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Development and evaluation of mobile drip irrigation with center pivot irrigation machines

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Development and evaluation of mobile drip irrigation with center pivot irrigation machines

Asaad Abdelkader Abdalla Derbala

Dedication

To my

wife,
daughter Nesma,
son Mohammed
and family

A. Derbala

DEVELOPMENT AND EVALUATION OF MOBILE DRIP IRRIGATION WITH CENTER PIVOT IRRIGATION MACHINES

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LIST OF SYMBOLS

Symbol	Meaning	Unit
PC*	pressure compensating	---
NPC+	non-pressure compensating	---
q	emitter discharge	L/h
k_e	emitter discharge coefficient	---
H	operating pressure	kPa
x	emitter discharge exponent	---
CV	discharge coefficient of variation	%
S_q	standard deviation of discharge rates	L/h
$q_{av.}$	mean of emitter discharge rate	L/h
x_i	measured discharge value	L/h
x`	mean of discharge	L/h
U_s	statistical uniformity coefficient	%
$q_{var.}$	emitter flow variation	%
$q_{max.}$	maximum emitter discharge	L/h
$q_{mini.}$	minimum emitter discharge	L/h
EU	emission uniformity of emitters	%
q_n	average discharge in lowest 25% of discharge	L/h
q_a	average discharge of all emitters	L/h
FC	field capacity	%
PWP	wilting point	%
K	hydraulic conductivity	mm/h
A	irrigated area	m^2
r	distance between sprinkler and the pivot point	m
dr	narrow spacing between sprinklers	m
q_s	discharge of the tiny sprinkler	m^3/h
b	water application depth/revolution of the system	mm
T	time period required/one revolution of the system	h
W_{cg}	water content	g/g, %
W_w	wet weight of soil sample	g

W_d	dry weight of soil sample	g
W_{cv}	water content	vol., %
d_s	density of soil	g/cm³
d_w	density of water	g/cm³
IAR	instantaneous application rate	mm/h
w	width of irrigated area	m
L	distance between emitters	m
ε_p	distribution pattern efficiency	%
R	infiltrated water	mm
I	applied water	mm
Fr	friction force	N
mr	weight of water and tube	kg
μ	friction factor	---
g	acceleration of gravity	m/s²
D	depreciation	€/a
P	purchase or initial price	€
S	salvage value	€
a	life of system	year

1 INTRODUCTION

One of the oldest irrigation systems in the world is in the Nile Valley in Egypt, where irrigation has taken place for nearly 7000 years. Prior to the construction of the Aswan High Dam, Egypt was dependent on the uncertain natural flow of the Nile to provide needed irrigation water. As the final attempt to harness the Nile, the Aswan High Dam was erected and inaugurated in 1971. This provided water storage during all seasons and years as well as flood control which has provided agriculture with a steady, year-round and, until recently, plentiful source of irrigation water. And thus the Aswan High Dam provided the possibility to raise the efficiency of the irrigated agriculture. Before the High Dam, the lands in the Nile Valley were kept fertile by the annual flood of the river, which deposited a thick layer of silt each year on the ground of the Nile Valley. In the newly reclaimed areas, farmers use modern irrigation systems such as sprinklers and/or micro-irrigation. In these areas, surface irrigation techniques are banned by law. In the past two decades, modern irrigation systems, such as drip irrigation, center pivot and linear machines, were required to irrigate the new land. Given these conditions, it was necessary that this study be carried out in Germany also with regard to the high technical standard of irrigation systems reached in this country.

1.1 General information about irrigation systems and agriculture in Egypt

Egypt is located in the north-eastern corner of the African continent with a total area of about 1,002,000 km². Total population is about 70,712,345 (CIA, 2002) Egypt is an arid country which depends almost entirely on the River Nile for its water supply. It is estimated that the Nile provides 95% of the country's fresh renewable water supply. Agriculture is almost totally dependent on this source. In 1993, cultivated land was estimated to be 3 – 4% of the total area. The mean annual rainfall of 18 mm ranges from 0 mm/year in the desert to about 200 mm/year in the north coastal region. The mean monthly values of rainfall in different provinces of Egypt are illustrated in Figure 1.1. On the other hand, the mean monthly values of evapotranspiration in the same chosen provinces are very high in summer as shown in Figure 1.2. Almost all agriculture in Egypt is irrigated agriculture. Even the small, more humid area along the Mediterranean coast requires supplementary irrigation to produce reasonable yields. All irrigation is fully or partially controlled irrigation. The control and management of the river waters have become possible since the construction of the Aswan High Dam and the barrages on the Nile. All lands are irrigated from the Nile, except in the provinces of Matrouh, New valley and South-Sinai, where the groundwater is used in the irrigation process. The places of surface and modern irrigation systems in Egypt are shown in Figure 1.3.

Water is the major constraint not only in Egyptian agriculture but also in all of the world. Water resources are limited to the country's share of the River Nile water which is fixed according to the 1959 agreement between Egypt and Sudan at 55.5 billion m^3/year, plus minor quantities of rainfall and groundwater. The remaining 96 – 97% of land is barren desert. Ancient irrigation styles depended very much on the physical geography of the area and the engineering skills available.

The irrigation system in the old lands (S) of the Nile Valley and Delta is a combined gravity and water lifting system. The main canal system takes its water from head regulators, located upstream of the Nile dams. The Egyptian irrigation system extends over 1,200 km south of Aswan to the Mediterranean Sea. The agricultural areas are served by over 31,000 km of public canals, 80,000 km of field canals, and 17,000 km of public drains (El-Atfy, 1999). The water is distributed along branches where the flow is continuous. Distributaries receive water according to a rotation schedule. Finally, the water is pumped from these distributaries with a 0.5 m to 1.5 m lift to irrigate the fields. The irrigation system in the newly reclaimed areas (M) is based on a succession of pumping stations from the main canal to the fields with a total lift of 20 to 30 m. For this purpose, new irrigation systems such as center pivot, linear sprinkler, and micro irrigation are used.

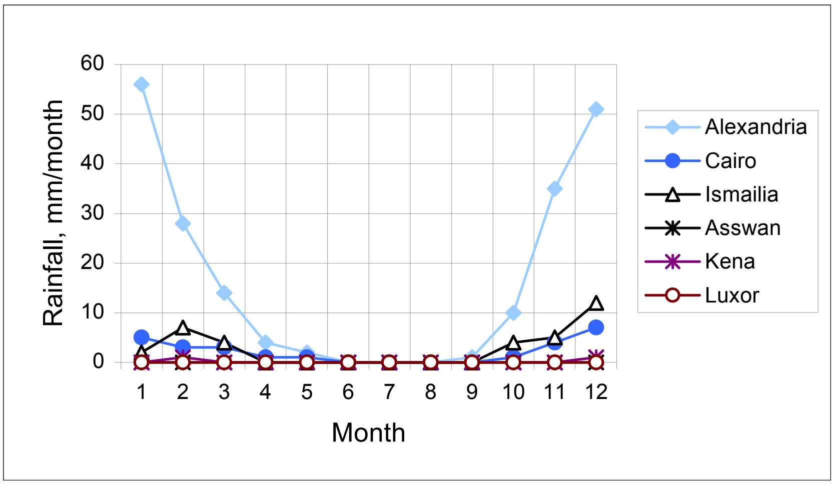


Figure 1.1: Mean monthly values of rainfall in different provinces in Egypt (Hargreaves and Samani, 1986)

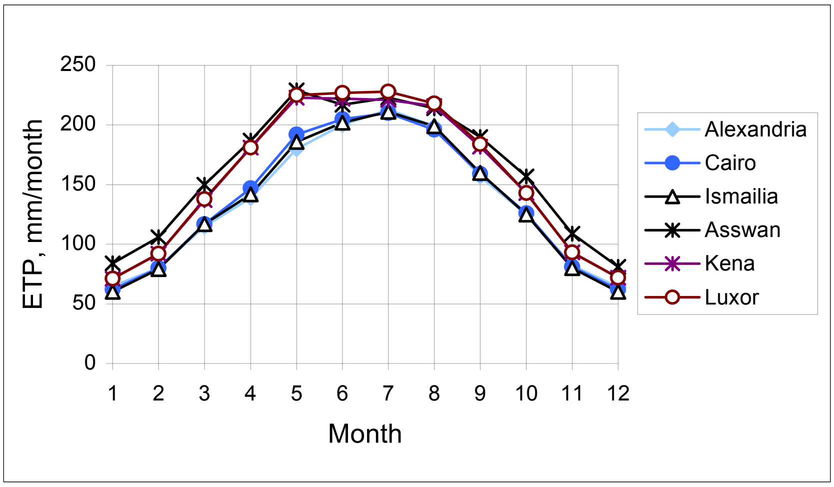


Figure 1.2: Mean monthly values of evapotranspiration (ETP) in different provinces in Egypt (Hargreaves and Samani, 1986)

Egypt has made giant efforts to reclaim land in the Tushka, Western Desert, Gulf of Suez, East Port-Said and North-Sinai to allow its people to finally break out of the confines of the tiny Nile Valley and Delta. Water resource management is a key to the future of Egypt and is a national priority. Water demand management is a relatively new concept in Egypt and other parts of the world. It includes water pricing, changes in crops and technologies. To increase the supply of water resources, the government is examining the agricultural reuse of drainage water, the reuse of treated municipal water, and the improvement of irrigation efficiency. The environmental limitations must be considered and appropriate for the reuse technology developed.

Figure 1.3: The places of surface (S) and modern (M) irrigation systems in Egypt

Egypt is gifted with good soils, relatively good climatic conditions, perennial sources of irrigation water, and professional engineers and farmers. These provide excellent conditions for agricultural production and the application of intensive agriculture. The present water supply barely sustains the current demand in Egypt, and the demand for water is increasing. Currently the population is growing by about 1 million a year. Egypt is expected to face a population of about 86 million by year 2025 (Abu-Zeid and Rady, 1992). The real challenge confronting Egypt now is how to manage and develop the limited natural resources such as water, land, and energy to meet the increasing requirements of a steadily growing population. Extensive research and numerous studies have been carried out in different fields with regard to the development of water resources and the improvement of irrigation and drainage methods as well as the means of protecting the environment from pollution.

The main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduced yield or poor harvest quality. The ability of a sprinkler system to apply water uniformly throughout the irrigated area is one major factor which decides whether or not proper crop growth can be maintained. Ideally, an irrigation system would apply water in a completely uniform manner so that each part of the irrigated area receives the same amount of water. Significant efforts in sprinkler irrigation system design and management are directed towards dealing with problems related to irrigation uniformity, or the lack of it. Irrigation uniformity is related to crop yields through the agronomic effects of under- or over-watering. Insufficient water leads to high soil moisture tension, plant stress and reduced crop yields. Excess water may also reduce crop yields below potential levels through mechanisms such as leaching of plant nutrients, increased disease incidence or failure to stimulate the growth of the commercially valuable parts of the plant.

1.2 Irrigation systems in Egypt today

In Egypt, different irrigation systems are used to irrigate both the old lands and newly reclaimed areas. These systems are surface, sprinkler and localised irrigation. The area irrigated with the aid of these systems is illustrated in Table 1.1. Generally speaking, many important irrigation- and drainage projects have been developed and installed in Egypt in the past ten years. The objectives of these projects were optimal water use and greater efficiency of water use; the maintenance and operation of dams, reservoirs, barrages; reuse of drainage water; better agricultural productivity and quality; extension of newly reclaimed areas by using modern irrigation systems, such as sprinkler and stationary drip irrigation systems as shown in Figures 1.4 and 1.5.

Table 1.1: Area irrigated by different irrigation systems in Egypt (ICID, 2002)

Irrigated area	**Surface**	**Sprinkler**	**Localised**	Total
ha	2,746,000	450,000	104,000	3,300,000
%	83.21	13.64	3.15	100

Figure 1.4: Sprinkler irrigation systems in newly reclaimed areas

Sprinkler irrigation can be adapted to many crops, soils and topographic conditions. Sprinkler systems are classified according to whether the sprinkler heads are operated individually (gun or boom sprinklers), or as a group along a lateral line, and according to how they are moved or cycled to irrigate the entire field. A center pivot system consists of a single sprinkler lateral with one end anchored to a fixed pivot structure and the other end continuously moving around the pivot while applying water.

Figure 1.5: Stationary drip irrigation systems in newly reclaimed areas

This short presentation of irrigation techniques shows that water distribution systems in Egypt have undergone substantial changes in the past 20 years. For many years, surface irrigation systems have been employed in the Nile delta and valley. However, it is impossible to use these systems in newly reclaimed areas. Today, we need to save large quantities of water to reclaim new areas everywhere in Egypt. This study is intended to make a contribution towards the efficient use of water and thus provides useful insights for Egyptian government and water management authorities.

2 PROBLEMS AND OBJECTIVES

Egypt is largely dependent on irrigation water for agricultural production. Egypt is an arid country which depends almost entirely on the River Nile for its water supply. The water resources in Egypt are becoming scarce (El-Atfy, 1999). Due to population pressure and demands for both increased quantity and better quality of food and fibre, imports of food have reached alarming proportions in recent years. Policymakers are greatly concerned about future water shortages, conservation of scarce water supplies and the present performance of irrigation systems in Egypt. The Ministry of Public Works and Water Resources has made giant efforts to reclaim and plant new lands in the desert. The ministry is also in charge of plants and systems which discharge water into canals, drains and the Nile.

Various water saving techniques have been developed for surface irrigation systems in the old areas, which include land leveling, small ditch or furrow irrigation, canal and ditch leakage prevention, and closed conduit water transportation. In the newly reclaimed areas, the sprinkler irrigation systems have become one of the most popular types of irrigation systems in Egypt. However, they have some disadvantages such as runoff, droplet evaporation, drift losses, and canopy evaporation. Evaporation losses due to sprinkler irrigation have been the subject of numerous field, laboratory and analytical studies (Christiansen, 1942).

The stationary drip irrigation system is the most efficient method of applying water to specific plant bed areas. The stationary drip systems apply water only to the area in need of water. Runoff and the effects of wind are eliminated. Other benefits are reduced weed growth, low pressure requirements, efficient fertilizing with the aid of injection systems, and energy conservation. Direct energy savings in drip irrigation are achieved by means of reduced operating pressure as well as reduced pumping volumes. However, the drip irrigation systems have some disadvantages such as high maintenance requirements, potential clogging, environmental effects, and high costs. In all cases, stationary drip installation requires additional and more complex equipment than the typical sprinkler system.

Irrigation efficiencies vary with the type of irrigation system used and with other factors such as soil, crop and climatic conditions including wind velocity, relative humidity and air temperature. The choice of an optimal method for the application of irrigation water can also significantly improve the efficiency of water use. Methods of maximizing benefits and selecting the most suitable irrigation system should be put forward. In order to achieve sustainable agricultural development, irrigation should also be planned and managed in such a way that both water and energy can be conserved.

The development of irrigation is characterised by numerous technological solutions for the improvement of technical and economic performance as well as improved management and handling. In arid regions such as Egypt, center pivot systems experience greater amounts of evaporation than in other climates. Thus, improving irrigation efficiency is extremely important. Several proposals have been made to improve and modify sprinkler irrigation systems by using mobile drip irrigation in order to conserve water and energy (Phene et al., 1981, Chu, 1984; Helweg, 1989; and Sourell, 1991). However, the classic dripping irrigation materials were used in none of these solutions. Therefore, the objectives of this study were to:

1- Develop and evaluate the mobile drip irrigation (MDI) system with center pivot machines.
2- Save water and energy by using the MDI system.
3- Compare the total costs of stationary drip, center pivot sprinkler and mobile drip irrigation.

To achieve these objectives, the study was accomplished in four stages. First, laboratory experiments were carried out to choose the better type of emitters for the center pivot machine. Second, water quantities at all pivot outlets and the length of the drip tubes were calculated, and the sprinklers on the pivot were replaced by the drip tubes. Third, field experiments were carried out in order to measure both the soil water content and the friction forces between the tubes, the soil and the plants. Fourth, the costs of mobile drip irrigation, stationary drip irrigation and the traditional center pivot machine were analyzed.

3 ANALYSIS OF CURRENTLY USED IRRIGATION TECHNOLOGY

Irrigation water is very important for crop cultivation. Water is needed for seeds to germinate, seedlings to emerge and many plant growth functions. In arid areas, the crops cannot be grown without irrigation. Irrigation must provide almost all of the crop water requirements to meet the evapotranspiration (ET) needs. In addition, irrigation must be managed to remove salt that accumulates in the soils since nearly pure water is removed by ET. Irrigation technology has made considerable progress during the past decades, but many projects and farm irrigation systems have not been improved significantly.

Irrigation requirements depend on precipitation during the growing season, the soil type, and the rooting depth of the crops. The characteristics of farm water supply can have a significant effect on the selection of a farm irrigation system. Factors such as location, available quantity, time distribution of the quantity, and the quality of the water supply can exert an influence on the evaluation of applicable farm irrigation systems.

3.1 View of present irrigation systems

Farm irrigation systems can be classified into irrigation methods by the manner in which water is applied to the soil. A common classification used is to divide the systems into (a) surface irrigation methods where small open channels or overland flow is used to distribute the water over a cropped field, (b) sprinkler irrigation methods where water is distributed aerially to the cropped field and (c) trickle irrigation methods where small point applicators are used to apply the water. A fourth method, subsurface irrigation, is accomplished by controlling the level of the water table or by applicators which apply the water below the soil surface, which results in the water being distributed through the soil by capillary forces (Thompson et al., 1980). Generally, irrigation systems can broadly be classified as either surface systems or pressurized systems as shown in Figure 3.1.

Generally, irrigation projects are expensive to construct, maintain and operate, and thus the returns must and can be high to repay the investments made. Maximum returns are dependent on intensive crop production and the use of multiple cropping patterns. Therefore planning and design must include the selection of the right kinds and combinations of crops depending on the soil, the climate, the available quantity of water, and the market conditions. Multiple cropping also introduces more stringent time limits for seedbed preparation, planting, harvesting and water application. On the other hand, the area irrigated by means of any irrigation system is different from place to place and depends on many factors. Localised irrigation systems have many advantages. So far, however, they have not been very popular because they are very expensive. The percentage of areas irrigated world-wide with the aid of different irrigation systems is illustrated in Table 3.1.

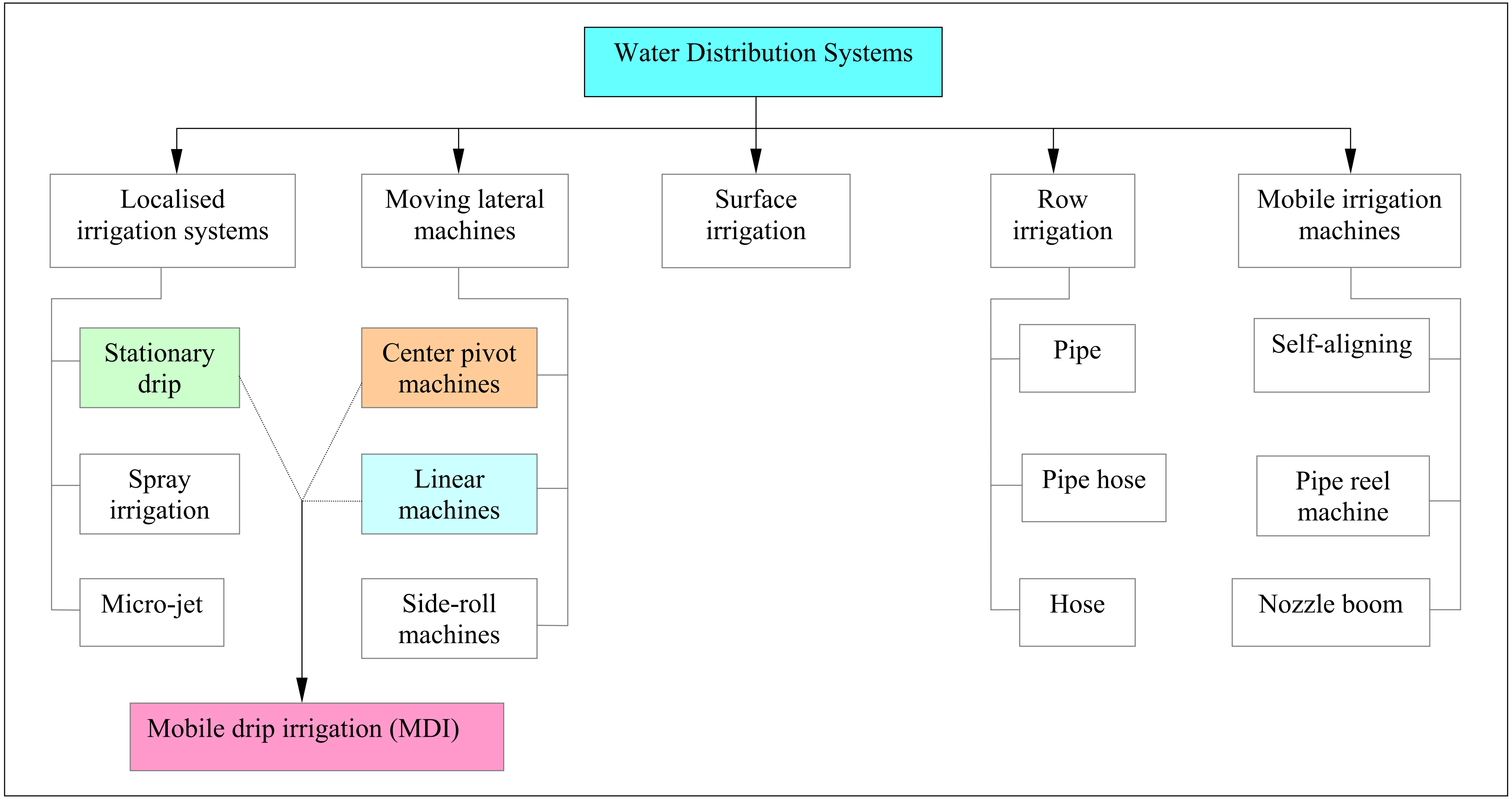


Figure 3.1: Classifications of farm irrigation systems (after Sourell, 1991)

Table 3.1: Percent of irrigated area in the world using different irrigation systems

Place	Irrigated area, 1000 ha, FAO-yearbook (1996)	Portion of irrigated area from cultivated lands and permanent crops, %	**Surface (%)**	**Sprinkler (%)**	**Localised (%)**	Source of data
Europe	25.151	7.9	35	61	4	*
Asia	175.442	34				*
Middle East			88	11	1.4	*
Soviet Republic			58	42	0.05	*
Africa	12.280	6.4	78	20	0.2	*
North America	30.142	10.9	60	35	5	*
California			67	24	9	*
South America	9.826	8.9	80	20		*
Australia	2.605	4.9	40	53	7	Bucks (1993)
Total	255.446	17.3				
Mean			63	34	4	

* FAO, Aquastat, 1998

3.1.1 Surface irrigation

Surface irrigation uses open channel flow to spread water over a field. The driving force in such systems is gravity and hence the alternate term, gravity flooding. Most surface irrigation systems in arid and semi-arid areas are designed to raise the soil water content of the root zone to its field capacity even though water may be wasted. Generally, surface irrigation systems require a smaller initial investment than other types of irrigation systems (Hart et al., 1980). There are three common types of surface irrigation systems: basin irrigation, border irrigation and furrow irrigation.

