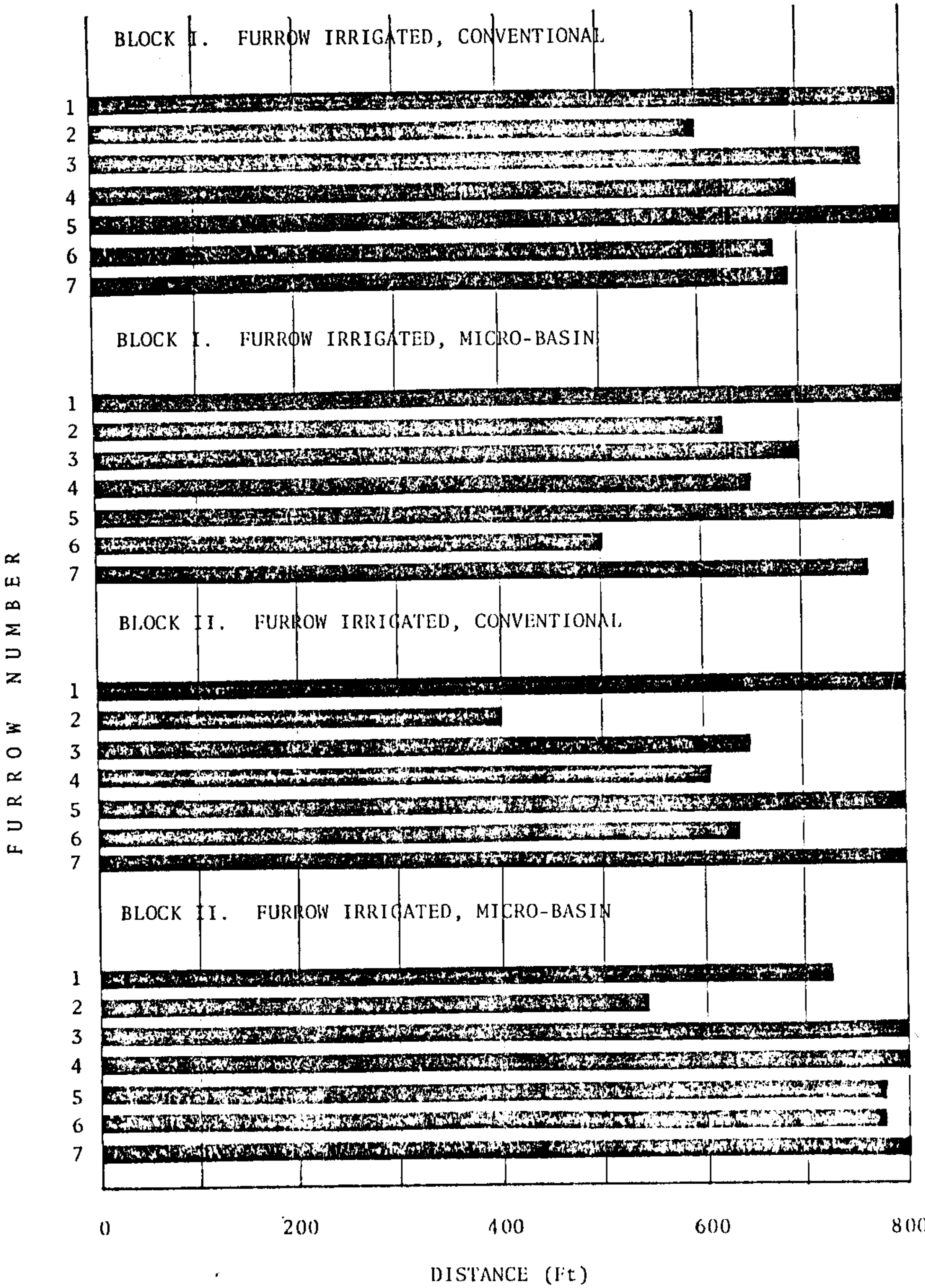


Figure 24. Distance of water movement in furrow, August 10, 1979.

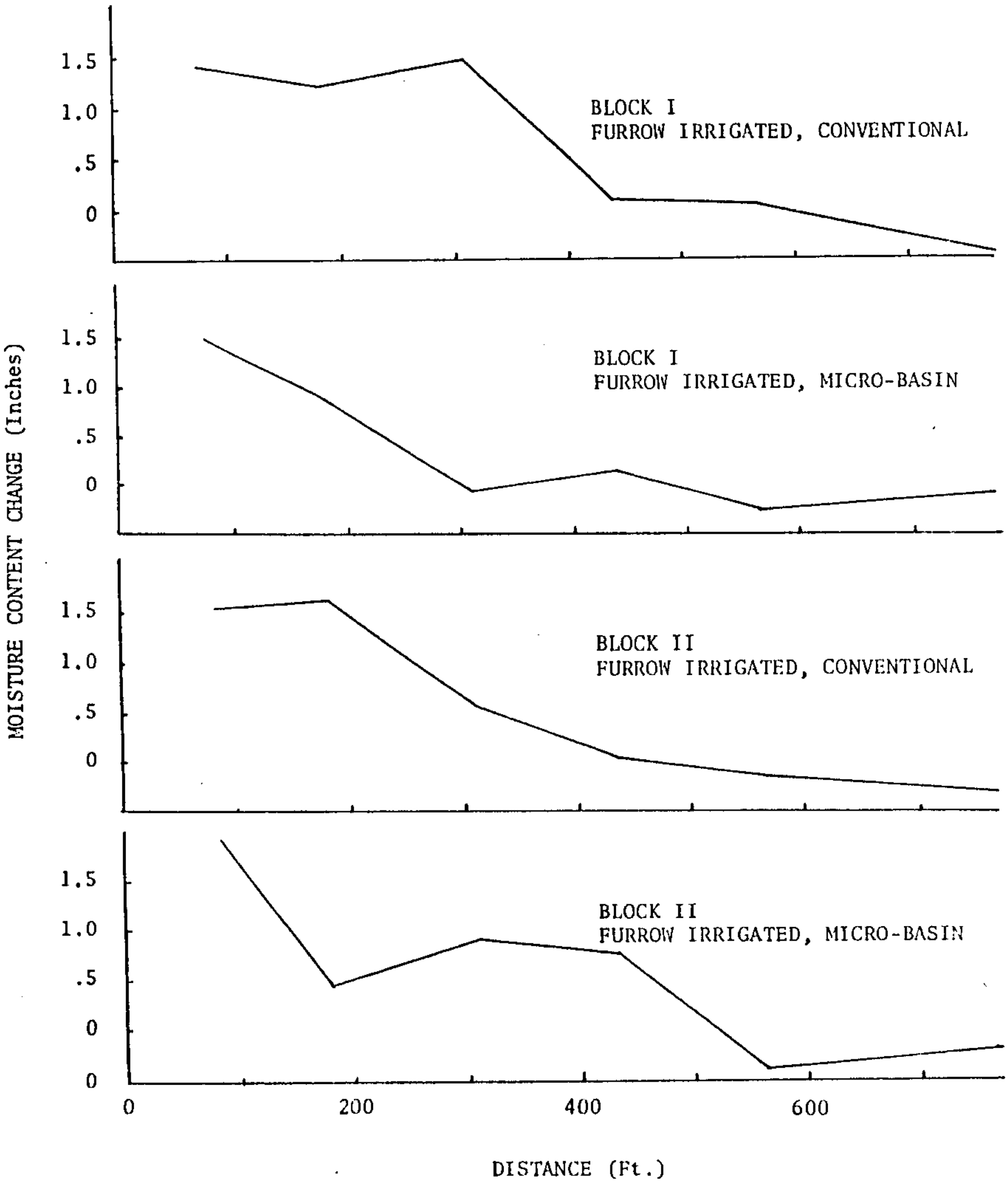


Figure 25. Change in soil moisture due to furrow irrigation, August 10, 1979

TABLE III

COEFFICIENT OF UNIFORMITY OF FIELD DATA

Block	Treatment*	Date	Δ Time (Min.)	Wind Velocity (MPH)	Wind Direction**	Distribution Pressure (PSI)	Flow Rate (GPM)	C_u-nozzle (%)	C_u-surface (%)
I	SP	8/6/79	76	12	SSW	51	200	99.0	92.4
II	SP	8/8/79	61	9	S	50	202	98.9	89.8
I	LEPA	8/7/79	63	11	S	6	214	95.9	95.9
II	LEPA	8/9/79	76	10	SSW	6	218	95.8	95.8

* LEPA - Low energy precision application

SP - Sprinkler irrigated

** - System direction of travel was east

TABLE IV

FURROW DISTRIBUTION EFFICIENCY

Block	Treatment*	Date	Δ Time (Min.)	Wind Velocity (MPH)	Wind Direction	Distribution Pressure (PSI)	Flow Rate (GPM)	Distribution Efficiency %
I	F-C	8/10/79	325	3	W-N	1.0	48	39.0
II	F-C	8/10/79	325	3	W-N	1.0	48	30.0
I	F-MB	8/10/79	325	3	W-N	1.0	48	36.0
II	F-MB	8/10/79	325	3	W-N	1.0	48	45.0

* F - Furrow irrigated

C - Conventional tillage

MB - Micro-basin

Application efficiency may, therefore, be defined by the following equation:

$$E_a = \frac{W_D - e_a - e_{ws} - e_{ss} - DP - R}{W_D} (100) \quad [7]$$

where E_a is application efficiency, W_D is water delivered to the field, e_a is spray evaporation in the air, e_{ws} is evaporation from a free water surface, e_{ss} is evaporation from the soil surface during irrigation, DP is deep percolation and R is runoff.

Water delivered to the instrumented test plots was measured by timed volumetric catchments from each discharging sprinkler and LEPA nozzle and from two flow meters with totalizing capabilities. The amount of water applied to each treatment was approximately 1.3 acre-inches per acre with only slight variation due to small changes in flow rate and speed of the lateral system.

Spray evaporation losses in the air were limited to the sprinkler treatment. This loss was determined by the difference in total water discharged through the sprinkler heads and the water received in the sprinkler cans.

For purposes of these tests, evaporation from the soil surface and the free water surface was assumed negligible during the irrigation period for the sprinkler and LEPA treatments. Application time per unit area is very short for the LEPA method. Rain gauge and evaporation pan data did not indicate surface evaporation losses during the sprinkler application. However, a free water surface was present for a significant period of time during furrow irrigation and evaporation was estimated for it.

Micro-basin irrigation results in the existence of a free water surface for a significantly longer period of time after water application ceases than does conventional tilled soil. Therefore, evaporation from this free water surface was considered in calculating application efficiency.

Gross water applied in each test was less than that required to fill the root zone, thus, deep percolation losses did not occur in the sprinkler or LEPA tests. These losses were possible in the furrow irrigated plots due to low distribution efficiency. However, neutron moisture measurements extending below the root zone did not indicate deep percolation losses. Runoff from all plots was measured with trapezoidal flumes equipped with water level recorders.

Evaporation losses were estimated from class A USWB evaporation pan data taken during each treatment period. These data were checked with potential evaporation which was calculated from a modified energy balance-aerodynamic evaporation equation in the form of

$$E_p = \frac{0.000673}{\Delta + 0.27}\left[\Delta R_n + (0.1728)\ (1.0 + 0.24W)\ (e_{\bar{s}} - e_d)\right] \quad - - - - [8]$$

where E_p is the potential hourly evaporation in inches, Δ is the slope of the saturated vapor-pressure curve of air at absolute temperature in mm Hg/°F, R_n is net hourly radiation in langleys, W is the mean wind velocity at 2 meters above the ground in miles per hour, $e_{\bar{s}}$ is the saturated vapor pressure at mean air temperature in mm Hg and e_d is the saturated vapor pressure at mean dew point in mm Hg. The variables in this equation were obtained from weather instruments in the field where the testing took place. A comparison of the two estimating procedures for establishing E_p rates on August 8, 1979, can be seen in Figure 26.

The average water surface of the sprinkler and LEPA micro-basin areas and the furrow irrigated areas was established at one-fourth and one-tenth, respectively, of the surface area watered. These estimates were based on both photographs and field observations. The average opportunity time for