3.1.1.1 Basin irrigation

The field to be irrigated using the basin method is divided into level, rectangular areas bounded by dikes or ridges. Water is turned on at one or more points until the desired gross volume has been applied to the area. Most crops can be irrigated with the aid of basin irrigation. High application efficiency can be achieved easily with little labor. Basin irrigation can also be applied efficiently by inexperienced workers. Accurate initial land leveling is essential, and level surfaces must be maintained. Basins require relatively large inflow rates, and special structures may be needed to prevent erosion.

This method is useful and often used for salt leaching through deep percolation in the reclamation of saline soils. Due to the expenses for plot leveling, however, its use is restricted to level lands. Small basins used in the irrigation of orchards are commonly refered to as checks. Basins may be square, rectangular, or irregular in shape, and may vary in size from 2 m to 2 or more hectares (FAO, 1984).

3.1.1.2 Border irrigation

Border irrigated fields are divided into graded strips by constructing parallel dikes. The ends of the strips are usually not closed. The main factors to be considered are border length and slope, stream size per unit width of border, soil intake rate and degree of flow retardance by the crop as water flows down the strip. Border irrigation can be used on most soils. It is, however, best suited to soils with a moderately low to a moderately high intake rate. Border irrigation is best suited to slopes of less than 0.5% (Hart et al., 1980).

Because of its wide adaptability and the ease of water application, careful consideration should be given to this method of irrigation. The physical properties of the soil, the location of the area, and anticipated land use are important factors which need to be considered before border irrigation is applied. These factors, along with the size of the irrigation system available, not only determine the suitability of this method, but also determine the proper width and length of the border strips.

Howe and Heermann (1970) studied the performance of border irrigation on different soil types. They reported that good uniformity was achieved on higher gradients. It was also easier to reach high uniformities on low gradients. Peak uniformities were never achieved on steeper slopes; however, this may be attributed to lower grading precision.

3.1.1.3 Furrow irrigation

Furrows are sloping channels shaped in the soil where infiltration occurs laterally and vertically through the wetted perimeter. Furrows can be designed with a variety of shapes and spacings. Most furrows in row crops are either parabolic in cross section or have flat bottoms and about 2 to 1 side slopes. Most crops can be irrigated using the furrow method except those grown in ponded water, such as rice. This irrigation method is best suited for medium to moderately finely textured soils featuring relatively high available water holding capacity and conductivity, which allow for significant water movement in both the horizontal and vertical directions. The water does not get into contact with the plant stems. Thus, scalping is avoided. Surface runoff occurs except for places where the field is level, and water is impounded until intake is completed. Labor requirements may be high as irrigation streams must be carefully regulated to achieve uniform water distribution. Salts from either the soil or water supply may concentrate in the ridges and depress crop yields (Achtnich, 1980). Unnecessary water losses will occur from deep percolation if the furrows are too long. This system of irrigation is also used extensively by farmers to irrigate crops planted on beds, ridges, or nearly level land. The beds or ridges are made by either ploughing the land to form beds or making deep furrows in the tilled land.

3.1.2 Pressurised irrigation systems

In the most recent decades of the long history of pressurised systems or irrigation, new methods have been developed and have begun to spread quickly in many countries of the world. The diffusion of these new methods mostly takes place in industrially developed countries, although the necessity of their application can also be found in developing countries, especially in those with arid and semi-arid climates (Balogh and Gergely, 1985). These new methods can also be used with good results even in areas with a subhumid climate.

There are many types of pressurised systems, such as sprinkler irrigation systems and micro-irrigation systems. In pressurized irrigation systems, the water is generally moved dynamically from the water source through the pump into the pipe. Letey et al. (1990) indicated that although pressurised systems provide greater water application uniformity than surface irrigation, economic analysis must be made to justify the additional investment costs.

3.1.2.1 Solid set and hand move systems

This category is composed of a network of sprinkler units which are kept in the same place during the irrigation period. This irrigation system can be used for frost protection. It can also be employed to apply fertilizers, pesticides, insecticides and fungicides by adding them to irrigation water. A field irrigated using this system is equipped with pipes, sprinklers and valves in sufficient quantity to avoid moving the sprinkler laterals and the sprinklers themselves during or between the applications of water (FAO, 1982).

3.1.2.2 Moving lateral systems

The objective of irrigation is to uniformly apply water over the area for crop use. Sprinkler irrigation systems should be designed to apply water at a rate less than the intake rate to prevent surface runoff. Among the sprinkler irrigation systems used in the world, they are certainly the ones requiring the smallest number of working hours, but they also need the largest outlay per hectare (FAO, 1982). Generally, sprinkler irrigation systems can be adapted to many crops, soils and topographic conditions.

All sprinkler irrigation systems in this category have sprinkler laterals which are moved between irrigation settings. The most common system has a single center mainline with one or more laterals which irrigate on both sides of the mainline. Spacing of the sprinklers on the laterals and the spacing between subsequent sets of each lateral are such that the water distribution patterns from the sprinklers overlap almost completely.

The basic components of moving sprinkler systems are: a water source, a pump, a pipe network for the distribution of water throughout the field, sprinklers and water flow control valves. The following types of moving systems are commonly used today: center pivot, linear and side-roll.

3.1.2.2.1 Center pivot machines

In center pivot machines, sprinklers are placed along a lateral line approximately 400 m long. The center pivot is a self-propelled, continuously moving machine that rotates around a central pivot point. A center pivot machine consists of a single sprinkler lateral with one end anchored to a fixed pivot structure and the other end continuously moving around the pivot. The center pivot machine was designed to irrigate circles of a very large radius as shown in Figure 3.2 using practically no manual labor and requiring only a very small part of the hydraulic power furnished by the pumping mechanism in order to move the machine.

Figure 3.2: Center pivot machine suitable for the irrigation of circles of a very large radius

The water is supplied from the source to the lateral through the pivot. The lateral pipe with sprinklers is supported on drive units and suspended by trusses. A pipe lateral equipped with sprinklers is mounted on wheeled supports; the joints of the laterals or its flexibility allow adjacent elements to form an angle at each support. The supports, or towers, are equipped with hydraulic or electric motors which are started up by an appropriate device when two adjacent towers or spans form a certain angle. The center pivot system can generally complete one revolution in 12 to 96 hours (Benami and Ofen, 1984). The speed of rotation of the lateral is controlled at the end tower farthest from the swivel joint. The rate and depth of water application are determined by a combination of the speed of rotation, the discharge of the sprinklers and the size of the wetted area. In the case of center pivot systems, application rates should be directly proportional to the distance from the pivot because the discharge and the rates of travel of the sprinkler heads must increase in proportion to the irrigated area (Kincaid et al., 1969).

At the same time, the center pivot machine must be reliable because in arid areas it will be operated more hours during the cropping season than almost any other piece of farm equipment. The center pivot lateral must be able to be repaired on the field because another lateral cannot be quickly substituted for a disabled one. Drive units are mounted on wheels that are located 24.4 to 76.2 m apart along the length of the lateral pipe, which may vary from 61 to 792.5 m (Addink et al., 1980). The rate at which the drive unit and lateral pipe advance around the pivot is determined by the speed of the outermost drive unit.

In all types of center pivots, no matter whether they are powered electrically or hydraulically, it is usually necessary for safety reasons to install an electric circuit designed to shut off the pump, and therefore the rotating movement, by means of signals transmitted to the pivot point when malfunctions occur in the operation of the machine. To increase the profitability of center pivots, it was considered possible to move them by hauling them from one pivot point to another, and thus to irrigate at two or even three pumping sites. In this case, the length of the center pivot to be moved should not exceed 200 to 300 m. Otherwise, the stress would be too great to be borne by the metal trusses. Moreover, the manufacturers had to reinforce the framework of the movable laterals thoroughly in recent years because they warped during traction (FAO, 1982). The design of center pivot systems was largely developed on the basis of different factors.

Generally, a unique problem for sprinkler systems is that the water application pattern is susceptible to distortion by the wind. While wind velocity and direction are not controllable variables, their effect on irrigation uniformity is significant. Therefore, sprinkler systems must be designed with anticipated wind conditions in mind. For a given wind condition, the primary factors affecting uniformity are nozzle type, nozzle size, operating pressure and spacing between nozzles. The trend has been to place the nozzles within the crop canopy only ca. 45 cm above the ground in order to eliminate droplet evaporation, drift losses, and canopy evaporation. This has a distinct disadvantage because it reduces the wetted diameter and increases the instantaneous application rate (Alam, 1999). Uniformity can be influenced not only by the irrigation equipment in the system, but also by the way the system is managed.

The corner attachments, which are not used on a large number of machines, allow the corners of square fields to be irrigated. The corner attachment is an additional tower that is operated only as needed. It swings out from the end of the lateral line to irrigate the corners. Operation of the corner attachment is controlled by a signal sent through a buried electric cable. In addition, a lateral line on most pivots consists of several pipe sizes depending on system capacity. Pressure losses in the lateral pipe due to friction should not exceed 20% of nominal sprinkler operating pressure (Robert and Sneed, 1996). Safety controls on the pivot include proper wiring and grounding, especially of electric drive units, and micro-switches at each tower to keep towers properly aligned. The speed of the center pivot machine and the required depth of irrigation water can be controlled by the control box as illustrated in Figure 3.3.

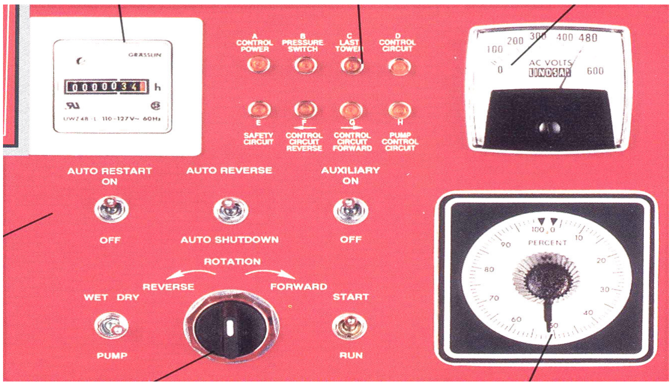


Figure 3.3: Center pivot control box for pivot speed and the required depth of irrigation water

3.1.2.2.2 Linear irrigation machines

In the linear irrigation machines, the sprinkler lateral is carried on towers like in center pivots. Each tower has a motor; the elements of the lateral form a critical angle, thus starting the motor when this angle is reached. All movements being co-ordinated, the trailer moves along a straight field edge or along a straight line crossing it, while the sprinkler lateral advances, staying at right angles to the trailer's direction, with the sprinklers in operation. The field for irrigation can be rectangular or simply square. The linear move machine can best be described as an adaptation of the center pivot. But instead of moving in a circle, the linear system moves in a straight line through the field, generally at right angles to the row direction. The hardware is very similar to the center pivot, but instead of a pivot point that is anchored while the machine rotates around it, there is a "boss" tower that moves with the rest of the machine.

The linear move machine is designed to be used on a rectangular field. It can supply water at any convenient place along the length of the lateral line. Of the machines currently on the market, some follow a canal and lift water directly from the canal. Others are supplied with water through a buried main line with hydrants using a 400 to 600 foot (about 122 – 183 m) section of high pressure, flexible, rubber coated, synthetic hose from mainline hydrants to the boss tower of the machine. The manner of water supply directly from a canal to the linear machine is shown in Figure 3.4.

Figure 3.4: Water supply directly from canal to the linear machine

A linear irrigation system which has been labeled a low energy precision application (LEPA) was presented by (Lyle and Brodovsky, 1981). This system distributes water directly to the furrow at a very low pressure through drop tubes and controlled emitters rather than by spraying it into the air at moderate to high pressures. LEPA can, to a certain degree, be considered as a type of traveling flood irrigation. Runoff is a concern for high capacity systems. The only measurable water loss occurring during LEPA testing was an evaporation loss from the ponded water in the micro-basins following irrigation. On the loam and clay loam soils, a free water surface remained for 30 min to 45 min following irrigation.

Generally, two main factors should be considered for a full economic analysis of a sprinkler system: a) returns from the crop yields which result from the particular water distribution uniformity achieved in the irrigated field; b) the costs of equipment, labor, water and energy resulting from the selected operating pressure head and sprinkler spacing (Benami and Ofen, 1984).

3.1.2.2.3 Side-roll laterals irrigation machines

A side-roll lateral or wheel-move machine has wheels mounted on lateral pipes with the pipe serving as the axle of the wheel as shown in Figure 3.5. Rigid couplers permit the entire lateral, which is up to 400 m long, to be rolled forward by applying power at the center or the end while the pipe remains in a nearly straight line. Most common sprinkler spacing is 12.2 m, the wheels are usually placed in the center of each length of pipe (Addink et al., 1980). In the case of the side-roll system, the sprinkler lateral can be set on wheels, using a pipe as a driving shaft. A motor installed in the middle of the lateral makes it rotate as a whole when it is time to move the lateral from one station to the next. The lateral moves at right angles to the pipe direction. This machine can also pull along a set of small sprinkler lines during its movement.

In side-move laterals with trail-line pipes, water is admitted from the side-roll pipe through double-gasket swivel couplers on the lateral. These couplers do not rotate when the wheel line is rolled forward. The trail lines are flexible enough to become essentially parallel to the ground and thus allow the sprinklers to be nearly vertical. When the wheel line reaches the end of the field, the trail lines must be moved to the other side, and the position of the sprinklers is shifted into an upright position. The side-roll is an example of intermittent mechanical move.

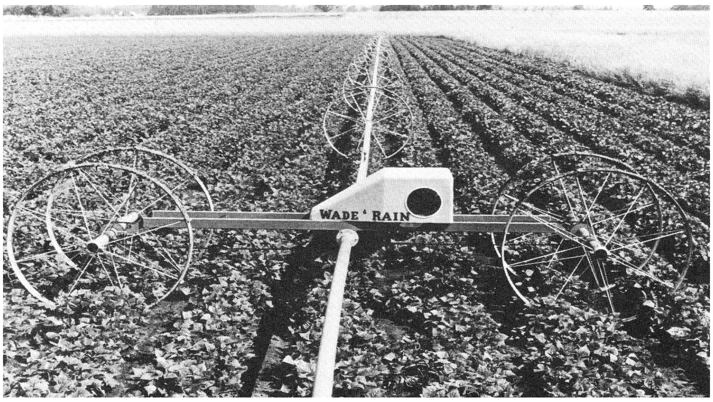


Figure 3.5: A side-roll lateral or wheel-move machine

3.1.2.3 Hose reel irrigation machines

A hose reel irrigator consists of a reel, a polyethylene hose, a driving mechanism, a sprinkler cart, a large sprinkler, an automatic drive shut-off and a chassis. The gun is supported by a trolley or a skid. The pipe feeding the gun is wound on a drum installed near the hydrant, the water is sent from the hydrant through the pipe and activates a hydraulic motor which makes the drum rotate, winding the pipe and pulling the irrigating gun as shown in Figure 3.6. The hose reel irrigator is a self-propelled irrigation machine which has a large reel with semi-rigid polyethylene tubing and a driving mechanism. The hose irrigator, which is part of the continuous mechanical move lateral, is available in several sizes between 100 m and 600 m of polyethylene hose with diameters ranging from 50 mm to 140 mm. The flow rate may range from 20 to 50 m^3/h. The reel also has to withstand the high torque required to pull the hose when filled with water (Sourell et al., 1999; and Azouggagh, 1994).

Generally, the hose is designed to withstand the operating pressure as well as the tensions developed as it is pulled, filled with water, across the field full of water. This system is adaptable to many field sizes and shapes with topography from level to rolling and irregular. An unattended traveller can irrigate a rectangular strip as long as 800 m. A traveller can also be moved at highway speed to irrigate several fields.

Figure 3.6: A hose reel irrigation machine

3.1.3 Localised irrigation systems

In the most recent decades of the long history of irrigation, new methods have been developed and have begun spreading quickly in many countries of the world. Trickle or drip irrigation is a relatively new method that has developed mainly during the last decade. Water is applied by means of mains, mainfolds and plastic laterals, usually laid on the ground surface. Evenly spaced along the laterals are drippers, from which water trickles onto the soil and into it to supply the water needs of plants. Tricklers or drippers are sometimes replaced by holes in the walls of the plastic tubings. Drip irrigation systems are generally of the solid-set type. Mainfolds and laterals are stationary, much the same as with sprinkler irrigation systems in which low flow-rate sprinklers are used to apply the water. Trickle irrigation allows frequent and slow application of water to limited areas around the plants. As water is applied only around the plants, water is saved since the evaporative surface is reduced. There are three types under this category: drip, sprayers, and micro-jet systems.

3.1.3.1 Stationary drip irrigation systems

Emitters are point sources of water operating at low inlet pressure and small discharge, for example 2, 4 and 8 L/h (Benami and Ofen, 1984). The water trickling onto the ground surface enters the soil profile and percolates downwards and outwards. The result is a limited cone-shaped volume of moist soil surrounding the plant root zone. The size and shape of the cone depend on the discharge of the emitter, the duration of application and the type of soil (Bresler, 1977), as shown in Figure 3.7. In stationary drip irrigation, the drip lines are placed on the soil surface. The distance between both the emitters and the drip lines are dependent on many factors, such as type of soil, type of crop, and the hydraulic characteristics of the emitters.

Initially, drip irrigation was claimed to provide many advantages as compared with conventional methods: application of water at slow rates, only small areas around the trees are wetted, water savings, weed growth is reduced, fertilizers can be injected into the irrigation water, and plant growth and yield are enhanced. Drip irrigation, like other irrigation methods, will not fit every agricultural crop, specific sites, or objectives (Howell et al., 1980). Several problems are associated with the drip method. Emitter clogging is considered the most serious problem in drip irrigation. The causes of clogging are attributed to physical, chemical and biological factors. When clogging occurs, emission uniformity is greatly reduced, and crop damage may occur before clogging is detected. Improvement in the filtration process and chemical treatment of the water can reduce clogging problems. For crops with high plant densities requiring large amounts of pipe per land unit, drip irrigation may not be economical.

Dan et al. (1976) reported that several types of drip irrigation have been found suitable for the cultivation of various crops, but the spacing of laterals and the selection of emitter discharge and location must be based on the consideration of a number of factors: crop characteristics, soil properties, water quality and agrotechnical practices. The suggested spacing between emitters is 60 – 75 cm for heavy soil, 50 cm for medium soil, 40 cm for light soil, and 30 cm for very light soil.