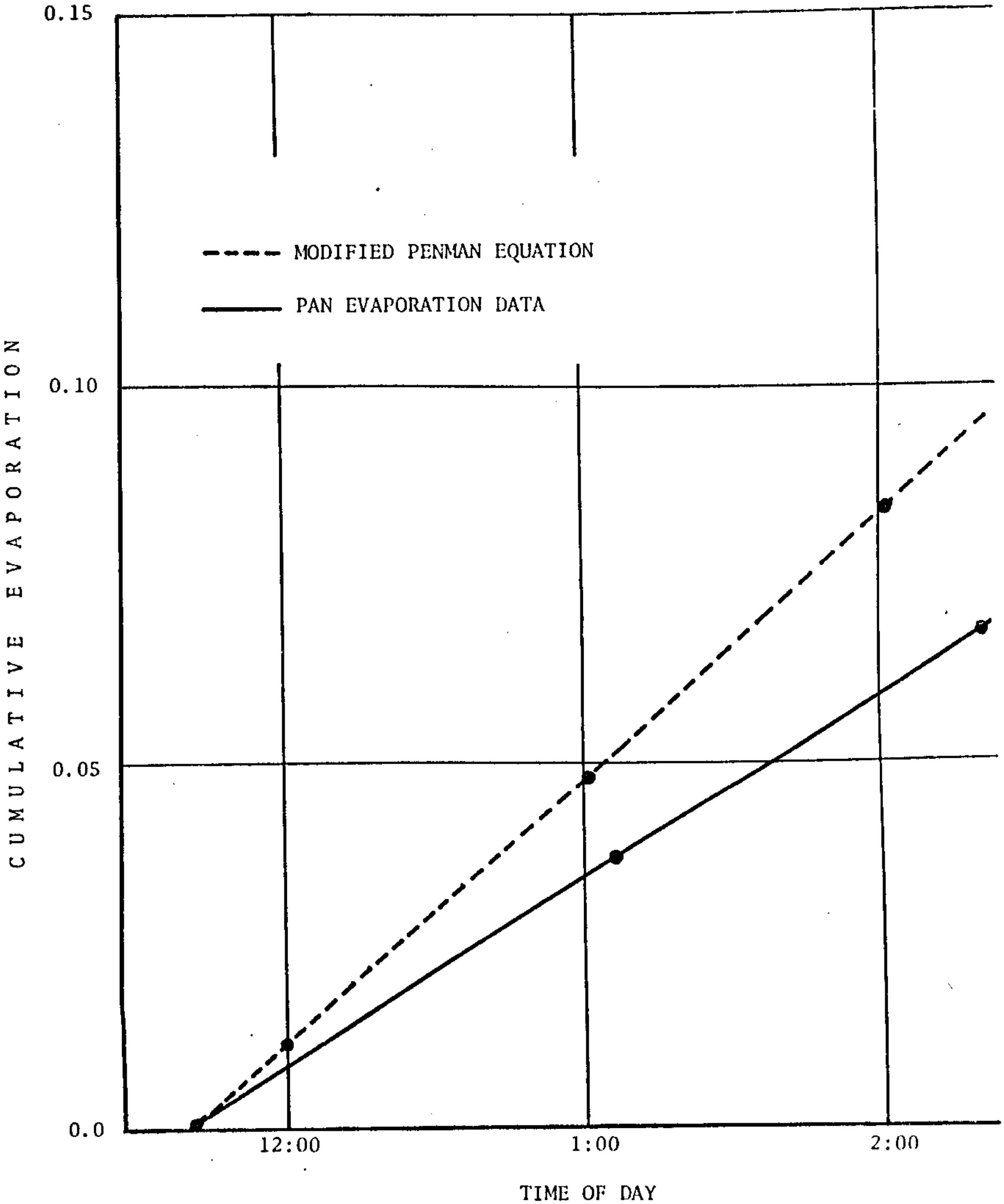


Figure 26. Cumulative evaporation based on a modified Penman equation and pan evaporation data for August 8, 1979.

evaporation was 45 and 63 minutes for the micro-basin sprinkler and LEPA treatments and 325 minutes for the furrow irrigated treatments. In other words this is the average time period a free water surface was present. The average evaporation rate during the time of each treatment was based on the pan evaporation data. Water evaporation data is given in Table V.

Table VI summarizes the application efficiency data along with the resulting application efficiencies. One will note high applicaton efficiencies for the furrow treatments. This is due to negligible runoff and deep percolation losses from the 1.3 acre-inch irrigation. However, as seen previously, the distribution of this water was extremely poor. The LEPA-micro-basin treatment was superior in both application and distribution efficiency categories.

Rainfall Utilization

The installation of micro-basins with basin tillage implements is considered an integral part of the LEPA irrigation system. One will note from Table VI that they are essential in maintaining a high application efficiency with LEPA irrigation. In addition to their function of increasing irrigation application and distribution efficiencies, the micro-basins also provide a means to capture rainfall and minimize runoff. Irrigation demand is decreased by an amount equal to the rainfall which is retained in the basins and stored in the soil root zone.

Trapezoidal flumes and recorders provided a record of rainfall runoff from each irrigated treatment in addition to irrigation runoff. The flumes were brought into operation on July 15 and recorded runoff through September 14, 1979. Several runoff producing rains occurred before installation but that data is unavailable. Table VII presents the rainfall and runoff occurring in this two month period which is normally considered the most critical in relation to moisture stress in cotton.

TABLE V

SURFACE WATER EVAPORATION

Date	Block	Treatment*	Surface Area Watered (ft^2)	Average Water Surface (ft^2)	Average Evaporation Rate (in/hr)	Period of Evaporation (hrs)	Water Evaporated (gal)
8/6/79	I	SP-MB	4500	1125	.037	.75	19.46
8/7/79	I	LEPA-MB	4667	1167	.034	1.05	25.97
8/10/79	I	F-C	16733	1673	.026	5.42	147.00
8/10/79	I	F-MB	16130	1613	.026	5.42	141.00
8/8/79	II	SP-MB	4563	1141	.024	.75	13.07
8/9/79	II	LEPA-MB	4433	1108	.006	1.05	4.35
8/10/79	II	F-C	15667	1576	.026	5.42	138.00
8/10/79	II	F-MB	17467	1747	.026	5.42	153.00

* LEPA = Low energy precision application

SP = Sprinkler irrigated

F = Furrow irrigated

C = Conventional tillage

MB = Micro-basin

TABLE VI

APPLICATION EFFICIENCY TEST DATA

Test Data	Block	Treatment*	W_D	e_a	e_{ws}	e_{ss}	DP	R	E_a
			Gal						
8/7/79	I	LEPA-C	3383	0	0	0	0	608	82.0
		LEPA-MB	3551	0	26	0	0	0	99.3
8/6/79		SP-C	3885	537	0	0	0	245	79.9
		SP-MB	3808	481	19	0	0	0	86.9
8/10/79		F-C	15519	0	147	0	0	0	99.1
		F-MB	15519	0	141	0	0	0	99.1
8/9/79	II	LEPA-C	4286	0	0	0	0	422	90.1
		LEPA-MB	4041	0	4	0	0	0	99.9
8/8/79		SP-C	3502	116	0	0	0	125	93.1
		SP-MB	3478	158	13	0	0	0	95.1
8/10/79		F-C	15523	0	138	0	0	0	99.1
		F-MB	15523	0	153	0	0	0	99.0

* LEPA = Low energy precision application

SP = Sprinkler irrigated

F = Furrow irrigated

C = Conventional tillage

MB = Micro-basin

TABLE VII

RUNOFF DATA, JULY 15-SEPT. 14, 1979

Runoff Producing Rains		Runoff (Inches) (Average Blk. I & II)							
		Micro-Basin Treatments				Conventional Tillage Treatments			
Date	Inches	F-D	F-I	SP	LEPA	F-D	F-I	SP	LEPA
7/17	0.59	0	0	0.016	0.019	0.176	0.214	0.151	0.218
7/18	0.77	0	0	0.023	0.035	0.248	0.224	0.316	0.350
7/31	0.69	0	0	0.017	0.007	0.113	0.108	0.216	0.237
8/2	0.51	0	0.002	0.010	0.013	0.065	0.074	0.091	0.077
8/16	0.69	0	0.001*	0.002	0.047	0	0.002	0.063	0.035
8/20	0.44	0	.005*	0.001	0.025	0.003	0.003	0.089	0.057
8/24	0.38	0	0.005*	0.001	0.012	0.011	0.005	0.046	0.032
9/3	0.99	0	0.022*	0.01	0.048	0.050	0.028	0.095	0.105
9/7	0.99	0	0	0	0.010	0.004	0	0.009	0.013
	1.71 Non-Runoff Producing Rains								
TOTALS	7.76	0	0.035	0.080	0.216	0.670	0.658	1.076	1.124
		Avr. Runoff = 0.083 in.				Avr. Runoff = 0.822 in.			
		% of Rainfall = 1.06%				% of Rainfall = 11.4%			

* Basins Removed for Furrow Irrigation

F-D = Furrow-Dryland
F-I = Furrow-Irrigated
SP = Sprinkler
LEPA = Low Energy Precision Application

Table VII reveals that an average of only one percent of the rainfall which fell on the micro-basin treatments was lost as runoff during this period. In actuality this runoff came from the ends of the plots where flat channels were provided to carry runoff from the field plots to the flumes. No runoff actually occurred in the micro-basin plots except while the micro-basins were removed for irrigation in the furrow irrigated treatments. Slightly over 11 percent of the rainfall was lost to runoff in the conventional tilled treatments. If one assumes about one percent of this also came from the channel area, the result is a 10 percent net gain in rainfall savings to the micro-basin treatments over those with conventional tillage.

Water Use Efficiency

Water use efficiency may be defined as a ratio of crop yield per unit of water. The unit of water used will depend on the analysis or comparison desired. It can be total water utilized by the crop, including stored soil moisture, rainfall, and irrigation water applied. Or it may be only one or any combination of the three, again as determined by the analysis desired. The analysis to be made in this study was that of yield per gross water delivered by the three irrigation methods. However, a meaningful evaluation of water use efficiency was not possible due to unique climatic conditions during the 1979 growing season.

These climatic conditions included one of the wettest springs on record, which included 3.41 inches of rainfall in May and 4.93 inches in June. This excess rainfall was conducive to cotton seedling disease and Ascochyta Blight which reduced cotton stands significantly. This necessitated replanting on June 14 which is considered very late to obtain a mature cotton crop. In addition to the rainfall, the temperature throughout the growing season was much below average. Monthly temperatures in °F were below the 86 - year average by the following amounts: May - 2.9°, June - 3.2°, July - 1.9°, August - 4.0°, and September - 0.7°. These factors combined to cause a negative yield response to water received, whether by retained rainfall or by irrigation. Anticipating this is the reason for the very light irrigation application of only 1.3 acre-inches.

The negative yield response to water is shown in Figure 27. The water received included rainfall retained (obtained from runoff data) and net irrigation (function of application efficiency) from July 15 through September 14. The regression coefficient was significant at the 0.01 level with a correlation coefficient of -0.64.

Due to the above facts, it is obvious that calculations of water use efficiency would be meaningless for evaluation of these irrigation methods from the available data. However, the cotton yields and analysis of variance will be given in Table VIII.

Energy Use Efficiency

Energy required for the application of water for irrigation is proportional to the gross water delivered and to the pumping head or pressure required for the application as follows:

$$E_R \approx Qh \qquad [9]$$

where E_R is the required energy, Q is the gross application, and h is the head or pressure required. The head (h) referred to in this case is that required only by the application system and is a function entirely of the operating constraints of that system. The gross water application (Q) is a function of the net application desired and the overall irrigation efficiency.

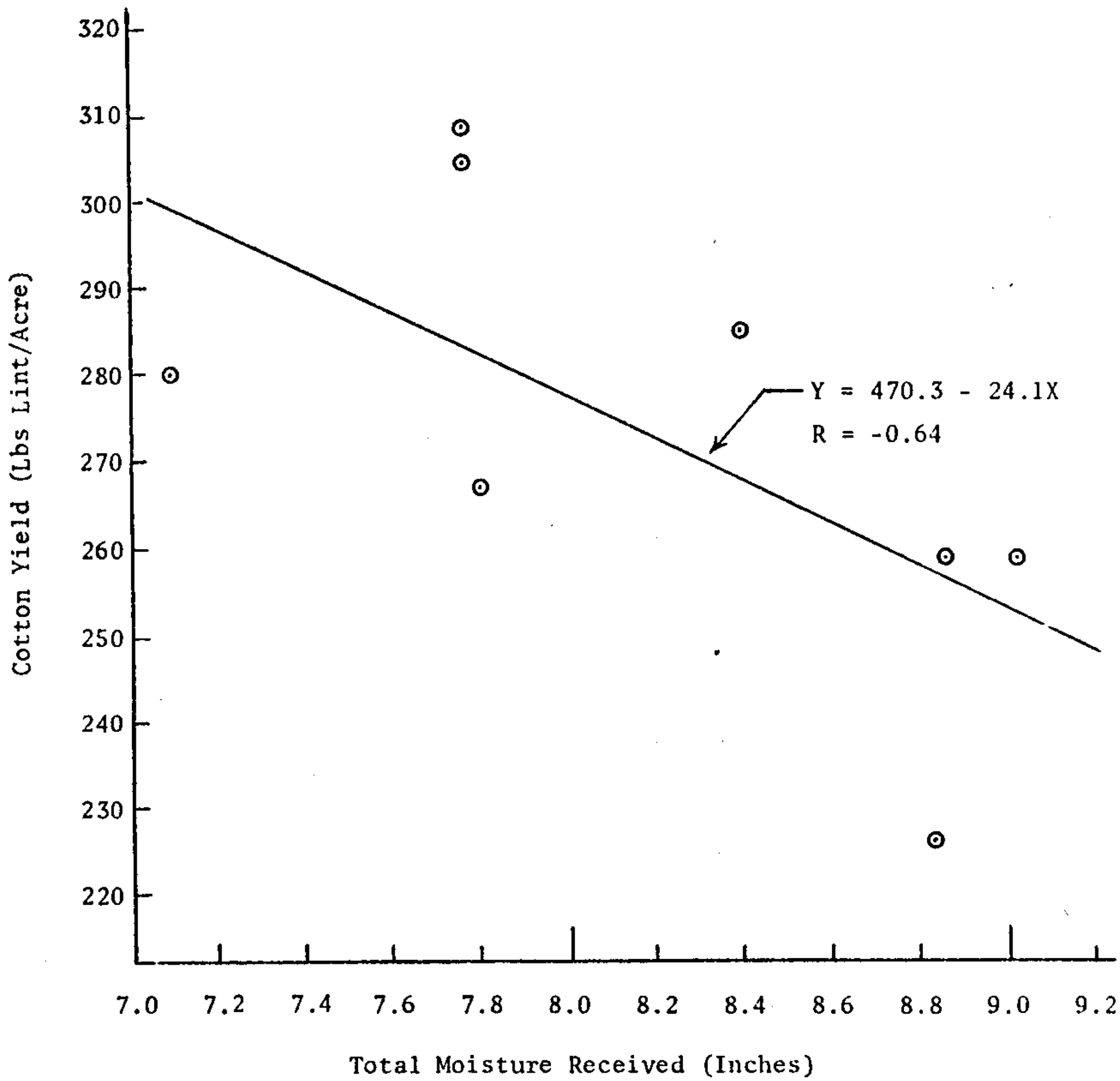


Figure 27. Cotton yield response to water, 1979.