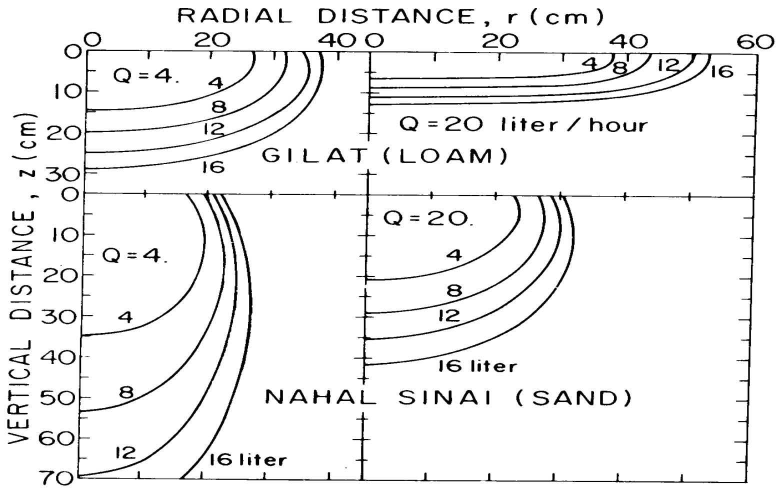


Figure 3.7: Effect of emitter discharge, duration of application and type of the soil on size and shape of the cone (after Bresler, 1977)

3.1.3.2 Sprayer and Micro-jet irrigation systems

Sprayers and micro-jet systems are used as watering units. Different designs of these systems have been devised. Pressure requirements are lower than for sprinklers, which need 2 to 4 bar (200 – 400 kPa), whereas these systems require 0.1 to 3 bar. In the case of sprayers and micro-jet systems, a spraying distance of about 3 to 8 m can be reached with pressure from 0.1 to 3 bar (FAO, 1982).

This system is often attached to the plastic laterals using small, flexible plastic tubes rather than metal risers. The tubes enable the sprayers to be placed at any desired position relative to the trees and can also be used to raise the sprayers to any desired height above the ground surface in order to protect the young trees against frost or severe heat. Sprayers wet the irrigated area only partially, thus allowing a saving in irrigation water. It is a quite common current practice to reduce applications by 10 – 20% when sprayers are used. This figure may be altered as additional experience is gained (Benami and Ofen, 1984).

3.1.3.3 Mobile drip irrigation systems

Many authors have described the mobile drip irrigation, but the classic dripping irrigation materials were never used. In some cases, holes in pipes, similar length of hoses with different types of emitters, similar length of hoses with one type of emitters were used with linear and center pivot machines. In these cases, the irrigation intensity was very high. At the same time, the classic drip irrigation materials with a center pivot were never used. Therefore, the application of mobile drip irrigation with center pivot machines will be important.

The use of drop tubes with a moving irrigation system appears to have been introduced first by Rawlins et al. (1979). They mentioned the use of micro-basins and noted that the crop response is similar to stationary drip installation with closely spaced emitters. One advantage they mentioned was that saline water will not damage the foliage if such a system is used. In trickle irrigation systems, no water is lost by wind drift and spray evaporation, as is the case in sprinkler systems, which depend on the soil to deliver water to the end of the field. Because of these factors, trickle irrigation can deliver water to crops at efficiencies above 80%, whereas surface irrigation usually operates at lower efficiencies between 60 and 75% and is thus potentially able to conserve water and energy (Phene et al., 1981). However, the labor requirements for the annual installation and retrieval of trickle tube laterals and the large capital investment prevent the general adoption of trickle irrigation for field row crops.

The travelling trickle irrigation system applies water continuously in a narrow band at several points as it travels across the field precisely at constant velocity. Discontinuous motion resulting from conventional mechanical guidance used in traveling sprinkler irrigation systems, which depends on mechanical tension to trigger electrical or hydraulic switching of individual tower drives, would cause excessive ponding of water in some areas and insufficient water supply in others. This is not critical in the case of traveling sprinkler irrigation systems because sprinkler heads cover a large enough soil area and provide sufficiently uniform water distribution for practical purposes. Sometimes, however, this practice creates mechanical and structural stress, which can result in structural failures and/or damage (Phene et al., 1981).

The mobile drip irrigation (MDI) means that the sprinklers of center pivot machines are replaced by drip tubes. Drop tubes are about 3 m long without emitters and connected to the drip tubes. The drop and drip tubes are dragged behind the center pivot machine. These tubes apply the water directly at ground level. The applied water is protected by the crop cover. Hence, evaporation and wind drift losses are reduced. Such reductions in water application losses enhance water use efficiency. A center pivot irrigation machine can be adapted to provide the mobility and the water supply for such a concept (Chu, 1983).

In this study, different available types of emitters were tested and evaluated in the laboratory to choose the better type. Then, the sprinklers of a center pivot machine will be replaced by the better type of emitter in the field. In addition, emitter tests, the choice of emitters and the calculation of the water requirements at all outlets of the pivot are very important in the design of a center pivot machine. After these laboratory experiments, the water quantities at all outlets will be calculated from different sources. Moreover, additional field experiments will be required to determine the distance between drop tubes, the length of drip tubes, soil water distribution and the friction forces of tubes at all outlets on a center pivot machine. At the same time, it is very important to analyse the costs of mobile drip irrigation in order to establish the difference between this irrigation system and both center pivot sprinkler systems and stationary drip irrigation.

3.2 Parameters of water distribution from different irrigation systems

To evaluate different irrigation systems, many parameters must be considered. In the case of stationary drip irrigation, the parameters are relatively different from the parameters in the case of a center pivot machine or mobile drip irrigation.

3.2.1 Evaluation parameters of stationary drip irrigation system

The use of dripping as a method of irrigating large fields has become quite common practice in agricultural production not only in Egypt but also in the world. Drip irrigation is being adapted to almost all types of crop production, to all types of land and to relatively saline water. Several problems are associated with the stationary drip method. Emitter clogging and high costs are considered the most serious problems in drip irrigation. Some parameters are employed to evaluate stationary drip irrigation, such as emission uniformity, pressure losses, water distribution, as well as the advantages and the disadvantages of this system.

3.2.1.1 Uniformity and the coefficient of variation

Environmental factors, such as temperature, may affect both pipe line life and the emitter discharge rate. The uniformity of soil water distribution is one of the most important factors of irrigation efficiency. Depending upon the type of emitter, variations in the discharge rate resulting from water temperature changes can cause non-uniformity of water application (Parchomchuk, 1976).

Nakayama and Bucks (1981) developed a simulation model to evaluate the uniformity and the average water discharge rate of a trickle system with different degrees of clogging. Various combinations of clogging were introduced into the model to determine how they affected average discharge rates and uniformity coefficients for single and multiple emitter placements per plant. They reported that uniformity was greatly reduced even when 1 to 5% of all emitters were clogged with 2 to 8 emitters per plant.

Bralts and Kesner (1983) presented a statistically based method for the field evaluation of drip irrigation submain units using the coefficient of variation and the statistical uniformity coefficient. They presented the nomograph to be used in estimating the field uniformity of a drip irrigation system.

3.2.1.2 Pressure losses

Howell and Barinas (1980) presented a method of estimating the pressure losses across emitters connected on-line and several types of polyvinyl-chloride and barbed polyethylene fittings. They concluded that the pressure losses across the on-line emitter were highly dependent on the emitter type and the flow rates. The one on-line emitter tested had significantly larger pressure losses at the small flow rates than the on-line emitters. The emitter pressure losses are significant when laterals with large numbers of emitters are used or when in-line emitters are used.

Madramootoo et al. (1988) evaluated the hydraulic performances of five different trickle irrigation emitters at operating pressures ranging from 69 to 138 kPa. They observed that the discharge curves were found to be within ± 10% of manufacturer's rated curves for all emitters tested. They also concluded that the choice must be based not only on the particular pressure compensating abilities of an emitter, but also on its flow rate sensitivity over the range of pressure expected within a field installation.

Al-Amoud (1995) studied the effect of on-line emitters on the energy losses in trickle irrigation laterals. He indicated that there are significant energy losses due to the emitter connections. The values of these losses are a function of the area of the emitter barb protrusion and the lateral pipe diameter. Higher energy losses result with smaller pipe diameters and larger protrusion areas of emitter barbs.

3.2.1.3 Water distribution

Drip irrigation systems do not apply water with perfect uniformity along the crop row. Some of the variability is caused by manufacturing imperfections in the emitters and by emitter clogging. Several manufacturers have designed emitters to reduce discharge variations caused by friction-induced pressure changes in the lateral pipe or tubing. Water flow from emitters in stationary drip irrigation systems varies from design discharge rates because of manufacturing imperfections, clogging, and pressure changes that occur in a pipe with spatially varied flow. Myers and Bucks (1972) concluded that improved manufacturing techniques, improved filters, and chemical treatment of the water can reduce the first two problems. Emitter discharge variation, caused by friction-induced pressure changes in the lateral pipe, can be reduced by high head loss emitters operated at high pressure.

Goldberg et al. (1971) studied the effect of stationary drip irrigation on the distribution of roots, water and minerals in a 3-dimensional soil profile. They mentioned that within the width of the bed, there was a reduction in moisture content in the upper-most layer and in the lowest layer. In both of these layers, the most marked decrease occurred in the region between the emitters. At other depths in the width and length of the bed, the moisture content was fairly uniform. Bralts and Kesner (1982) concluded that the calculation of coefficient of variation can be simplified for use in the field evaluation of the drip irrigation submain. The usefulness of this method resides in the fact that it will allow engineers, researchers, purchasers and irrigators to estimate the field uniformity of a drip irrigation system without the use of complicated statistical equations.

Little et al. (1993) compared different irrigation systems and mentioned that the average distribution achieved by stationary drip irrigation was 75%. They also concluded that the distribution uniformity and management of the irrigation system improved so that the correct amount of water is applied. This can lead to substantial savings in cost and the volume of water applied. Also they concluded that no correlation could be observed between the age of the system and the distribution efficiency values.

The emitter discharge rate is expressed as a flow rate, and the amount of irrigation water released from an emitter is the flow rate multiplied by irrigation time. Since the irrigation time is constant for all the emitters, the emitter discharge as well as the total amount of water discharged by emitters can be considered to have a normal distribution. Anyoji and Wu (1994) concluded that when the coefficient of variation of the emitter flow is designed to be less than 20%, it can be expected that irrigation application efficiency will be over 92%.

Battikhi and Abu-Hammad (1994) evaluated different irrigation systems and they concluded that the stationary drip irrigation systems provide high distribution and application efficiency, while distribution and field application efficiencies were 77% and 91%, respectively.

3.2.1.4 Advantages and disadvantages

Initially, drip irrigation was claimed to have many advantages over conventional methods: application of water at slow rates, only small areas around the trees are wetted, water savings, weed growth is reduced, fertilisers can be injected into the irrigation water, as well as enhanced plant growth and yield. Drip irrigation, like other irrigation methods, will not fit every agricultural crop, specific sites or objectives (Howell et al., 1980).

Rosegger et al. (1981) evaluated the water use and the total yield of sugar-beet, potatoes and corn under both sprinkler and stationary drip irrigation systems. They showed that by using stationary drip irrigation instead of sprinklers, about 30 – 35% of water can be saved without any significant effect on the crop yields.

Letey et al. (1990) reported that the pressurised irrigation systems provide better control over the amount of water applied and, in most cases, better irrigation uniformity than gravity flow systems. In addition, they require higher initial capital expenses than gravity flow systems, and an analysis is needed to determine whether the improved performance of pressurised systems justifies the additional costs.

3.2.2 Evaluation parameters of center pivot sprinkler machines

Pivots are available as low, medium and high pressure units. This refers to the sprinkler or spray nozzle operating pressure. The early pivots were high pressure units with typical sprinkler pressures of (482 – 620 kPa). Later, smaller rotary impact sprinklers were used and pressures were reduced to (250 – 413 kPa). Recently, low pressure spray nozzles have been introduced which can operate at pressures as low as (69 – 104 kPa). The major disadvantage of the low pressure spray nozzles is a very high instantaneous water application rate. The instantaneous application rate is the rate of water application (mm/h) to a finite area of land as the machine moves across that area. Most soils have an intake rate of less than 1.27 mm/h therefore, high application rates about (10 – 12 mm/h) often cause runoff on most soil types.

The center pivot sprinkler systems have many advantages (lower labor requirements, very high versatility, lower cost). Center pivot sprinkler systems have also proven to be very useful in applying light applications very quickly, which is beneficial in promoting seed germination and controlling wind erosion. It also has disadvantages (evaporation losses, higher energy requirement). Evaporation losses as high as 45% of the total water applied have been reported (Christiansen, 1942). This high loss of irrigation water is critical in areas with a limited water supply.

A large percentage of the energy used to operate a self-propelled center pivot sprinkler system is expended to maintain the high operating pressure which usually ranges from 414 kPa to 552 kPa (Ali and Barefoot, 1978). One reported reason for this high operating pressure is the provision of better water distribution on the field. If the operating pressure can be reduced without materially affecting the system's ability to distribute water uniformly, energy could be saved and the system's operating cost could be lowered.

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. Using the center pivot sprinkler systems in windy conditions cause some portions of the field to be very wet, while other portions are too dry. Those wet and dry areas result in lower coefficients of uniformity, but more importantly, they can cause a decrease in the yield. In the case of no wind, more uniform distribution was obtained with less area receiving either heavy or light application of water.

Thus, wind and runoff are two main problems of center pivot sprinkler systems not only with regard to water distribution, but also in view of the quality of horticultural crops in particular. Plants may be affected by chemigation processes. In the case of mobile drip irrigation, however, the chemicals can be applied easily and successfully.

3.2.2.1 Wind velocity and sprinkler irrigation systems

Clark and Finley (1975) determined the water losses from a system of 15 sprinklers irrigating an area of 0.167 ha. Their work revealed that wind velocity and vapour pressure deficits had the most influence on evaporation, while operating pressure had a minor influence. They stated that at high wind velocities, the wind was the dominant factor causing the water losses.

Lyle and Brodovsky (1982) compared the field performance of their low energy precision application (LEPA) irrigation system with impact sprinklers over a two-year period. They found that wind affected water distribution by a sprinkler system but had little effect on the LEPA. Average water distribution uniformities were 90% and 96% for the sprinkler and LEPA systems, respectively. However, these machines may cause problems. Since the discharge rate from drop tubes of LEPA systems is higher than the soil's intake rate, ponding in the furrow may occur. This creates potential for surface runoff and lower application uniformities (Hanson et al., 1988).

Steiner et al. (1983) analysed the efficiency of a center pivot sprinkler system under various climatic conditions. They concluded that average spray loss was about 15% under conditions characterized by higher evaporation and that losses were dependent upon the sprinkler design, the depth of application, and the environmental conditions at the time of pumping.

Kincaid et al. (1986) compared very low pressure spray heads with high pressure impact type sprinklers for use on center pivots. They measured spray losses in the field and reported that the main factors influencing spray losses were spray elevation and wind velocity. Seasonal losses up to 12% were found for the highest sprays, while losses for the 1 and 2 m elevation sprays were less than 5%.

Kohl et al. (1987) measured evaporation losses from a line source equipped with low pressure spray nozzle sprinklers under field conditions. The sprinklers were operated at 100 kPa and equipped with smooth and coarse serrated spray plates. They concluded that evaporation losses ranged from 0.5 to 1.4% in smooth spray plate sprinklers and from 0.4 to 0.6% in coarse serrated sprinklers. Richards and Weatherhead (1993) described the effect of wind on the application pattern in this phenomenon. First, the center of gravity of the wetted area moves under the wind drift. Second, the range depends on the angle between the emission direction of the droplets and wind direction in the horizontal plane.

3.2.2.2 Runoff and sprinkler irrigation systems

The resulting runoff and soil erosion may reduce irrigation water application depth and crop yield and thus adversely affect profitability. Kincaid et al. (1969) found runoff values as high as 22% under high pressure conditions on a silt loam soil due to the use of a center pivot sprinkler system. Application rates associated with reduced pressure systems are greater than high pressure rates because a given amount of water must be applied over a smaller wetted area. These higher application rates may cause problems with increased runoff, in particular on soils with lower infiltration rates and sloping topography.

Gilley and Mielke (1980) analysed the problems of reduced pressure sprinkler irrigation and reached the conclusion that reduced pressure will save energy, but could create management problems, such as increased surface runoff, soil erosion and non-uniformity of water application. They also indicated that lower irrigation efficiency caused by the application of reduced pressure may offset energy savings achieved by pressure reduction.

Von Bernuth and Gilley (1985) evaluated center pivot application packages and compared them based upon potential runoff and economic criteria. They concluded that the use of reduced operating pressure packages leads to decreased pumping power, but disadvantages such as reduced infiltration and increased application rates may result. In addition, spray type systems were most acceptable on sandy soils only if some surface storage was assumed. Since potential runoff exists and can be very high, the use of center pivots on finely textured soils should be analysed carefully.

Low-pressure center pivot systems with conventional high, medium and low pressure impact sprinklers produce runoff when operating on low-intake rate soils (Johnson et al., 1987). Buchleiter (1992) evaluated the performance of LEPA equipment on a center pivot machine at three different radii and three different slopes. He indicated that runoff amounts in excess of 30% of the application depth for a downslope of 3% and 55% of the application depth for an upslope of 8% illustrate the necessity of controlling runoff.

Ben-Hur et al. (1995) studied the effect of runoff on water distribution and peanut yield on a field irrigated with a lateral moving sprinkler irrigation system. They concluded that preventing runoff improved the distribution uniformity of available water in the field and increased average peanut yield.

3.2.2.3 Water distribution

Christiansen´s coefficient of uniformity is generally used as a basis for describing the uniformity of water distribution in sprinkler irrigation systems. The mean application rate of the seven combined patterns corresponding to each sprinkler spacing, which yielded uniformities of 80% or above, was computed by taking the mean of the application rates from the center array after the patterns had been meshed together (Ali and Barefoot, 1978).

Sprinkler distribution patterns play an important role in the effectiveness of water distribution by sprinkler irrigation systems. Water application uniformity over a field, which is one of the most important factors in the operation of a sprinkler irrigation system, can be determined by superimposing the individual distribution patterns in the system. A sprinkler distribution pattern depends on many factors, such as sprinkler type, nozzle size, angle, operating pressure and nozzle modification. In field conditions, it also depends on temperature, humidity and wind (Seginer et al., 1991).

Duke et al. (1992) provided an analysis of the economic benefit to be realized by improving the uniformity of irrigation based on the individual irrigator’s economic scenario. It is apparent that the irrigator may be able to significantly improve management strategies by simply scheduling irrigation based on an optimum irrigation depth that minimizes the combined losses from over-irrigation and deficit irrigation. They concluded that the improvement of uniformity is one of the most important management decisions the operator can make.

Ben-Hur et al. (1995) determined the amount of runoff and its effect on water distribution and peanut yield in a field irrigated with a moving sprinkler irrigation system. They concluded that the Christiansen uniformity coefficient values of water application achieved by the moving sprinkler irrigation system were 92% and 89% when the catch cans were placed in lines across the field at 1 m intervals parallel to the irrigation system and at 2 m intervals perpendicular to the irrigation system, respectively.

The spacing of the spray sprinklers is a key decision in the design of center pivot and linear move sprinkler machines. Faci et al. (2001) compared two types of spray sprinklers. The first was a rotating spray plate sprinkler and the second was a fixed spray plate sprinkler. They concluded that the fixed spray plate sprinkler resulted in a more uniform drop size than the rotating spray plate sprinkler. In addition, the average drop diameter was generally smaller in the fixed spray plate sprinkler than in the rotating spray plate sprinkler.

3.2.2.4 Advantages and disadvantages

Center pivot sprinkler machines have many advantages, such as high water application uniformity, suitability for almost all crops, ease of soil cultivation and low total costs. At the same time, they have many disadvantages, such as high energy requirements, water losses and wind drift. Losses due to evaporation and wind drift are affected by many factors which may change constantly during the growing season. These factors were discussed in previous parts. On the other hand, center pivot machines are not recommended for the irrigation of heavy soils with low intake rates (Benami and Ofen, 1984). On some of the light and shallow soils previously considered unsuitable for irrigation, the center pivot method has proved highly successful in the cultivation of crops such as vegetables, potatoes, corn, sugar beet and wheat. This is largely attributed to the light, frequent applications, which continuously provide favourable soil moisture conditions for the plants.

Shalhevet et al. (1983) determined the water production function for the crop and crop-water relations in the case of potatoes under sprinkler and drip irrigation. They estimated the evaporation component and they concluded that about 13% of total evapotranspiration (ET) under sprinkler irrigation was lost in evaporation, and only 4% under drip irrigation. In terms of marketable yield, they also concluded that average potato size was slightly larger under drip than under sprinkler irrigation. At the same time market quality was larger under sprinkler irrigation than under drip irrigation.