TABLE VIII

Analysis of Variance of 1979 Cotton Yields*

	Diked				Conventional			
		Irrigated				Irrigated		
Reps	Dryland	Furrow	Sprinkler	LEPA	Dryland	Furrow	Sprinkler	LEPA
1	256	208	229	292	281	253	327	311
2	348	310	224	160	278	317	207	298
Mean	302	259	226.5	226	279.5	285	267	304.5

*Yields = lbs. lint/acre

Source of Variation	DF	SS	MS	F
Treatment	7	12,947.9	1,849.7	
Land Preparation	(1)	945.56	945.56	0.27
Irrigation Method	(3)	4,450.32	1,483.4	0.43
Interaction	(3)	7,552.02	2,517.34	0.732
Error	8	27,481.48	3,435.18	

LSD (0.05) = 135 lbs/acre

Numerous researchers have proposed the use of the product of application efficiency and distribution efficiency to determine the total amount of water which should be applied to satisfy the net requirement throughout the designated root zone for the entire irrigated area (2, 10). Thus equation 9 would be expressed as

$$E_R \approx \frac{q}{E_a\ E_d} h \qquad [10]$$

where q is the net application desired, E_a is the application efficiency, and E_d is distribution efficiency. Equation 10 may be rewritten as

$$E_R \approx \frac{h}{E_a\ E_d} q$$

and by substituting C_e for $h/E_a\ E_d$ we obtain

$$E_R \approx C_e\ q \qquad [11]$$

where C_e is designated an energy coefficient which is directly proportional to the operating pressure required by an application system and inversely proportional to the application and distribution efficiency of that system under given soil and climatic conditions. Again, C_e in this case applies only to the application system and excludes other components such as conveyance system and pumping system. The energy coefficient thus provides a useful value for direct comparison of the energy required to do a comparable or equivalent job of irrigation between systems for a given q. Energy coefficients obtained in the 1979 field tests are given in Table IX.

Table IX indicates that the LEPA-micro-basin treatment was the most energy efficient of the non-gravity methods, as determined by the low energy coefficient (C_e). This is due to both the low operating pressure and the combination of high distribution and application efficiencies. The absence

TABLE IX

Application System Energy Coefficients, 1979 Tests

Block	Treat-ment*	Operating Pressure-h (ft.)	Distribution Efficiency	Application Efficiency	Energy Coefficient C_e**	Avg. Block I&II	C_e ratio to LEPA-MB
I	LEPA-MB	14	0.96	0.99	14.7	14.7	
II	LEPA-MB	14	0.96	1.00	14.6		
I	LEPA-C	14	0.96	0.82	17.8	17.0	1.16
II	LEPA-C	14	0.96	0.90	16.2		
I	SP-MB	118	0.92	0.87	147.4	141.5	9.63
II	SP-MB	116	0.90	0.95	135.7		
I	SP-C	118	0.92	0.80	160.3	149.4	10.17
II	SP-C	116	0.90	0.93	138.6		
I	F-MB	2	0.36	0.99	5.6	5.1	0.34
II	F-MB	2	0.45	0.99	4.5		
I	F-C	2	0.39	0.99	5.2	5.9	0.40
II	F-C	2	0.30	0.99	6.7		

* LEPA = Low energy precision application

SP = Sprinkler

F = Furrow

MB = Micro-basin tillage

C = Conventional tillage

** $C_e = \frac{h}{E_a E_d}$

of micro-basins in the LEPA tests lowered the application efficiency enough to require 16 percent more water and therefore energy to obtain comparable irrigation results. Conventional tillage lowered sprinkler application efficiency only six percent from that achieved with micro-basins in place. However, the sprinkler-micro-basin treatments required 9.6 times more energy for the system to do an equivalent job of irrigation to that of the LEPA-MB system. The furrow methods were the most energy efficient. However, the low distribution efficiencies are not acceptable. A greater application would increase E_d but could potentially lower E_a so that the product could possibly be near the same value.

The data presented in Table IX is interesting but is very limited; representing only two series of tests with similar climatic conditions. The wind speeds were much lower than the yearly average wind speed on the Texas High Plains. Sprinkler application and distribution efficiencies were much higher than can be expected during the spring pre-plant irrigation season. However, energy savings of considerable magnitude are indicated by these tests when the application system alone is considered.

At this point it must be recognized that the application system is not divorced from the conveyance and pumping system and that excess water pumped due to low application efficiency requires excess energy in proportion to the total pumping head, which includes dynamic pumping lift plus head losses in the conveyance system. The energy coefficient when the total head is considered thus becomes

$$C_{et} = \frac{H+h}{E_a\ E_d} \qquad [12]$$

where H is total pumping head excluding that required by the application system. This equation provides the vehicle with which energy comparisons may be made between systems for any pumping conditions encountered. Pumping conditions for these tests required a total pumping head of approximately 280 feet, excluding the application systems. This value is thus used to calculate the total energy coefficients and are compared in Table X. This table indicates that the LEPA system offers a significant advantabe over the other two methods of irrigation in terms of energy required to do an equivalent job of irrigation when the total pumping head is considered.

Economic Analysis

Equation 12, from the previous section, may be utilized for economic analysis of modifying an existing irrigation system to a LEPA system on the basis of energy conservation alone. Data required is the existing pumping level, system operating pressure, and irrigation application and distribution efficiencies. Due to limited data from this reported project, other sources will be used for the efficiency data necessary for the analysis.

Numerous agencies have conducted demonstrations and tests on the Texas High Plains to quantify sprinkler irrigation efficiencies (4, 7, 9, 27), including the limited data from this reported research. These data have been combined and will be presented as a range along with an average value which will be used for this analysis.

Furrow irrigation efficiency data is rather scarce in addition to being extremely variable. Musick, et al. (17) reported that graded furrow irrigation systems on Pullman clay loam soils could be managed with application efficiencies exceeding 90 percent, primarily by limiting runoff.