Thompson et al. (1993) applied the combined model under field conditions for a solid-set sprinkler irrigation system with respect to water efficiencies during the irrigation of a crop. They concluded that irrigation water temperature is significant in determining evaporation losses of droplets during flight. Wind velocity has a marginal effect on inflight droplet evaporation. However, it has a significant effect on droplet flight distance, and droplet evaporation losses for a given droplet size are approximately proportional to nozzle height.

3.2.3 Evaluation parameters of mobile drip irrigation systems

Phene et al. (1981) studied the performance of a travelling trickle irrigation system (TTIS). This was tested in combination with linear move machines. They showed that the yield of tomatoes produced with (TTIS) at 105% of potential evapotranspiration measured with a screened evaporation pan was nearly double that of furrow irrigated tomatoes but required approximately 40% less water.

Chu (1983) presented the design procedure of a trail tube irrigation system including the selection of tube length, tube flow rate, tube size, hole size and hole spacing. He proposed two adjustments so that the theoretical result can be applied easily in practice. The first adjustment is the application of some of the calculated results for the longest tube to the design of a shorter tube. The second adjustment is the division of the tube into several sections and the use of average hole spacing in order to replace the variable hole spacing in each section. Sourell and Schön (1983) studied and developed a continuously moving drip irrigation system designed in particular for small and medium-sized farms.

Under drip irrigation systems, the geometry of the wetted soil volume takes a spherical or ellipsoidal shape when water is applied from a point source or a cylindrical shape when water is applied from a line source. Depth-width-discharge combinations which can yield the estimated wetted soil volume are computed using an equation proposed by Schwartzman and Zur (1986). Soil water content distribution within the wetted volume is not uniform. It decreases with the radial distance from the water source. Thus, the geometry of wetted soil under a point source is representative of most practical situations in drip irrigation design. Such behaviour is in sharp contrast to the geometry and dynamics of the wetted soil volume under sprinkler irrigation where the total soil surface area is wetted and vertical soil water content distribution is essentially constant. Under sprinkler irrigation, the wetted soil volume is well represented by wetted soil depth.

Helweg (1988 and 1989) modified the traveling trickler system for use on a center pivot machine. He suggested that the traveling trickler system can save 40% of the water and one-fourth of the operating pressure when compared to the traditional center pivot. Amir and Dag (1993) published field data on the width and depth dimensions of wetted soil volumes under moving emitters and reported that wetting patterns under moving emitters were in good agreement with those for stationary emitters. In lightly textured soils, an increase in the depth of applied water would lead to a particularly significant decrease in the width-to-depth ratio. In addition, an increase in emitter discharge would increase the width-to-depth ratio with a more pronounced effect in medium-to-heavily textured soils (Zur, 1996).

3.3 Comparison and evaluation of irrigation systems

Goldberg and Shmueli (1970) studied the performance of three irrigation systems. These systems were sprinkler, furrow and drip irrigators. They reported that drip irrigation is a significant improvement over furrow irrigation (a) It is furrow irrigation with no water flowing in the furrows. This is significant because there is no need for accurate levelling, which is complicated and expensive in practice. Furthermore, no erosion due to flowing water occurs; (b) Water distribution is uniform and accurate. The problem of uneven water distribution along the furrow is a common one, especially in more coarsely textured soils. The drip irrigation method guarantees that each nozzle discharges exactly the same amount of water. Thus, water is saved, and uniform application is guaranteed. (c) In drip irrigation, there is no surplus water at the end of the furrow, which in furrow irrigation continues to increase as the soil's infiltration rate decreases.

Bernstein and Francois (1973) compared three irrigation systems. These systems were sprinkler, furrow and drip irrigators. They reported that when the same amount of low salinity water (450 mg/l total salts) was applied using three methods of irrigation, the drip irrigated plots provided approximately 50% higher yields than the furrow and sprinkler- irrigated ones. With stationary drip irrigation, salts accumulated in the surface soil midway between the drip orifices and at the perimeter of the wetted zone. For mature crops, the water requirements of the three irrigation methods are similar and the amount of water saved through drip irrigation would largely depend on the inefficiency of the method it replaces.

Battikhi and Abu-Hammad (1994) studied the performance of three different irrigation systems. These systems were surface, sprinkler and drip irrigators. They found that field application efficiency was 82% and 64% for surface irrigation on citrus and vegetables, respectively, whereas it was 88% for citrus under sprinkler and 91% for vegetables under drip irrigation.

Sourell (2000) compared the common irrigation methods and proposed further technical developments in order to achieve an increase in the water and energy efficiency of mobile and semi-mobile irrigation machines. The proposed concept of mobile drip irrigation is applicable to both boom trailer and center pivot or linear move machines. He reported about a 17% reduction in water application and 50% less pressure when he compared the mobile drip on a boom trailer with the mobile machine with a gun sprinkler.

The mobile drip irrigation system which is specifically designed for grain crops promises to be more efficient than any center pivot modifications yet proposed. The mobile drip irrigation system features a manifold connection to the existing center pivot and a connection between small drop tubes and drip tubes with emitters. In center pivot machines, these tubes would be dragged diagonally over the irrigated crops. The ends of the drip tubes are folded back and the amount of water applied directly to the soil.

4 THE DEVELOPMENT OF THE MOBILE DRIP IRRIGATION SYSTEM (MDI)

The idea of mobile drip irrigation is to connect both the advantages of stationary drip irrigation and center pivot sprinkler machines. The sprinklers on a center pivot machine will be replaced by the emitters and drip tubes as illustrated in Figure 4.1 to avoid water losses caused by the wind. The right way to operate mobile drip irrigation is to choose the best type of emitter, the accurate calculation of the water demand, and the amount of water applied at all outlets on the center pivot machine, and proper installation. Laboratory experiments, field experiments and an analysis of the total costs are needed to evaluate this new system. The basic concept of a mobile drip irrigation is shown in Figure 4.2.

4.1 The laboratory experiments

In the development of new water distribution systems, water distribution measurements are very important. When using drip irrigation systems, we must know how the water is distributed and how much water can be obtained from the emitters at different operating pressures. The emitter discharge is dependent on water temperature, the manufacturer's characteristics and the operating pressure. Emitter discharge, the coefficient of variation and water distribution uniformity at different pressures are very important parameters because the design of mobile drip irrigation with a center pivot machine depends on both emitter discharge and the distance between the emitters.

4.1.1 Materials and Methods

Five different types of commercial In/On-line emitters were tested in the laboratory to choose the better type. These emitters are shown in Figure 4.3. They are were available on the market and its manufacturer's characteristics are presented in Table 4.1. In the laboratory, all tests were performed at six operating pressures ranging from 25 kPa to 225 kPa (0.25 to 2.25 bar). To compare different types of emitters, the standard water temperature must be 23 °C ± 1 (International Standard, 1991). The water temperature was adjusted at 22 °C, and measured using a mercury thermometer with an accuracy of 1 °C. The water in the line was heated first by using an electrical heater.

In these experiments, the operating pressures were 25, 50, 100, 150, 200 and 225 kPa. They were measured with the aid of a manometer with an accuracy of 5 kPa. The total length of the drip line was 6 m and the distance between emitters was 15 – 20 cm. The drip line was a polyethylene pipe (PE) with an outer diameter of 16 mm. For each pressure, a new sample of emitters was tested. Two-litre measuring cylinders with 20 ml divisions were used to collect the water from the emitters as shown in Figure 4.4. The measurements were repeated three times with one repetition lasting10 min. When the chosen pressure was reached, pressure in the drip line was controlled using a pressure regulator. Emitter discharge was measured over a range of six pressures to determine the manufacturing variation of 30 emitters of each type. The discharge of the emitters was measured volumetrically and a stopwatch was used to measure the flow times. The water volumes were collected in the graduated cylinders and manually read and recorded.

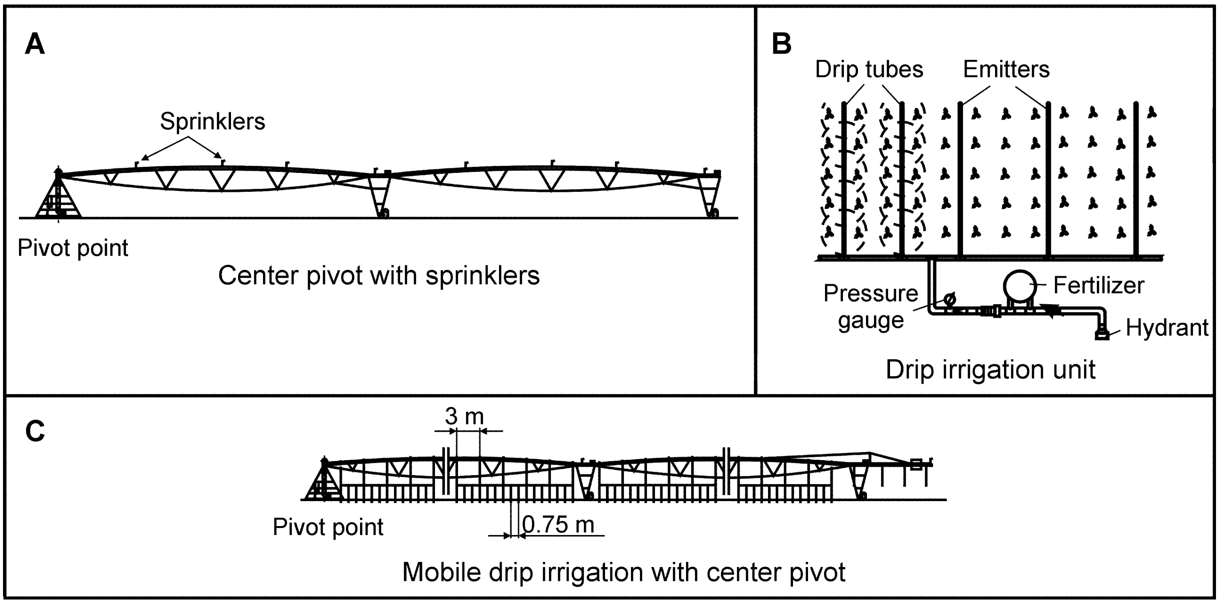


Figure 4.1: Replacement of centre pivot sprinklers by drip tubes

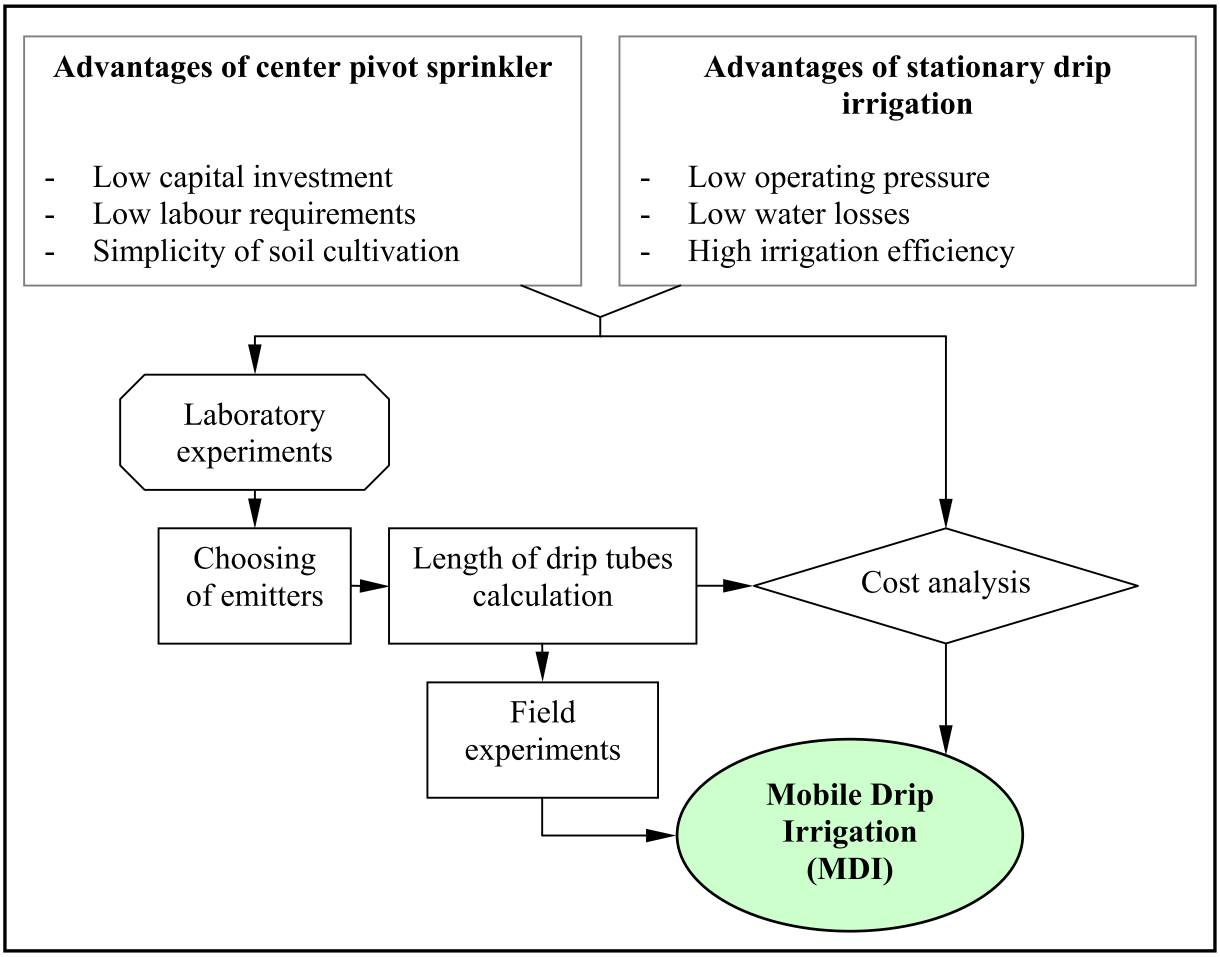


Figure 4.2: The basic design of a mobile drip irrigation system

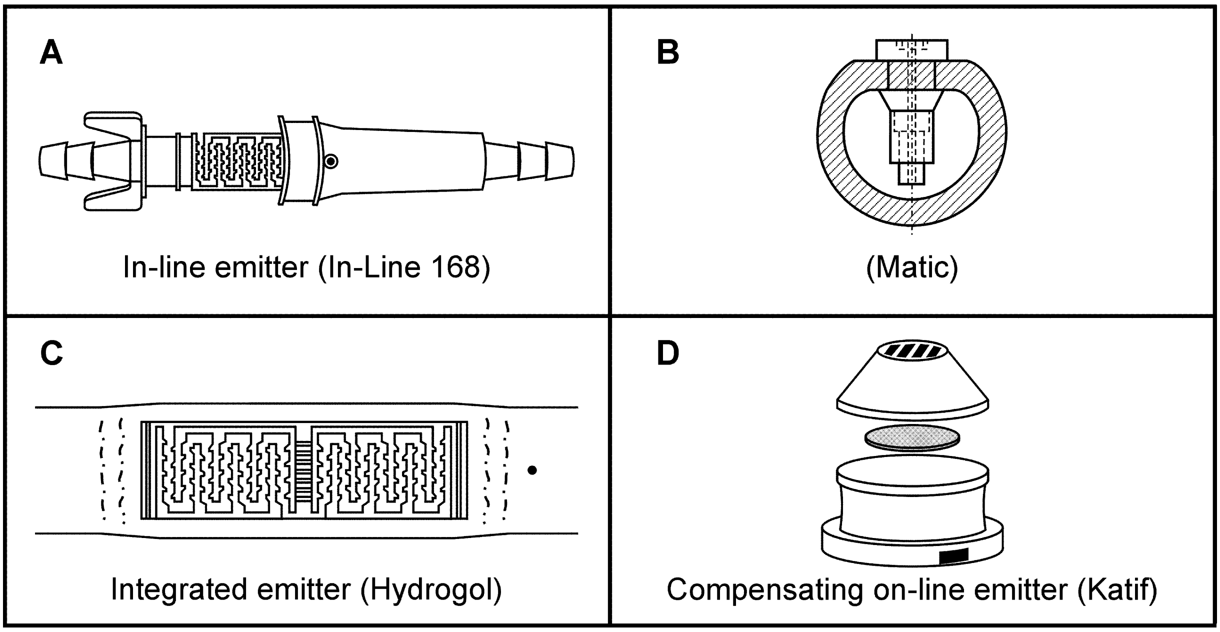


Figure 4.3: Five different types of commercial In/On-line emitters

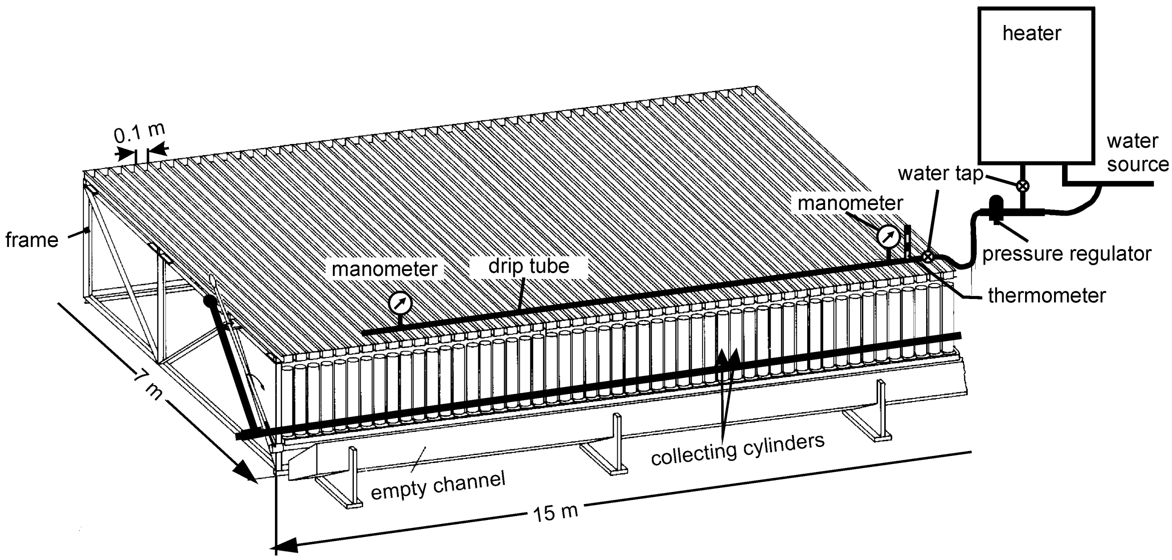


Figure 4.4: Measurement of the emitter discharge rate in the laboratory

Table 4.1: The general manufacturers characteristics of all tested emitters

Emitters	**Nominal discharge, L/h at 100 kPa**	Company	Type		**Manufacturers (CV) at 100 kPa**
Matic	**4.00**	Aqua-pro	PC*	On-line	**13%**
Katif	**3.75**	Plastro	PC*	On-line	**5 – 10%**
Katif	**8.40**	Plastro	PC*	On-line	**5 – 10%**
In-line168	**8.30**	Netafim	NPC+	In-line	**10%**
Hydrogol	**9.50**	Plastro	NPC+	In-line	**5 – 10%**

PC* = pressure compensating
NPC+ = non-pressure compensating

There are some very important parameters to evaluate the performance of emitters. These parameters are emitter discharge (q), the emitter discharge exponent (x), the coefficient of variation of the discharge (CV), emission uniformity (EU) and emitter flow variation ($q_{var.}$).

4.1.1.1 Emitter discharge and emitter discharge exponent

In the design of drip irrigation systems the relationship between emitter discharge and operating pressure is calculated based on the emitter flow function given by Keller and Karmeli (1974) and Howell et al. (1980) as follows:

$$q = k_e H^x \tag{4.1}$$

where:

q = emitter discharge, in L/h,

k_e = emitter discharge coefficient that characterize the emitter dimensions,

H = operating pressure at the emitter, in kPa, and

x = emitter discharge exponent which is a characteristic of the emitter flow regime.

4.1.1.2 Coefficient of discharge variation and emission uniformity

The coefficient of variation is a parameter related to uniformity and it is a composite statistical measure. It is calculated by dividing the standard deviation by the mean. The coefficient of variation of the discharge of all different types of emitters was calculated as follows:

$$CV = (S_q / q_{av.}) \times 100 \quad (4.2)$$

where:
CV = discharge coefficient of variation, in %,
S_q = standard deviation of discharge rates of the emitters in the sample, in L/h, and
$q_{av.}$ = mean of emitter discharge rate, in L/h.