TABLE X

Total System Energy Coefficients, 1979 Tests

Block	Treatment*	Total Head (H+h) (ft.)	Distribution Efficiency	Application Efficiency	Energy Coefficient C_{et}**	Avg. Block I&II	C_{et} ratio to LEPA-MB
I	LEPA-MB	294	0.96	0.99	309.3	307.7	
II	LEPA-MB	294	0.96	1.00	306.2		
I	LEPA-C	294	0.96	0.82	373.5	356.9	1.16
II	LEPA-C	294	0.96	0.90	340.3		
I	SP-MB	398	0.92	0.87	497.2	480.1	1.56
II	SP-MB	396	0.90	0.95	463.1		
I	SP-C	398	0.92	0.80	540.8	506.9	1.65
II	SP-C	396	0.90	0.93	473.1		
I	F-MB	282	0.36	0.99	791.2	712.1	2.31
II	F-MB	282	0.45	0.99	633.0		
I	F-C	282	0.39	0.99	730.4	839.9	2.73
II	F-C	282	0.30	0.99	949.5		

* LEPA = Low energy precision application

SP = Sprinkler

F = Furrows

MB = Micro-basin tillage

C = Conventional tillage

** $C_{et} = \frac{H+h}{E_a \ E_d}$

Wendt (28), however, reported application efficiencies ranging from 22 to 76 percent on the same soil. The low efficiencies were due entirely to deep percolation with no runoff allowed. Likewise, this writer has measured furrow application efficiencies as low as 27 percent and as high as 99 percent on a silty clay loam soil during one growing season. Also, a 10-fold difference in rate of advance has been demonstrated between adjacent furrows, with equal flow rate, by manipulation of compaction and surface retardance. For purposes of this analysis, furrow application efficiency is estimated at 70 percent.

Distribution efficiencies were not reported by Wendt or Musick. However, a distribution efficiency of about 75 percent can be estimated from data presented by Musick on an 1800-ft irrigation run. Therefore 75 percent distribution efficiency will be assigned furrow irrigation for this analysis. Irrigation efficiencies used for this economic analysis are summarized in Table XI.

Figures 28 thru 30 present the results of the analyses for converting various irrigation systems to a LEPA system on the basis of energy savings. Four conversion options are given and consist of: (1) linear LEPA with pressure regulation, (2) linear LEPA without pressure regulation, (3) pivot LEPA with pressure regulation and (4) pivot LEPA without pressure regulation. The systems analyzed for conversion include: (1) high pressure sprinkler systems given in Figure 28, (2) low pressure spray systems given in Figure 29, and (3) furrow systems given in Figure 30.

The abscissa of the figures is the existing pumping lift (H) excluding the pressure requirement of the system. The left ordinate gives the yearly savings per acre based on an energy cost of $0.05 per kilowatt hour. Curves

TABLE XI

Irrigation Efficiency Data for Economic Analysis

Irrigation System	(%) Application Efficiency* Range	Average	(%) Distribution Efficiency* Range	Average
High Pressure Impact Sprinkler	55-97	78	62-87	76
Low Pressure Spray Nozzle	63-96	80	62-87	74
Furrow	22-99	70	---	75
LEPA	99.1-99.9	99	94-97	95

*Irrigation efficiency data from the Texas High Plains.

are given for net yearly water application of one, two, three, and four acre-ft. per acre.

The ordinates to the right give the payback period on the investment for each conversion option. The conversion of the sprinkler and spray pivot systems to LEPA assumes the pivot system was already in possession and the cost is that of modification only. The conversion from a furrow system includes the purchase of the basic pipe and tower structure along with the modification expense. It is assumed the linear systems are capable of irrigating 320 acres, whereas, the pivot systems are limited to 130 acres for this analysis. The initial capital investment estimated for the conversions are as follows:

(1) furrow to linear LEPA (WPR) - $51,000,

(2) furrow to linear LEPA (W/O PR) - $47,000,

(3) furrow to pivot LEPA (WPR) - $43,000,

(4) furrow to pivot LEPA (W/O PR) - $39,000,

(5) pivot to linear LEPA (WPR) - $16,000,

(6) pivot to linear LEPA (W/O PR) - $12,000,

(7) pivot to pivot LEPA (WPR) - $8,000, and

(8) pivot to pivot LEPA (W/O PR) - $4,000, where WPR = with pressure regulation and W/O PR = without pressure regulation.

The following assumptions were made in the investment analysis to determine the payback period: (1) 15 year machine life and investment period, (2) 25 percent income tax bracket, (3) straight line depreciation, (4) zero down payment or 100 percent loan, (5) unpaid balance or commercial type loan, (6) 5 year loan repayment period, and (7) 15 percent annual interest rate on the loan.

One can note from Figures 28 and 29 that the investment for converting an existing pivot system to LEPA can be readily justified from an energy saving standpoint. However, the conversion of a furrow system operating at the assumed efficiencies could not be justified due to energy savings alone, if low pumping lifts exist and/or if small amounts of water are pumped annually. This is especially true for conversion to a pivot LEPA system that is confined to only 130 acres. When water is being mined, as in the Texas High Plains, there is a value which must be placed on the water saved by the LEPA system. But, this value will have little affect upon the short term cash flow upon which a farmer must operate and base his economic decisions.

There are numerous other positive economic benefits which should accrue from conversion to a LEPA system. Irrigation demand should be decreased due to greater rainfall retention of basin tillage. However, this practice should yield positive benefits regardless of the irrigation system with which it is coupled. Increased irrigated acreage and/or more timely irrigation scheduling will result in water short areas due to the

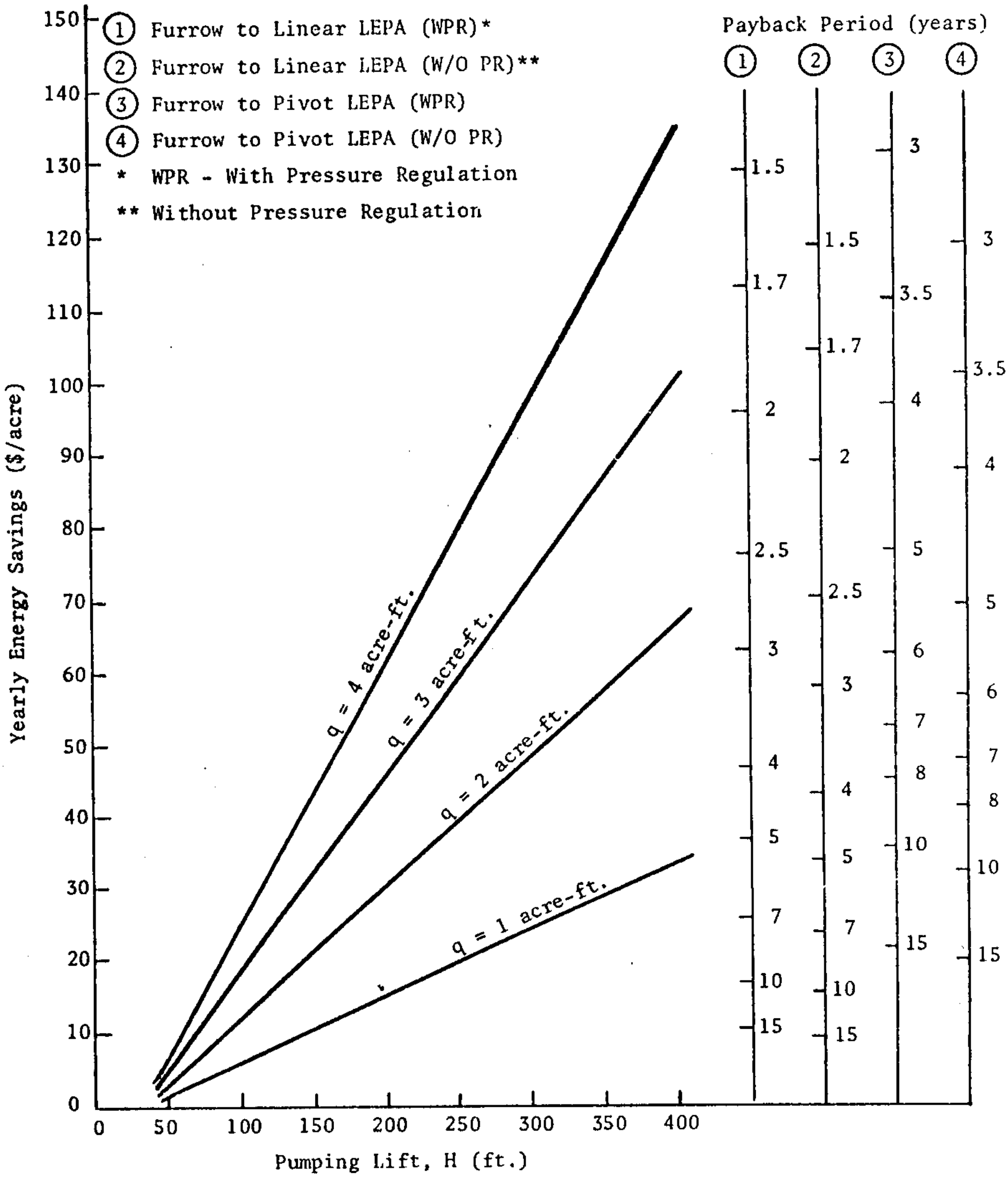


Figure 30. Potential energy savings due to converting furrow system to LEPA system.

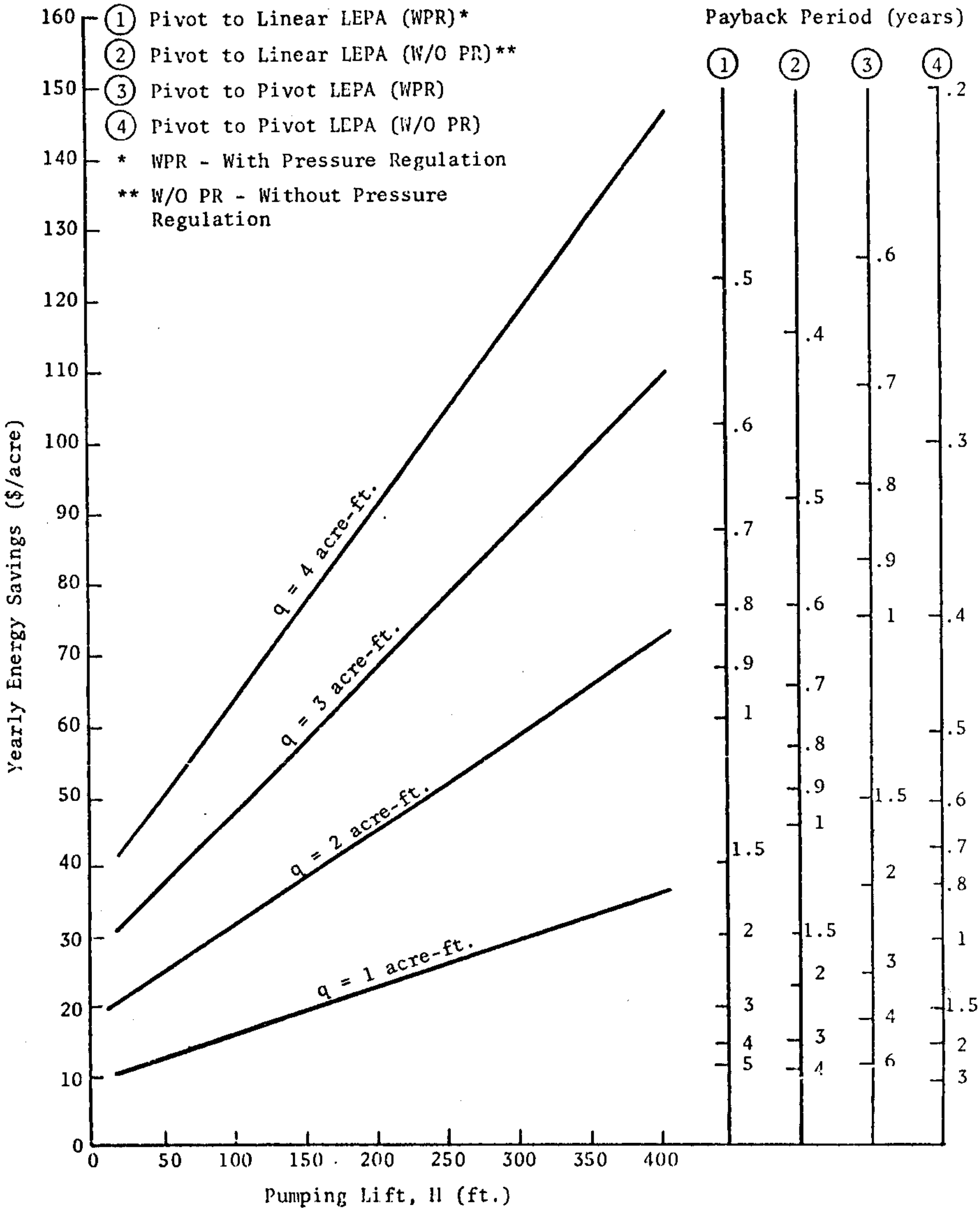


Figure 29. Potential energy savings due to converting low pressure spray system to LEPA.