The standard deviation values were calculated in the same manner using the following equation given by Wagenführ (1974) :

$$S_q = \frac{\sum_{i=1}^{N} | x_i - x` |}{N} \quad (4.3)$$

where:
S_q = standard deviation of discharge, in L/h,
N = sum of samples,
x_i = measured discharge value, in L/h, and
x` = mean of discharge, in L/h.

Bralts et al. (1981) recommended the use of the statistical uniformity coefficient (U_s) for the determination of the design uniformity of the drip irrigation lateral line including manufacturing variation. Bralts and Kesner (1982) reported that the use of the statistical uniformity coefficient is quick and accurate. The statistical uniformity coefficient can be expressed using the following equation:

$$U_s = (1 - CV) \times 100 \quad (4.4)$$

where:
CV = the coefficient of variation.

The range values of the coefficient of discharge variation are usually supplied by the manufacturer as illustrated in Table 4.1. It could also be obtained by taking a random sample of emitters and obtaining the discharge rates at the same temperature and pressure. The coefficient of variation is one of the significant parameters which influence the overall uniformity and efficiency of the system. Classifications of the coefficient of discharge variation values according to ISO standards are given in the International Standard (1991) as indicated in Table 4.2.

Table 4.2: Classifications of coefficient of variation values according to ISO standards

Category	Coefficient of discharge variation (CV)	Classification
A	**0 to ± 5%**	Good
B	**± 5% to ± 10%**	Medium
C	**> 10%**	Poor

Category (A) emitters feature a higher uniformity of emission rate and smaller deviations from the specified nominal emission rate. Category (B) emitters have a medium uniformity of emission rate and medium deviations from the specified nominal emission rate. Category (C) emitters feature a lower uniformity of emission rate and greater deviations from the specified nominal emission rate.

Keller and Karmeli (1974) have suggested two parameters to define the uniformity of application of a trickle irrigation system. Their emission uniformity involves the relationship between minimum and average emitter discharge rates within the system. They noted that this relationship is the most important factor for the uniformity of application, since a primary objective of irrigation system design is to ensure enough system capacity to adequately irrigate the least watered area. They recommended that EU values of 94% or more are desirable, and in no case should the designed EU be below 90%. The values of emission uniformity were tabulated for various emitters and system configurations on level ground. It was pointed out that in many cases the results can be applied to sloping terrain as well (Solomon and Keller, 1978). Emission uniformity was calculated by Keller and Karmeli (1974) as follows:

$$EU = (q_n / q_a) \times 100 \qquad (4.5)$$

where:

EU = the emission uniformity of emitters, in %,

q_n = average discharge from emitters in the lowest 25% of the discharge range, in L/h, and

q_a = average discharge of all emitters, in L/h.

4.1.1.3 Emitter flow variation

Emitter flow variation can be shown by comparing maximum and minimum emitter flows and was expressed by Wu and Gitlin (1983) as follows:

$$q_{var.} = (q_{max.} - q_{mini.}) / q_{max.} \times 100 \qquad (4.6)$$

where:

$q_{var.}$ = emitter flow variation, in %,

$q_{max.}$ = maximum emitter discharge, in L/h, and

$q_{mini.}$ = minimum emitter discharge, in L/h.

4.1.2 Results and Discussion

The experiments were conducted to investigate the performance of different emitters at different operating pressures. The tested emitters were categorized as non-pressure compensating (NPC) and as pressure compensating (PC). In addition, they were categorized as In/On-line emitters. From this stage, different performance parameters were calculated to illustrate the relationship between the operating pressure and discharge rate, the emitter discharge exponent, the coefficient of variation, flow variation and emission uniformity.

4.1.2.1 Emitter discharge and emitter discharge exponent

The pressure-discharge relationships of emitters are expressed by equation 4.1. In the case of the In-line 168 type, the emitter discharge was very uniformly distributed for all emitters at all operating pressures as shown in Figure 4.5. At the same time, the discharge increased linearly as the operating pressure grew because this type of emitters is an NPC. The discharge was about 4 L/h and 12 L/h at 25 kPa and 225 kPa, respectively for this type. In the case of the Hydrogol type, the emitter discharge was uniformly distributed in all emitters at all operating pressures as shown in Figure 4.6. The discharge grew linearly when the operating pressure increased because this type is an NPC. This means that the emitter discharge was strongly influenced by the operating pressure. The discharge was about 4 L/h and 16 L/h at 25 kPa and 225 kPa, respectively for this type.

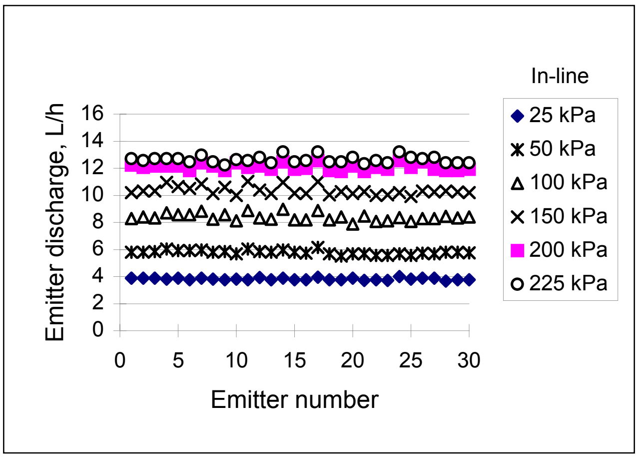


Figure 4.5: Emitter discharge rate at different operating pressures for an In-line 168 type

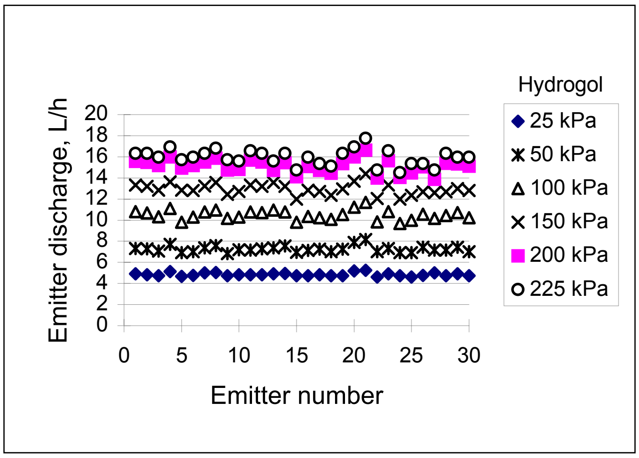


Figure 4.6: Emitter discharge rate at different operating pressures for a Hydrogol type

In the case of the Matic type, the emitter discharge was not uniformly distributed for all emitters at all operating pressures as shown in Figure 4.7. The discharge was about 2 L/h and 5 L/h at 25 kPa and 225 kPa, respectively for this type. In the case of Katif, 4 L/h, the emitter discharge was uniformly distributed for all emitters at all operating pressures except for 25 kPa as shown in Figure 4.8. At the same time, the discharge was relatively the same at all operating pressures because the type of emitters used was a PC. The discharge was about 2 L/h and 5 L/h at 25 kPa and 225 kPa, respectively for this type. In the case of Katif, 8 L/h, the emitter discharge was uniformly distributed for all emitters at all operating pressures as shown in Figure 4.9. The discharge was about 8 L/h and 10 L/h at 25 kPa and 225 kPa, respectively for this type.

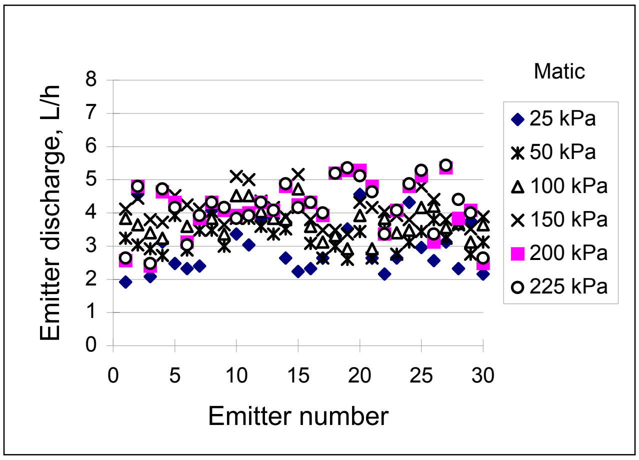


Figure 4.7: Emitter discharge rate at different operating pressures for a Matic type

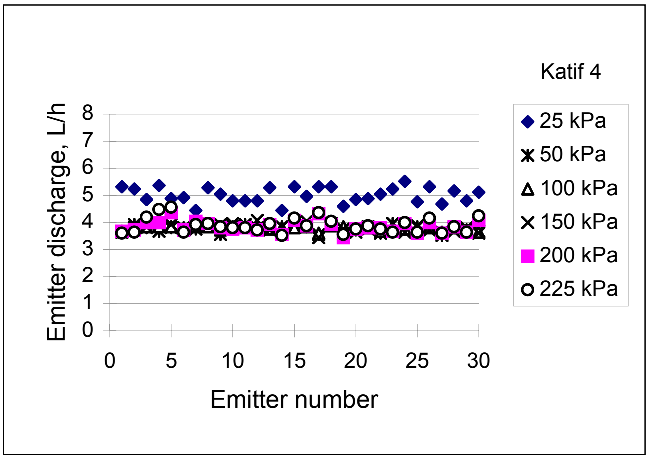


Figure 4.8: Emitter discharge rate at different operating pressures for a Katif (4L/h) type

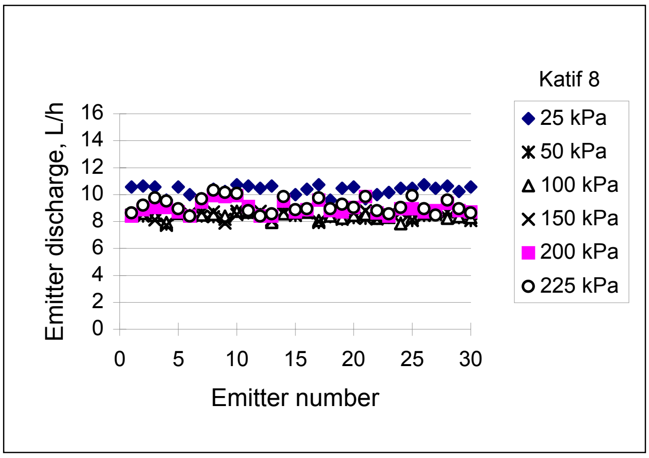


Figure 4.9: Emitter discharge rate at different operating pressures for a Katif (8L/h) type

The means of the measured discharge rates for all tested emitters at different operating pressures are illustrated in Figure 4.10. The emitter discharge rate was increased linearly with operating pressure by using the In-line 168 and Hydrogol types. However, it was relatively constant when the Matic and Katif 4 L/h and Katif 8 L/h types were used except for 25 kPa in both cases of Katif, whereas the higher value of discharge was at 25 kPa when Katif 4 L/h and 8 L/h was employed, because the operational principles of this type are different from the operational principles of the other systems. The operational principles of this type are shown in Figure 4.11. All laboratory measurements and data are indicated in the Appendix (A).

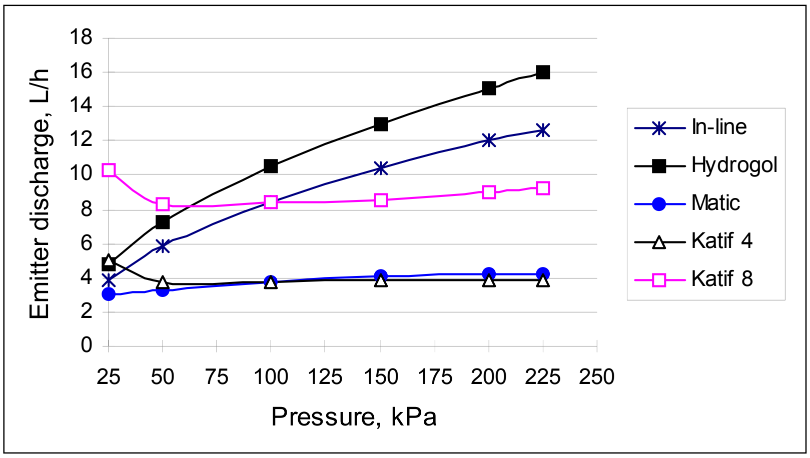


Figure 4.10: Means of measured discharge rates for all tested emitters at different pressures

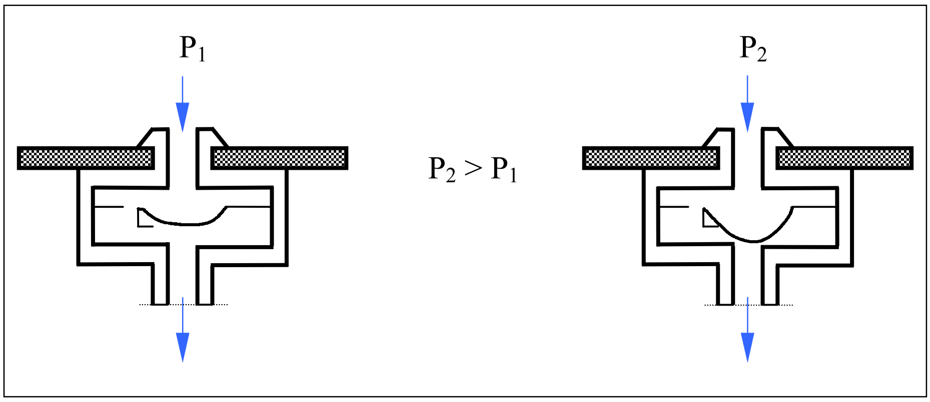


Figure 4.11: Operational principles of Katif emitters

The data from the laboratory experiments were analysed with an SAS program. The statistical analysis indicated that the effect of operating pressure on the emitter discharge in the case of both In-line 168 and Hydrogol was highly significant (NPC). However, it was not significant in the case of Matic, Katif 4 L/h and Katif 8 L/h (PC).

The emitter discharge exponent " x " is a very important factor for hydraulic emitter performance. The hydraulic characteristics of all tested emitters were calculated using regression analysis. These values are presented in Table 4.3, whereas the operating pressure was in kPa. In the case of the In-line 168 and Hydrogol types, the emitter exponent values were higher than 0.5. When the emitter exponent values are higher than 0.5, the flow type is turbulent. Therefore, these emitters are classified as NPC. The emitter exponent values in the case of Matic, Katif 4 L/h and Katif 8 L/h were very small. However, the pressure compensating mechanism of these emitters appears to function better at high pressures. The statistical coefficient of determination " r^2 " is also reported for each emitter type. If r^2 values are very close to 1, equation 4.1 is an appropriate model for the description of the relationship between the discharge and the pressure of these emitters. Low values of r^2 either indicate considerable data scattering or that the model used was not appropriate.

Table 4.3: The hydraulic characteristics of tested emitters

Emitters	k_e	x	r^2
In-line 168	0.675	**0.544**	0.999
Hydrogol	0.860	**0.541**	0.999
Matic	1.800	**0.158**	0.981
Katif 4 L/h	6.102	**-0.092**	0.512
Katif 8 L/h	10.674	**-0.039**	0.169

4.1.2.2 Coefficient of discharge variation and emission uniformity

The coefficient of discharge variation of emitters in the sample falling within a given deviation from the mean discharge was calculated using equation 4.2. The results indicated that the coefficient of discharge variation values for In-line 168, Hydrogol, Katif 4 L/h and Katif 8 L/h were followed by a normal distribution at each operating pressure. However, in the case of Matic type, the coefficient of discharge variation was relatively high. The emitter performance was classified on the basis of the coefficient of variation as outlined in Table 4.2 according to ISO, International Standard (1991). Emission uniformity was calculated using equation 4.5.

The relationship between operating pressure and both emission uniformity discharge and the coefficient of variation for In-line 168 and Hydrogol types are illustrated in Figure 4.12. In the case of In-line 168, the emission uniformity values were higher than 95% at all operating pressures. At the same time, the coefficient of variation values were less than 4% at all operating pressures. In the case of Hydrogol, the emission uniformity values were also higher than 95% at all operating pressures. On the other hand, the coefficient of variation values were lower than 5% at all operating pressures. However, in the case of Matic, the mean value of emission uniformity was about 80%. At the same time, the average coefficient of variation was about 17% as shown in Figure 4.13. When the Katif 4 L/h and Katif 8 L/h types were used, the emission uniformity values were higher than 90% at all operating pressures. At the same time, the coefficient of variation values were lower than 8% at all operating pressures as shown in Figure 4.14. The fluctuation of the coefficient of variation with pressure may be used to define emitter discharge sensitivity to pressure. The manufacturers coefficient of variation should be 15% or less to achieve reasonable uniformity of water application (Solomon, 1977). The results showed that an increasing value of the coefficient of discharge variation CV leads to decreasing emission uniformity EU for all tested emitters.

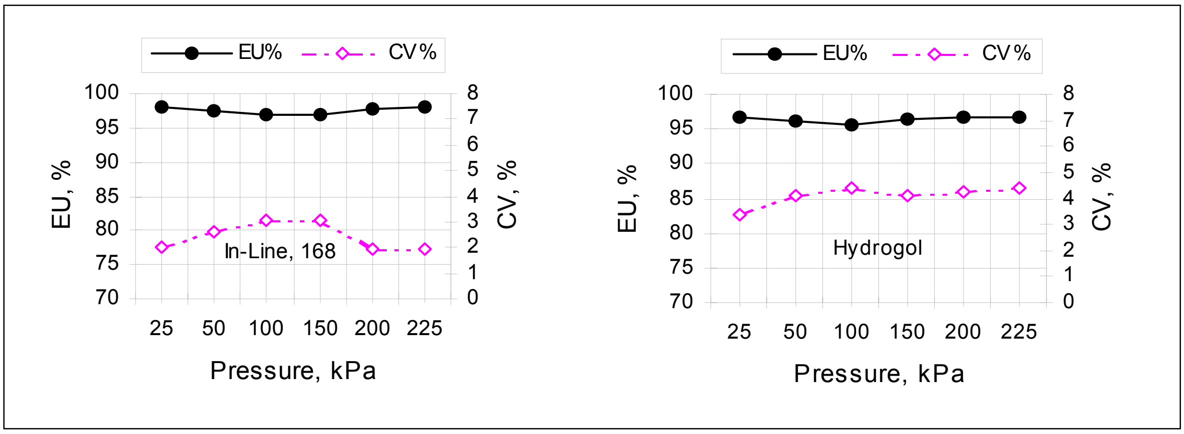


Figure 4.12: Relationship between the operating pressure and both the coefficient of variation and emission uniformity for the In-line 168 and Hydrogol types

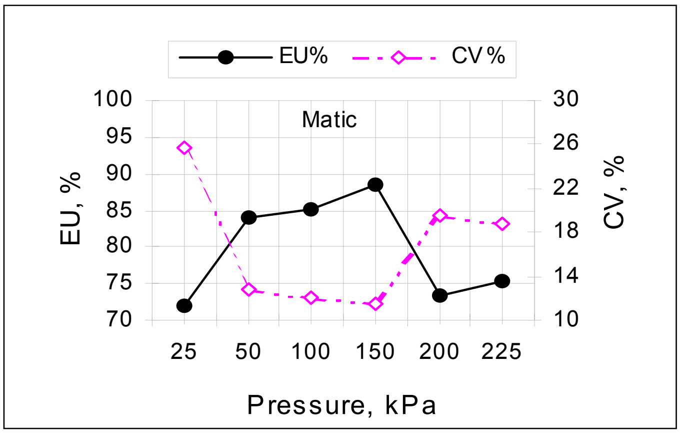


Figure 4.13: Relationship between the operating pressure and both the coefficient of variation and emission uniformity for the Matic type

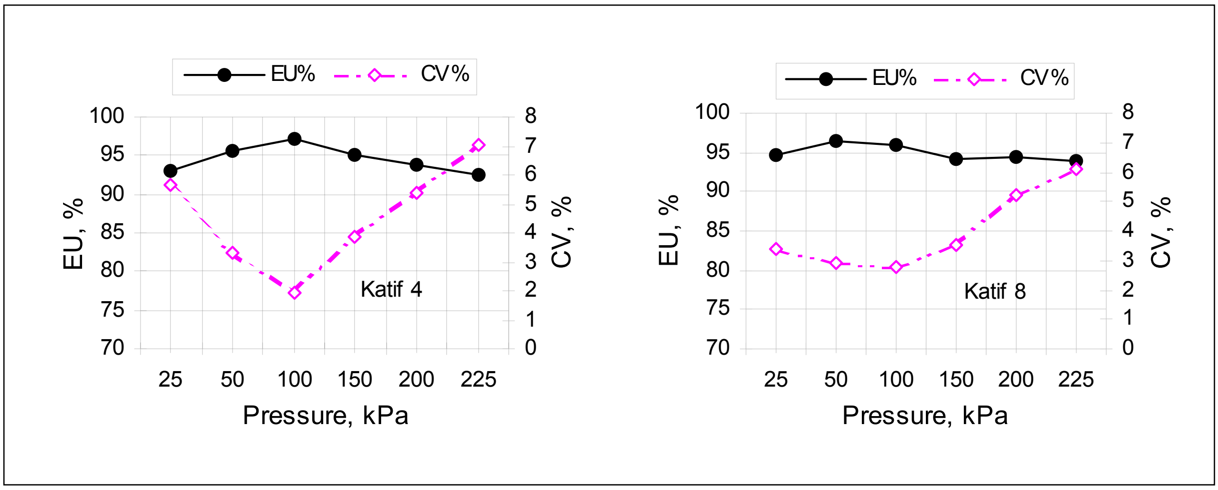


Figure 4.14: Relationship between the operating pressure and both the coefficient of variation and emission uniformity for the Katif types

4.1.2.3 Emitter flow variation

The emitter flow variations indicate the relationship between the maximum and minimum flow variation in percent of the maximum flow value. Emitter flow variation was calculated using equation 4.5. The mean values of flow variation for the In-line 168 and Hydrogol types (In-line emitters) were about 9% and 14% respectively at operating pressures ranging from 25 kPa to 225 kPa. However, in the case of Matic, Katif 4 L/h, and Katif 8 L/h (On-line emitters), the mean values of flow variation were about 46%, 16% and 13%, respectively at operating pressures ranging from 25 kPa to 225 kPa. These results are presented in Figure 4.15. Table 4.4 also illustrates some performance parameters which are used to evaluate all tested emitters under laboratory conditions.

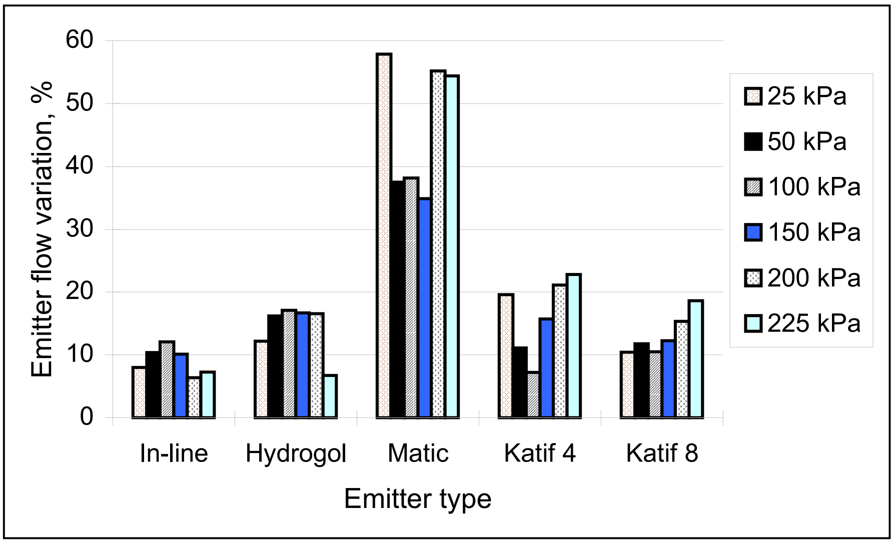


Figure 4.15: The relationship between different operating pressures and emitter flow variation for the tested emitters

Table 4.4: Performance parameters of all emitters tested under laboratory conditions

Performance parameters	Tested emitters	Operating pressures, kPa						Note
		25	50	100	150	200	225	
Discharge (q, L/h)	In-line 168	3.82	5.79	8.39	10.35	12.09	12.64	***
	Hydrogol	4.85	7.25	10.49	12.94	15.13	16.00	***
	Matic	3.03	3.26	3.71	4.09	4.15	4.18	*
	Katif, 4 L/h	5.01	3.78	3.78	3.81	3.85	3.89	**
	Katif, 8 L/h	10.33	8.33	8.41	8.51	9.00	9.20	**
Coefficient of variation (CV, %)	In-line 168	2.03	2.64	3.14	3.13	1.99	2.02	*
	Hydrogol	3.43	4.19	4.44	4.20	4.32	4.45	*
	Matic	26.09	13.08	12.30	11.72	19.80	19.19	***
	Katif, 4 L/h	3.48	2.97	2.80	3.56	5.28	6.20	**
	Katif, 8 L/h	5.76	3.39	1.96	3.94	5.46	7.14	**
Emission uniformity (EU, %)	In-line 168	97.97	96.96	96.63	97.00	97.79	97.89	***
	Hydrogol	96.64	95.68	94.61	94.91	94.33	96.82	***
	Matic	71.94	83.72	85.16	87.17	73.26	75.33	*
	Katif, 4 L/h	94.78	96.18	96.16	94.49	94.40	92.87	***
	Katif, 8 L/h	92.92	95.24	97.14	95.02	93.76	82.53	***
Emitter discharge flow variation ($q_{var.}$, %)	In-line 168	8.00	10.39	12.05	10.15	6.37	7.27	*
	Hydrogol	12.21	16.18	17.12	16.67	16.59	16.89	*
	Matic	57.89	37.50	38.14	34.88	55.22	54.41	***
	Katif, 4 L/h	10.45	11.76	10.50	12.27	15.32	18.60	**
	Katif, 8 L/h	19.57	11.11	7.22	15.69	21.10	22.81	**

* = Fair
** = Medium
*** = High

4.1.3 Conclusions from the laboratory experiments

The mobile drip irrigation in the field requires emitters which provide high emission uniformity, the lowest coefficient of variation, the lowest distance between the emitters and ease of installation, as well as high discharge in order to reduce both the length of drip tubes and the number of emitters. High emission uniformity and the lowest coefficient of variation to enhance water distribution on the soil surface.

Based on the laboratory experiments and previous tables and figures, the In/On-line emitters were evaluated. In-line 168 has many advantages, but it was difficult to install and distance between emitters was 0.25 m. In addition, the Matic´s coefficient of variation was higher than 12% at 100 kPa. It was also relatively difficult to install and distance between emitters was 0.20 m, but this distance can be changed to less than 0.10 m. The Katif types have many additional advantages, such as high emission uniformity and a low coefficient of variation. Nevertheless, the mean discharge rate achieved by these types was lower than 10 L/h at 100 kPa. These emitters were relatively difficult to install and distance between emitters was 0.20 m. This distance can be changed to less than 0.10 m.

The Hydrogol type was chosen for installation on a center pivot machine to continue the field experiments. This type was chosen because it has many advantages, such as the highest rate of discharge (about 10 L/h at 100 kPa). The lowest distance between this type of emitter was 0.15 m, but it was (0.20 m – 0.25 m) in other cases. When the Hydrogol type was used, the value of emission uniformity was higher than 90% at 100 kPa. The mean value of coefficient of variation was less than 5%, and Hydrogol was easy to install.

4.2 The field experiments

After choosing the better and more suitable type of emitters, these emitters must be successfully adapted to the center pivot machine. Therefore, the right positions of all drip tubes must be known because in the case of the center pivot, the water quantities at the end of the pivot are bigger than at the pivot point. Water distribution in the soil must be measured under the MDI. At the same time, the weight of water in the tubes during mobile drip irrigation is considered additional weight on the lateral of the center pivot machine. In this case, the friction forces between the tubes and the surface must be measured.

4.2.1 Materials and Methods

A center pivot machine was tested on a sandy loam soil in the experimental station of the Federal Agricultural Research Centre, FAL, during summer 2001. The total length of the machine was about 117 m (three towers). All data in this study were collected and calculated for a machine consisting of 9 towers. The total length of this pivot machine was approximately 428 m with a total irrigated area of about 57.55 ha without an end gun. Now, simulations for the center pivot (three towers) must be carried out. Towers number 1, number 5 and number 9 were chosen from the above-mentioned center pivot. The speeds of these towers were calculated and adapted to those of the small center pivot. The speeds of the small pivot were measured in the field and adapted appropriately to the big pivot. The speed of tower number 1, tower number 2 and tower number 3 at the small pivot was equal to speed of towers 1, 5 and 9 of the big pivot, respectively.

The soil water content was measured directly before irrigation and about 24 h after irrigation. Six samples were collected from four depths 10, 20, 30 and 40 cm between two drip tubes (0.75 m). The plan of the layout and the positions of soil samples between two drip tubes in the field under mobile drip irrigation with a center pivot machine are shown in Figure 4.16.

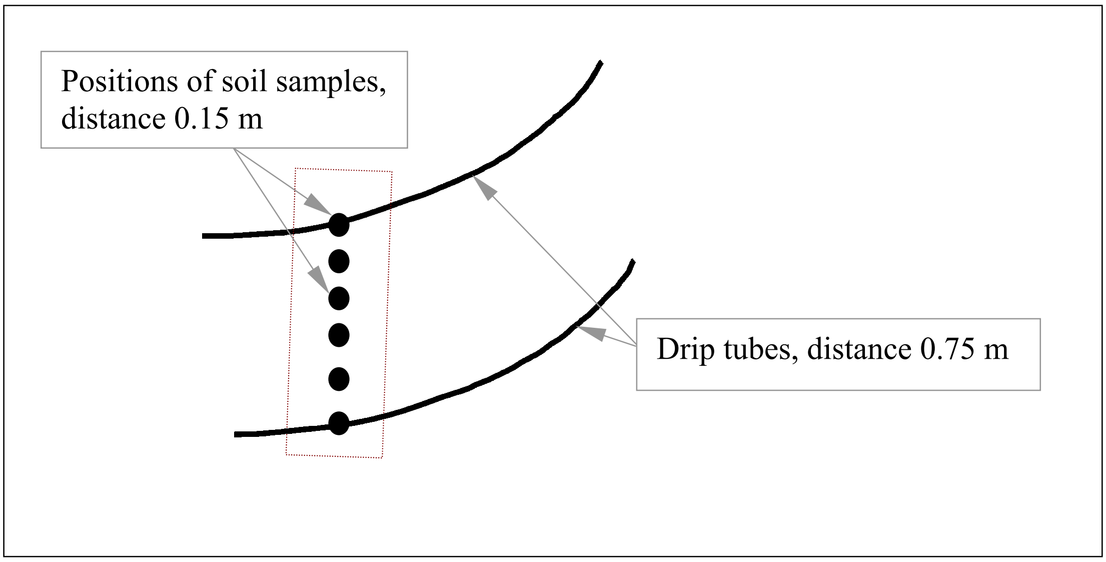


Figure 4.16: The layout plan and the positions of soil samples between two drip lines in the field under mobile drip irrigation

In the field investigations, two operating pressures (50 kPa and 100 kPa) were used at the inlet of the drop tubes. The operating pressure at the inlet of the pivot machine ranged from 175 and 225 kPa. Input options for the tested center pivot are illustrated in Table 4.5. Four replications were made for each pressure and each tower as shown in Figure 4.17. Soil water parameters were measured at the center of each tower.

Table 4.5: Input options for tested center pivot

Options	Value
Input pivot pressure, kPa	175 and 225
Inlet pivot pipe diameter, mm	160
Tower No.	1, 5 and 9
System of pressure control at inlet of drop tubes	Pressure regulator
Application irrigation depth, mm	20

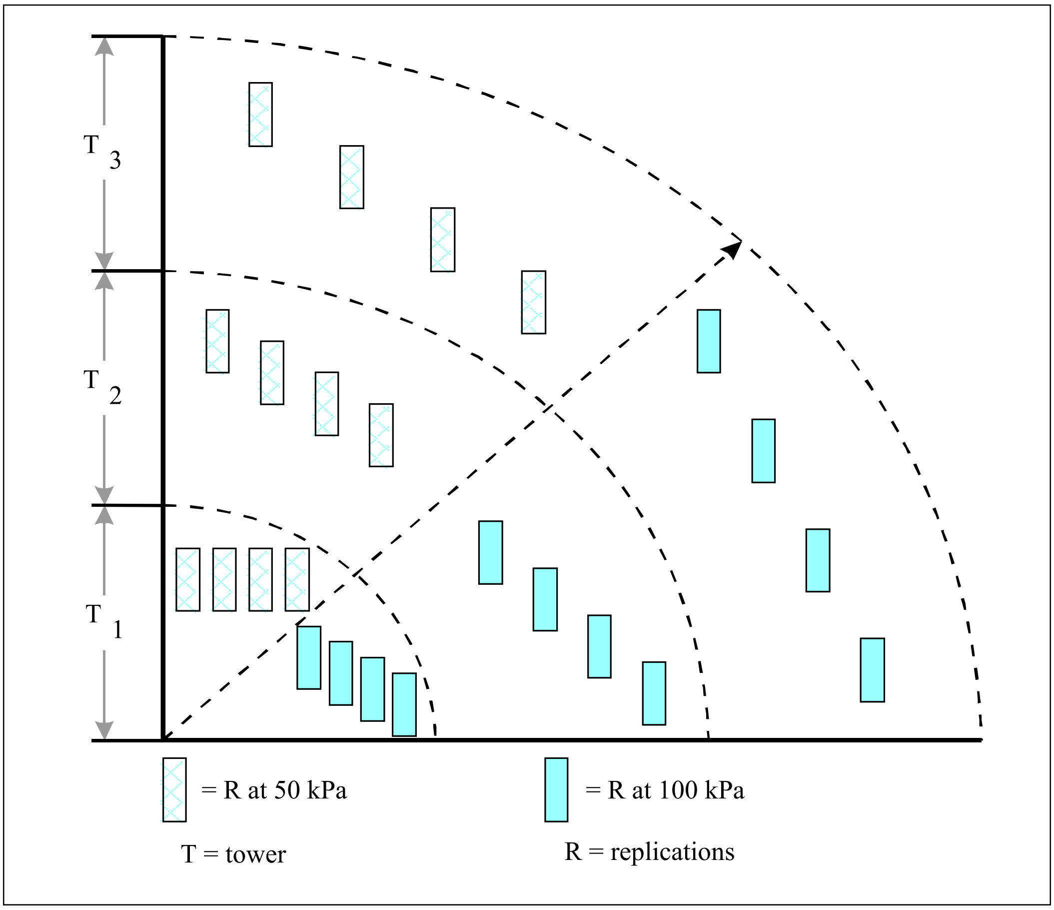


Figure 4.17: Plan of the replication positions in the field under mobile drip irrigation with a center pivot machine

The movement of the guide tower determines the speed of machine and the other tower follows with a start/stop or on/off sequence to maintain alignment. Consequently, the lateral does not move as a straight line, nor does it move at uniform speed. Sprayer positions were spaced every 3 m. They were replaced by drop tubes approximately 3 m in length. These drop tubes are not equipped with emitters and are only used for water delivery. At the same time, the number of emitters and the length of drip tubes at all outlets on the lateral of the center pivot machine were calculated and then connected with drop tubes before the irrigation process began. The operating pressures at all inlets of the drop tubes were regulated at two levels. The first, at 50 kPa and the second at 100 kPa of operating pressure. Evaporation from the soil surface and the free water surface was assumed to be negligible during the irrigation period for all treatments. Movement characteristics of towers number 1, 5 and 9 are shown in Table 4.6.

The texture of the experimental soil under the pivot machine was loamy sand. Some properties of the experimental soil are indicated in Table 4.7.

Table 4.6: Movement characteristics of three different towers

Characteristic	Average		
	Tower No. 1	Tower No. 5	Tower No. 9
On times, sec.	**10**	**50**	**60**
Off times, sec.	**60**	**60**	**50**
Speed, m/h	**6.50**	**30.30**	**55.20**

Table 4.7: Some properties of the experimental soil

Properties	Value
Depth of samples, cm	0 – 40
Texture	Loamy sand
Bulk density, g/cm³	1.42 – 1.50
Field capacity, FC (dry weight basis), %	15 – 19
Wilting point, WP (dry weight basis), %	3 – 5
Hydraulic conductivity, K (mm/h)	13 – 75

Current irrigation practice was to apply 20 mm as irrigation depth by drip tubes over the entire area under the mobile drip irrigation system during a 48 h cycle. The spacing between emitters on the lateral was 0.15 m. For the field study, a center pivot sprinkler machine was selected in addition to the proper type of emitters (Hydrogol). Then the sprinklers were replaced by the drop tubes which are connected to the drip tubes. A pressure regulator was used to adapt the operating pressure at the inlet of the drop tubes (50 kPa and 100 kPa). Furthermore, a water gauge and a manometer were used between the vertical tube and the horizontal tube as shown in Figure 4.18. The horizontal PE tube is an additional part and was used for the installation of the drip tubes. This PE tube was very important for the field experiments to be accomplished. The average slope value of the experimental soil was about 1 – 2%. The soil surface was covered by grass. Direct measures of the soil water content are needed in practically every type of soil study.

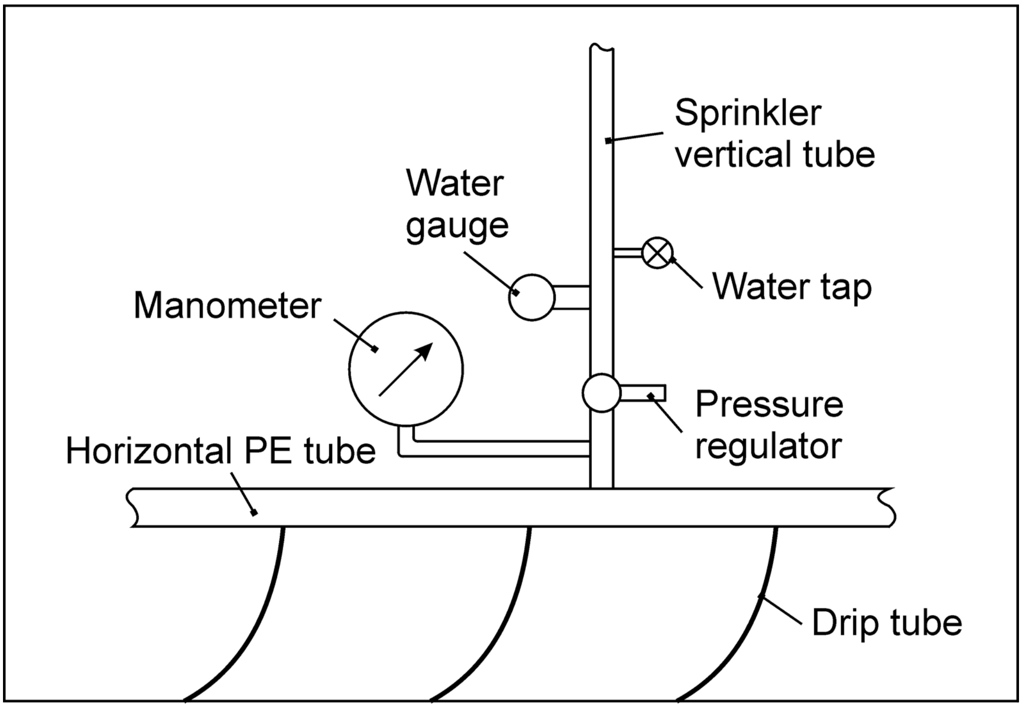


Figure 4.18: Water gauge, pressure regulator and manometer used to adapt the operating pressure at the inlet of the MDI drop tubes

In the field experiments, the irrigated area under all tubes, the water requirements, the length of drip tubes, the soil water content, irrigation depth, instantaneous application rates (IAR), distribution pattern efficiency (ε_p) and the friction force must be calculated or measured.

4.2.1.1 Water quantities at the pivot outlets

Chu and Moe (1972) imagined tiny sprinklers evenly distributed along a lateral to the boundary of the irrigated area. An element area located at the outer end of the system is shown in Figure 4.19.

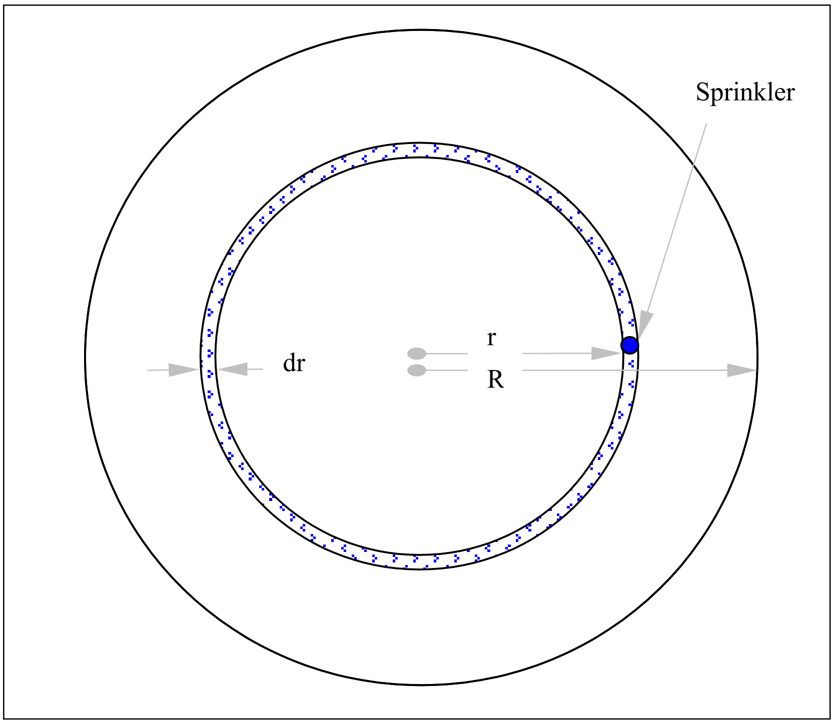


Figure 4.19: Schematic diagram of a center pivot system

If a tiny sprinkler is located at a distance " r " from the pivot point, the irrigated area covered by this sprinkler can be calculated using equation 4.7. The water quantities at all outlets on the lateral of a center pivot machine were calculated with the aid of Chu´s and Moe´s (1972) equations :

$$A = 2 \pi r \, dr \qquad (4.7)$$

where:

A = the irrigated area,

r = the distance between sprinkler and the pivot point, and

dr = the narrow spacing between sprinklers.