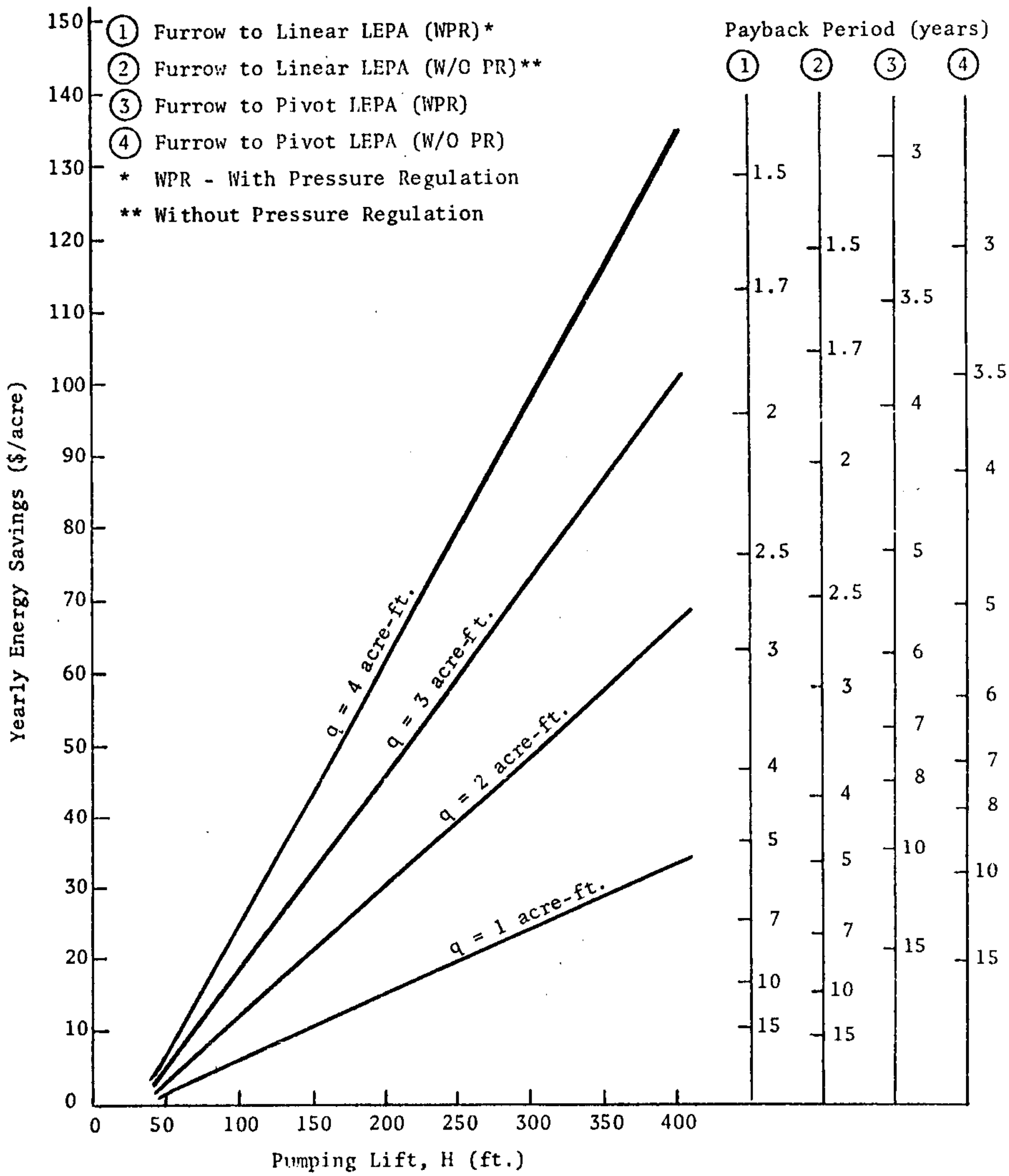


Figure 30. Potential energy savings due to converting furrow system to LEPA system.

high LEPA application efficiency. This along with high distribution efficiency should also result in a higher water use efficiency of the crop. However, due to lack of adequate crop data these analyses cannot be made at this time. As shown in the existing analysis, however, the conversion to a LEPA system can be justified by energy savings alone in all but a few situations.

SUMMARY AND CONCLUSIONS

The primary objective of this project, which was to maximize overall water use efficiency and minimize energy consumption through irrigation system design, has been realized. Design criteria have been met in the development of an irrigation system which moves in a linear fashion and distributes water uniformly at or near the soil surface at very low pressure. The system was labeled a low energy precision application (LEPA) system. Additional tillage and soil surface modification equipment has been developed to prevent runoff when water is applied in this manner and to retain rainfall.

Stationary and dynamic hydraulic testing was conducted to determine the uniformity of water application by the system and to quantify the hydraulic losses within the system. It is projected from this data, that the system will achieve distribution efficiencies in the range of 95 to 96 percent. It should also operate at pressures ranging from a low of approximately 4.5 psi for a 4-tower system delivering 100 gpm without pressure regulation to about 22 psi for a 1/4-mile, 10-tower system delivering 1,000 gpm with pressure regulation to the manifolds.

Application efficiencies in excess of 99 percent were measured in limited testing for comparison with a furrow irrigation and impact sprinkler systems. The climatic conditions were such that the resulting sprinkler efficiencies were much higher than would be expected for a yearly average in the Texas High Plains. Even so, the LEPA system demonstrated significant superiority over the sprinkler system in both application and distribution efficiencies.

When both irrigation efficiencies were combined with the system operating pressure to give an energy coefficient, the sprinkler system required about 10 times more energy than did the LEPA system for equivalent net application results. When system pressure was combined with the existing pumping lift to give a total system energy coefficient, the sprinkler system consumed about 1.5 times as much energy as the LEPA, and the furrow system about 2.5 times as much energy as determined from test data. However, the furrow system distribution efficiencies in these tests were very low and it is thought that this figure should be nearer 2 for furrow irrigation.

Micro-basin tillage increased the irrigation efficiencies of both non-gravity irrigation methods. Its use resulted in a 6 percent increase in the energy coefficient for sprinkler and a 16 percent increase in the LEPA energy coefficient. Basin tillage also retained all of the rainfall runoff in 1979 which averaged 10 percent during the summer months on the conventional tilled plots.

An economic analysis of the conversion of various irrigation systems to LEPA, proved to be economically feasible on the basis of energy savings alone in all but a few cases where either very low pumping lifts exist and/or where very small amounts of water are applied by furrow or gravity methods.

Reliable crop yield data, with which to obtain water use and energy use efficiency values, were not obtained in the 1979 field tests due to adverse climatic conditions. However, certain conclusions may be made at this time with the existing data and are as follows:

(1) A simple lateral move irrigation system can be constructed which derives its water supply from existing low pressure underground pipelines.

(2) Very low pressure operation is possible while still maintaining high application coefficients of uniformity.

(3) Almost complete control of application amounts is possible and can be managed by the lateral speed of the system. This control can completely eliminate deep percolation losses of water during irrigation.

(4) Furrow diking implements have been developed and the practice of basin tillage can successfully be integrated into row crop production during the growing season.

(5) Basin tillage effectively elimates runoff under a LEPA irrigation system from both rainfall and applied irrigation water and its conjunctive use with LEPA irrigation is recommended unless a soil is very permeable.

(6) Spray evaporation losses of conventional sprinkler systems are essentially eliminated with the LEPA system.

(7) The combination of low operating pressure and both high application and distribution efficiencies, results in potential water and energy savings of great magnitude for LEPA irrigation over sprinkler and furrow methods.

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