Then, the water required for this area or the sprinkler discharge is calculated as follows:

$$q_s = 2\ \pi\ r\ dr\ (b/T) \tag{4.8}$$

where:
q_s = the discharge of the tiny sprinkler,
b = depth of water application per one revolution of the system, and
T = the time period required for one revolution of the system.

Quantities of water at all outlets of the center pivot lateral were collected from different sources in the form of pivot charts from the companies Nelson (2001) and Valmont (2001). In this study, the water discharge at all outlets was calculated as a mean of these different literature data and it was used to design the mobile drip irrigation system. These water quantities provided theoretical irrigation depth in (mm).

4.2.1.2 Length of drip tubes

The length of the drip tubes at any point of the pivot lateral is dependent upon the emitter discharge and the distance from the pivot point. In all center pivot machines, the length of the drip tubes increases as the distance from the pivot point grows. To define the length of the drip tubes at any point, the pressure at the inlet of the tube, the emitter discharge, the distance between the sprinklers and the distance from the pivot point must be defined at first.

4.2.1.3 Soil water content

In the field, the determination of the amount of water available for plant growth requires direct measurement of the water content. At this stage, the soil water content was measured directly before and 24 h after irrigation. Soil samples taken before and after irrigation were dried at 105 °C in an oven for about 24 h to measure the water content in the soil layer at a depth of 0 to 40 cm. Two field experiments were made in the same field under the MDI to avoid differences in soil heterogeneity. The first experiment was accomplished on 14 May, 2001 and the second experiment was carried out on 1 June, 2001. Water content measurements by gravimetric methods involve weighing the wet sample, removing the water and reweighing the sample to determine the amount of water removed. Then, the water content is calculated by dividing the difference between wet and dry masses by the mass of the dry sample to obtain the ratio of the mass of water to the mass of dry soil. Multiplication by 100 provides the percentage of water in the dry mass sample.

Given the assumption that weighing precision is consistent with the desired precision of water content measurement, the accuracy of water content measurements depends upon the drying technique and the care taken in its application. Water content was computed in the samples before and after irrigation by using the method described in Hartge and Horn (1992) as follows:

$$W_{cg} = (W_w - W_d) / W_d \times 100 \qquad (4.9)$$

where:

W_{cg} = water content (g/g), in %,

W_w = wet weight of soil sample, in (g), and

W_d = dry weight of soil sample, in (g).

Then,

$$W_{cv} = W_{cg} \times (d_s / d_w) \qquad (4.10)$$

where:

W_{cv} = water content (vol. %),

d_s = density of soil, in g/cm³, and

d_w = density of water, in g/cm³.

The rate of movement of water through the soil is of considerable importance in many aspects of agriculture. The entry of water into the soil, the movement of water to the plant roots and the evaporation of water from the soil surface are a few obvious cases where the rate of movement plays an important role. The soil properties which determine the behaviour of soil water flow systems are hydraulic conductivity and the water-retention characteristics. The hydraulic conductivity of a soil is a measure of its ability to transmit water. The water-retention characteristics are an expression of its ability to store water. The amount water held in the soil layers varies from soil to soil and is related to the pore size distribution of the soil. At any given moment, the amount of water held in the soil is dependent upon many factors such as the type of plant cover, plant density, stage of plant growth, rooting depth, evaporation and transpiration rates, amount of water infiltrated, rate of wetting, nature of soil horizonation or layering, and the time passed since the last rainfall or irrigation event (Cassel and Nielsen, 1986).

The maximum amount of water retained by the soil reservoir is referred to as field capacity (FC). The amount of water retained at the dry end is the permanent wilting point (PWP). Available water capacity is the difference between these two limits and is defined as the quantity of water held by a soil at the full end that is available for plant use. For soils without shallow water tables, most of this water is generally considered unavailable to plants because it drains out of the soil rapidly.

It is important to realize that the limits of plant-available water are those for a soil profile from the soil surface to the bottom of the rooting zone. Rooting depth is time variant, thus causing field capacity and permanent wilting points, each represented by mean soil water contents over the entire rooting zone, to change with time, especially early in the growing season. Therefore available soil moisture is the difference at any given time between the actual soil moisture content in the root zone soil and the wilting point (Kruse et al., 1978).

4.2.1.4 Irrigation depth

The seasonal water needs are different from crop to crop and are dependent upon the range of growing periods. Crop water requirements are given in (mm), which is the normal way of expressing crop water needs. It is the depth of water which must be applied over a season to grow a crop. How much is applied at each irrigation and the interval between successive irrigations is determined by the ability of the soil to store water for the growth of crops. If the amount of irrigation water is given in (m^3) and the area of the land is expressed in hectar, irrigation depth can be defined easily. In this study, designed irrigation depth was 20 mm per irrigation. In the case of mobile drip irrigation with center pivot machines, irrigation depth can be defined by calculating the water content of the soil samples before and after irrigation.

4.2.1.5 Instantaneous application rate (IAR)

Longitudinal uniformity mainly depends on the control system of the machines. Longitudinal uniformity is fairly insensitive to frequent short pauses at least under the conditions of the experiments (Amir and Dag, 1993). They studied the effect of instantaneous application rates (IAR) on wetted contours. The IAR was calculated as follows:

$$IAR = q/wL\ (1000) \qquad (4.11)$$

where:

IAR = instantaneous application rate, in mm/h,

q = discharge of one emitter, in m^3/h,

w = width of irrigated area, in m, and

L = distance between emitters, in m.

They also concluded that a high IAR increases lateral dispersion width, while it reduces the depth of infiltration. High IAR increase uniformity but also the possibility of water runoff. The effect of the discharge on the width and depth of the wetting contours of moving low pressure emitters is similar to that of stationary point-source emitters.

4.2.1.6 Distribution pattern efficiency (ε_p)

Distribution pattern efficiency (ε_p) was calculated by using the method described in (Painter and Carran, 1978) as follows:

$$\varepsilon_p = R/I\ (100) \qquad (4.12)$$

where:

ε_p = distribution pattern efficiency, in %,

R = infiltrated water, in mm, and

I = applied water, in mm.

The effect of the poor uniformity of distribution of water in terms of its agronomic importance is uncertain. However, if a portion of a field does not get enough water to compensate for the soil water deficit, plants in this area are going to become stressed earlier and may produce less.

4.2.1.7 Friction force

In mobile drip irrigation, the drip tubes move behind the center pivot machine. In this study, the maximum length of the drip tube was about 16 m at the end of the ninth tower. This tube length was calculated by using 50 kPa operating pressure at the inlet of drop tubes. Under field conditions, the friction force required for one tube was measured by using a pocket balance. The measuring limits of this balance range from 0 to 25 kg and its accuracy is 0.5 kg. To measure the friction force requirement, the balance was fitted between the horizontal PE tube and the drop tube as shown in Figure 4.20. The length of the drop tube was about 3 m. It had no emitters and when connected with the drip tube with emitters, the maximum total length of the tube was about 19 m.

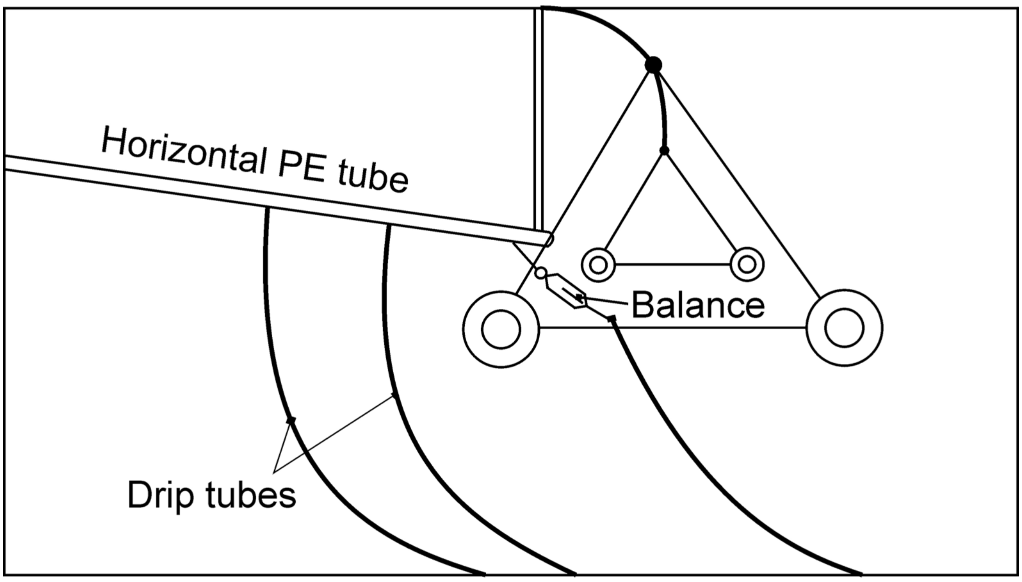


Figure 4.20: Measuring of the friction force in the field for MDI with a center pivot machine

Before the experiments, the emitters were clogged using plaster band to prevent water leakage. Both drop and drip tubes were filled with water and drawn behind the center pivot machine. The field was covered by grass (dry), which on average was 30 cm tall. The tubes moved at the same speed as the third tower (55.20 m/h). There were 20 replications in this field experiment. The friction factor was measured under different conditions. Its values are indicated in Table 4.8 (Sourell, 1991). When the weight of the water and the tube is measured, the friction forces can also be calculated using the method described in Sourell, (1991) as follows:

$$Fr = mr.\ \mu.\ g \qquad (4.13)$$

where:

Fr = friction force, in N,

mr = weight of water and tube, in kg,

μ = friction factor, dimensionless, and

g = acceleration of gravity, in m/s².

Table 4.8: Friction factor values (μ) for different conditions (after Sourell, 1991)

Condition	Friction factor, μ	
	Dry	Wet
Grass	**0.62 – 0.64**	0.59 – 0.79
Oil radish	0.64	0.49
Cereals	0.58	----
Uncovered soil	0.48 – 0.54	0.40 – 0.55
Sugar beet	0.38	0.36
Potatoes	0.44 – 0.51	----
Stubble	0.41	----

4.2.2 Results and Discussion

4.2.2.1 Water quantities at the pivot outlets

Water quantity or irrigation depth along the pivot lateral must be known for the design mobile drip irrigation with a center pivot machine. In the field experiments, the mean of irrigation depth was used to calculate the length of the drip tubes. The relationship between water quantities or irrigation depth and the lateral length of the center pivot based on data from different sources is illustrated in Figure 4.21. Chu and Moe (1972) calculated irrigation depth using equations 4.7 and 4.8. Given the data from the Nelson company, irrigation depth (20 mm) from all sources was uniformly distributed along the pivot lateral except for irrigation depth at tower number one. However, it was relatively high, ranging from 20 to 30 mm. Proper water quantities in the first tower are difficult to achieve (Nelson, 2001). The water flow rate at all outlets under this tower was very low because the acreage being irrigated by the first tower was very small. This situation dictates the use of very small nozzles and very few sprinklers or sprays which operate at the highest pressure of any span of the pivot. This condition may cause lower uniformity than other towers as well as lower efficiency due to misting and wind drift. Most designers purposely select larger nozzles sizes than those theoretically required to offset lower efficiency. All data calculated by Chu and Moe (1972), Nelson and Valmont are indicated in Appendix (B).

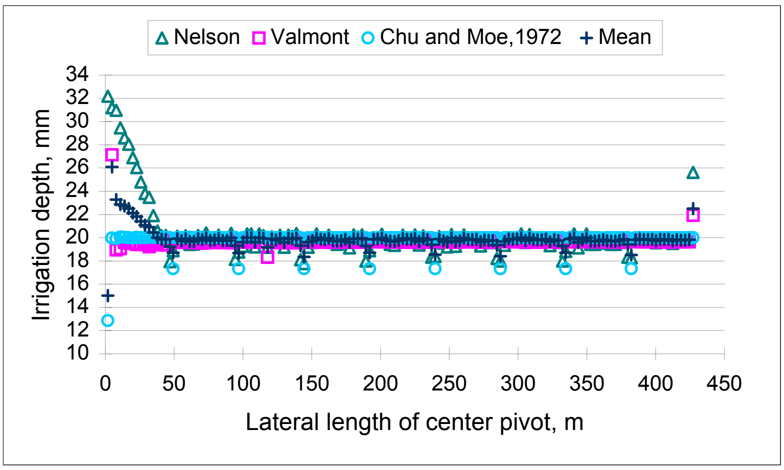


Figure 4.21: Irrigation depth at all outlets of a center pivot lateral (data from different sources)

4.2.2.2 Length of drip tubes

The length of the drip tubes was calculated at all outlets of a center pivot lateral at an operating pressure of 50 kPa and 100 kPa. The emitter discharge rate was about 7.25 L/h and 10.49 L/h at 50 kPa and 100 kPa, respectively. The amount of water required at any point was constant and the emitter discharge at 50 kPa was less than at 100 kPa. The calculated length of the drip tube at 50 kPa was longer than at an operating pressure of 100 kPa as shown in Figure 4.22. Drip tube length was calculated at all pivot points as indicated in Appendix (B).

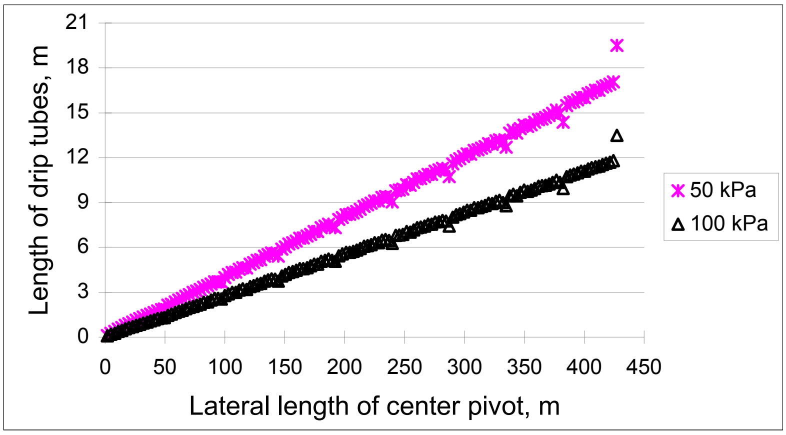


Figure 4.22: Length of drip tubes at two pressures under the conditions of mobile drip irrigation with a center pivot irrigation machine

4.2.2.3 Soil water content

Due to soil heterogeneity, the soil water content on a field can be different. In addition, water distribution in the soil strongly depends upon soil heterogeneity. Therefore, two experiments were accomplished here in order to study water distribution in the soil under the mobile drip irrigation system.

First experiment

Figure 4.23 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 50 kPa at the inlet of the drop tubes under the first tower. These are the results of the first experiment on 14 May, 2001. Before irrigation, the soil water content in the first 10 cm of soil depth ranged from 8% to 10% [vol.-%]. In the last 10 cm of soil depth (30 – 40 cm), the soil water content ranged from 14% to 16% [vol.-%]. Before irrigation, the water in the soil was very uniformly distributed. After irrigation, the soil water content in the first 10 cm of soil depth ranged from 20% to 24% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 14% to 18% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was uniformly distributed. Under these soil and climate conditions, this water content is enough to meet the plant requirements described in this study. The higher value of soil water content was measured under the right tube, whereas the length of drip tubes under this tower was relatively short. In this case, the drip tube may move from left to right and inverse sequence. To adjust this problem, an extra drop tube about two or three meters long can be used (without emitters). In this case, total drop tube length increases to approximately six meters under the first tower.

Figure 4.24 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 100 kPa at the inlet of the drop tubes under the first tower. These results are from the first experiment on 14 May, 2001. Before irrigation, the soil water content in the first 10 cm of soil depth ranged from 8% to 10% [vol.-%]. In the last 10 cm of soil depth, the soil water content ranged from 14% to 16% [vol.-%]. The water in the soil before irrigation was distributed very uniformly. After irrigation, the soil water content in the first 10 cm of soil depth ranged from 16% to 24% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 14% to 16% [vol.-%] during mobile drip irrigation with a center pivot machine. After irrigation, the water was distributed in a relatively uniform manner. The higher value of soil water content was only measured directly under the drip tubes. At 100 kPa, water distribution between two drip tubes was less significant than at 50 kPa. This result is similar to the results reported by Bresler (1977). That means that the water content and water distribution in the soil is influenced by the emitter discharge rate. Under all these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study.

Figure 4.25 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 50 kPa at the inlet of the drop tubes under the fifth tower. These results are from the first experiment on 14 May, 2001. Before irrigation, soil water content in the first 10 cm soil depth ranged from 8% to 14% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 16% to 18% [vol.-%]. Before irrigation, the water in the soil was uniformly distributed. After irrigation, the soil water content in the first 10 cm soil depth ranged from 20% to 24% [vol.-%]. In the last 10 cm depth, the soil water content ranged from 16% to 20% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was very uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study.

Figure 4.26 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 100 kPa at the inlets of the drop tubes under the fifth tower. These results are from the first experiment on 14 May, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 10% to 14% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 16% to 18% [vol.-%]. Before irrigation, the water in the soil was uniformly distributed. After irrigation, the soil water content in the first 10 cm soil depth ranged from 20% to 24% [vol.-%]. In the last 10 cm depth, the soil water content ranged from 16% to 20% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was very uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described this study. Under tower number five, the water content after irrigation was relatively higher than under tower number one because the water content before irrigation under tower number one was lower than under tower number five.

Figure 4.27 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 50 kPa at the inlets of the drop tubes under the ninth tower. These results are from the first experiment on 14 May, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 8% to 10% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 14% to 16% [vol.-%]. Before irrigation, the water in the soil was distributed very uniformly. After irrigation, the soil water content in the first 10 cm soil depth ranged from 16% to 22% [vol.-%]. In the last 10 cm depth, the soil water content ranged from 14% to 18% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water after irrigation was less uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study.

Figure 4.28 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 100 kPa at the inlets of the drop tubes under the ninth tower. These results are from the first experiment on 14 May, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 8% to 10% [vol.-%]. In the last 10 cm of soil depth, the soil water content ranged from 14% to 16% [vol.-%]. Before irrigation, the water in the soil was also uniformly distributed . After irrigation, the soil water content in the first 10 cm soil depth ranged from 18% to 22% [vol.-%]. In the last 10 cm depth, the soil water content ranged from 14% to 18% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was less uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study. Under tower number nine, the water content after irrigation was relatively lower than under both tower number one and tower number five.

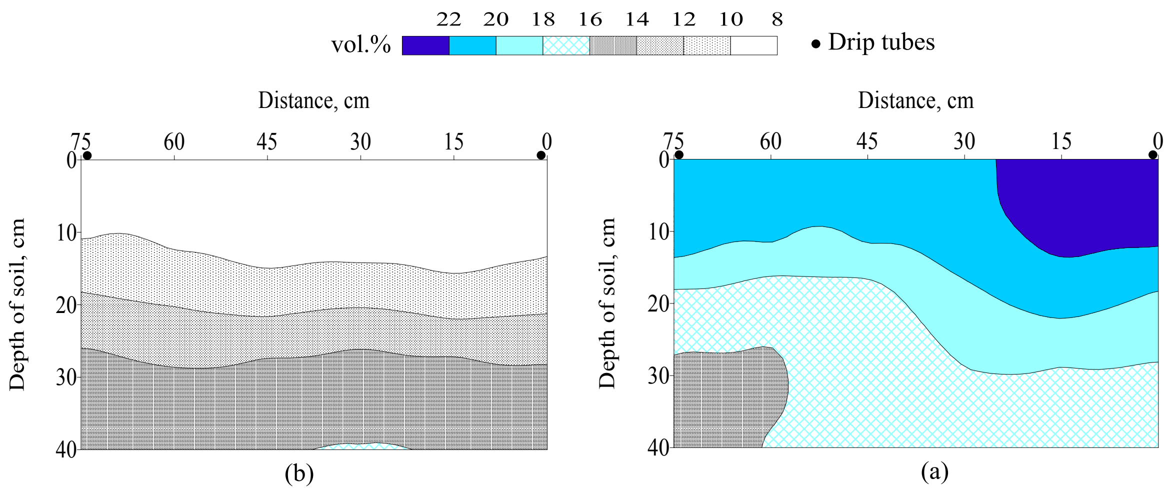


Figure 4.23: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 50 kPa under the first tower on 14 May

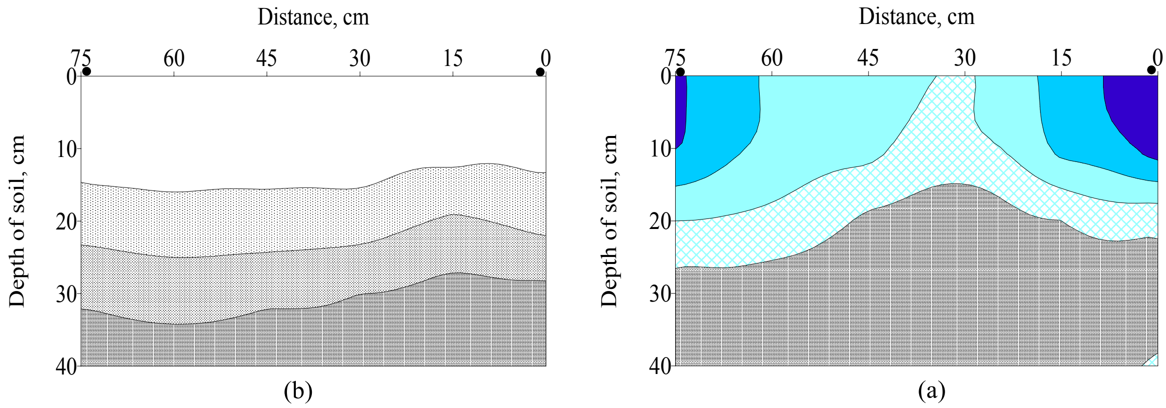


Figure 4.24: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 100 kPa under the first tower on 14 May

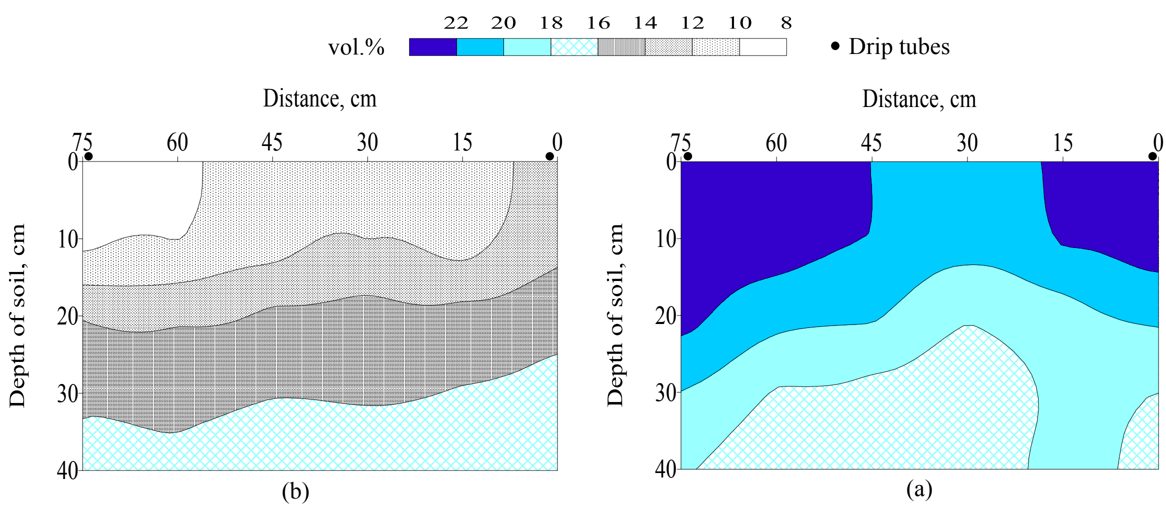


Figure 4.25: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 50 kPa under the fifth tower on 14 May

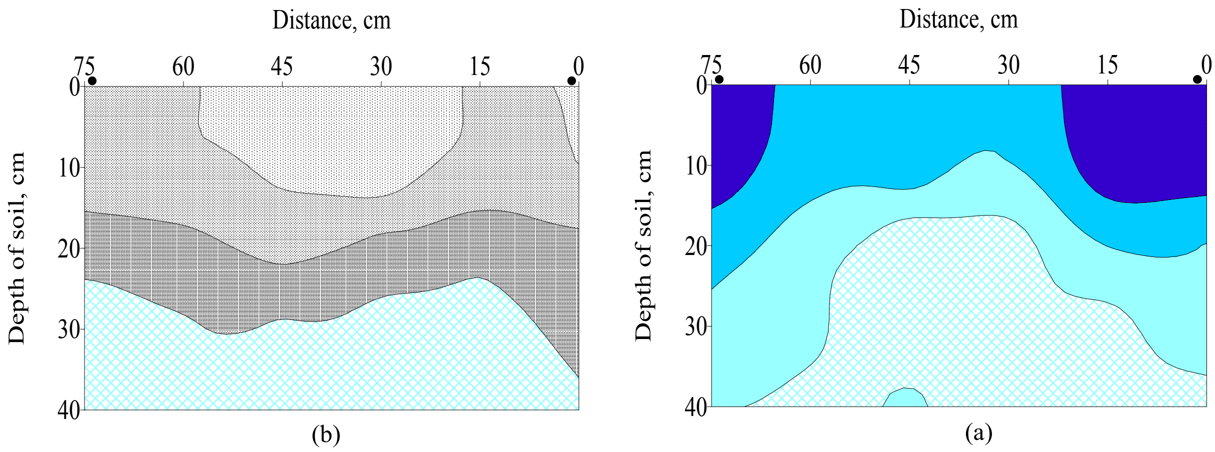
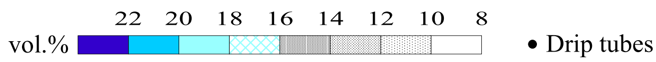


Figure 4.26: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 100 kPa under the fifth tower on 14 May



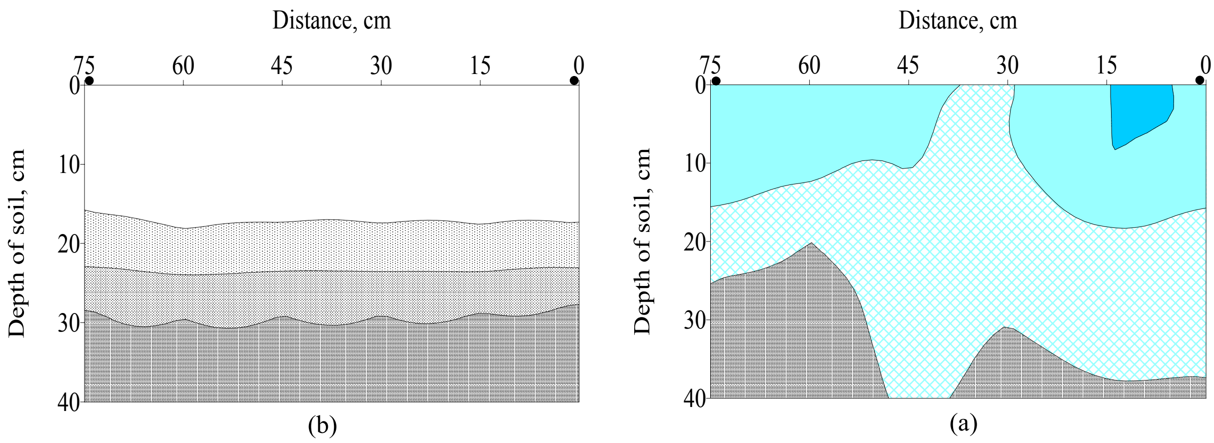


Figure 4.27: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 50 kPa under the ninth tower on 14 May

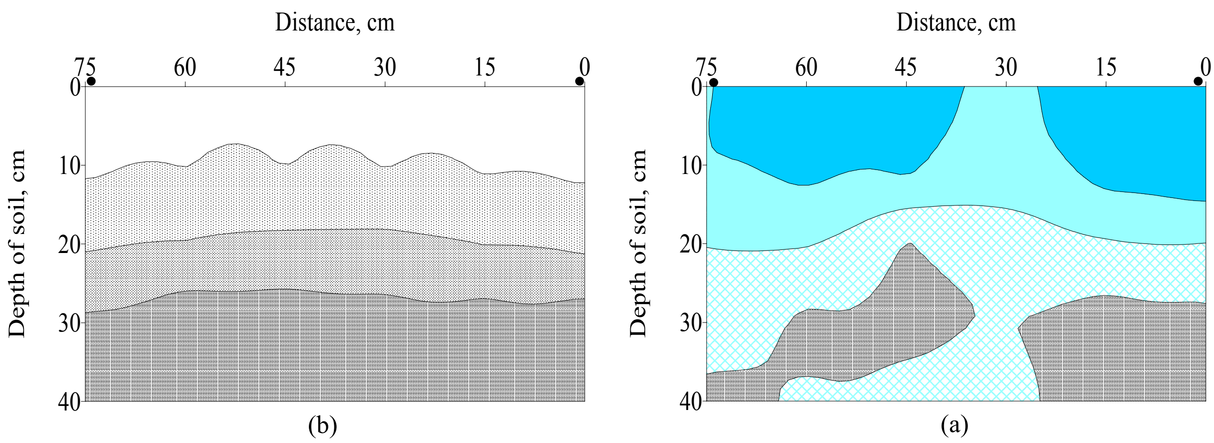


Figure 4.28: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 100 kPa under the ninth tower on 14 May

Second experiment

Figure 4.29 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 50 kPa at the inlets of the drop tubes under the first tower. These results are from the second experiment on 1 June, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 12% to 16% [vol.-%]. In the last 10 cm of soil depth (30 – 40 cm), the soil water content ranged from 12% to 14% [vol.-%]. Before irrigation, the water in the soil was uniformly distributed. After irrigation, the soil water content in the first 10 cm soil depth ranged from 18% to 24% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 14% to 18% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study. In this experiment, the soil water content is similar to the results recorded during the first experiment on 14 May. Higher soil water content values were measured under the left tube, whereas the length of drip tubes under this tower was relatively short. In this case, the drip tube may move from the left to the right and inverse sequence. To adjust this problem, an extra drop tube about two or three meters long can be used (without emitters). Only under the first tower, total drop tube length is extended to about six meters.

Figure 4.30 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure 100 kPa at the inlets of the drop tubes under the first tower. These results are from the second experiment on 1 June, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 10% to 14% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 14% to 16% [vol.-%]. Before irrigation, the water in the soil was very uniformly distributed. After irrigation, the soil water content in the first 10 cm of soil depth ranged from 20% to 24% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 14% to 18% [vol.-%] in the case of mobile drip irrigation with a center pivot machine. After irrigation, the water after irrigation was relatively uniformly distributed. The higher value of soil water content was only measured directly under the drip tubes. At 100 kPa, water distribution between two drip tubes was smaller than at 50 kPa. This result is similar to the result recorded during the first experiment on 14 May.

Figure 4.31 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 50 kPa at the inlets of the drop tubes under the fifth tower. These results are from the second experiment on 1 June, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 8% to 12% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 14% to 16% [vol.-%]. Before irrigation, the water in the soil was uniformly distributed. After irrigation, the soil water content in the first 10 cm soil depth ranged from 22% to 24% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 14% to 16% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was very uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study.

Figure 4.32 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 100 kPa at the inlets of the drop tubes under the fifth tower. These results are from the first experiment on 1 June, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 10% to 12% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 14% to 16% [vol.-%]. Before irrigation, water in the soil was also uniformly distributed. After irrigation, the soil water content in the first 10 cm of soil depth ranged from 22% to 24% [vol.-%]. In the last 10 cm depth, the soil water content ranged from 14% to 16% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was very uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study. Under tower number five, the water content after irrigation was relatively higher than under tower number one because the water content before irrigation under tower number one was lower than under tower number five.

Figure 4.33 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 50 kPa at the inlets of the drop tubes under the ninth tower. These results are from the second experiment on 1 June, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 8% to 10% [vol.-%]. In the last 10 cm soil depth, the soil water content ranged from 12% to 14% [vol.-%]. Before irrigation, water in the soil was very uniformly distributed. After irrigation, the soil water content in the first 10 cm of soil depth ranged from 16% to 22% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 12% to 14% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was less uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study. At the same time, these results are similar to the results of the first experiment on 14 May.

Figure 4.34 illustrates the soil water content between two drip tubes before and after irrigation at an operating pressure of 100 kPa at the inlets of the drop tubes under the ninth tower. These results are from the second experiment on 1 June, 2001. Before irrigation, the soil water content in the first 10 cm soil depth ranged from 10% to 12% [vol.-%]. In the last 10 cm of soil depth, the soil water content ranged from 12% to 16% [vol.-%]. Before irrigation, the water in the soil was also uniformly distributed . After irrigation, the soil water content in the first 10 cm of soil depth ranged from 20% to 22% [vol.-%]. In the last 10 cm of depth, the soil water content ranged from 14% to 16% [vol.-%] under the conditions of mobile drip irrigation with a center pivot machine. After irrigation, the water was very uniformly distributed. Under these soil and climate conditions, this water content is sufficient to meet the plant requirements described in this study. These results are also similar to the results of the first experiment on 14 May.

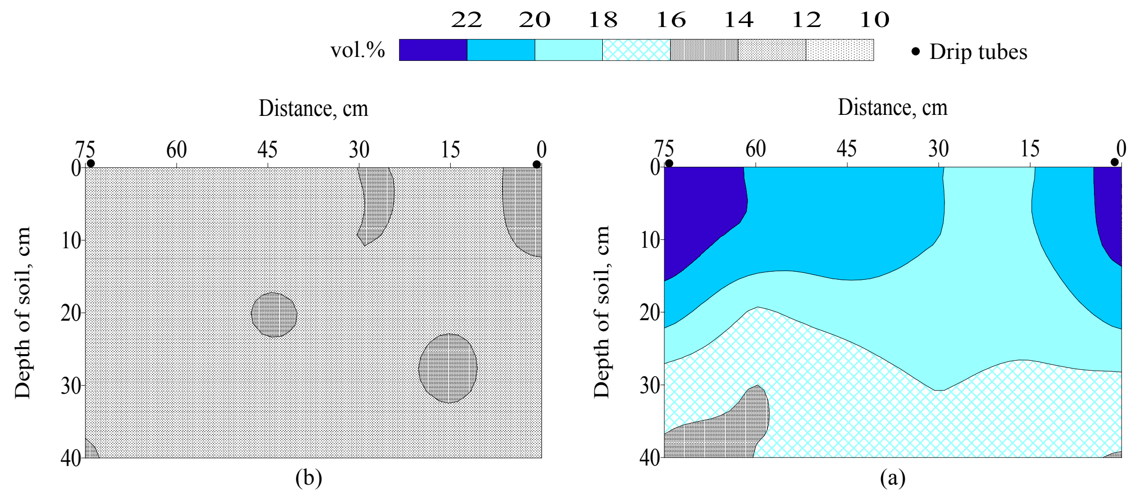


Figure 4.29: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 50 kPa under the first tower on 1 June

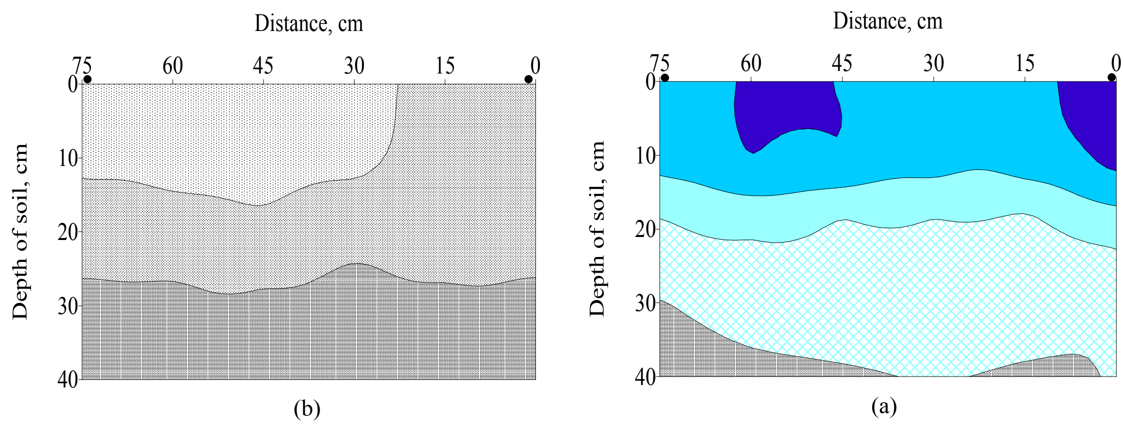


Figure 4.30: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 100 kPa under the first tower on 1 June

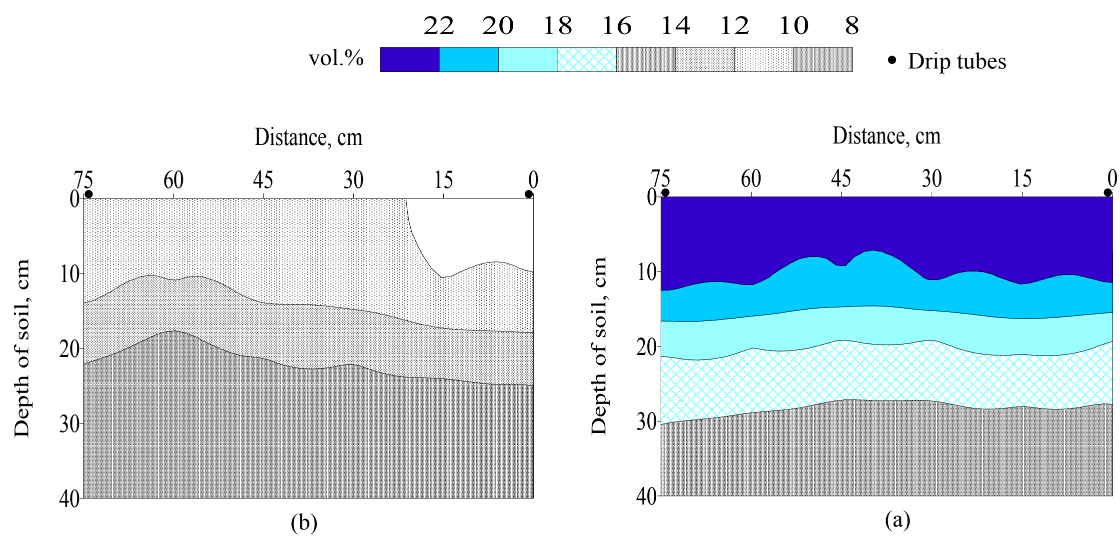


Figure 4.31: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 50 kPa under the fifth tower on 1 June

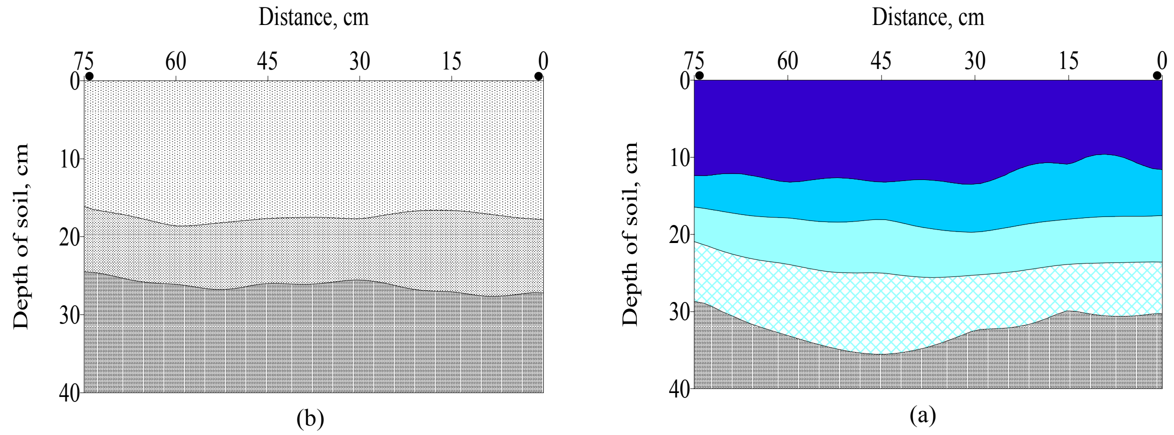
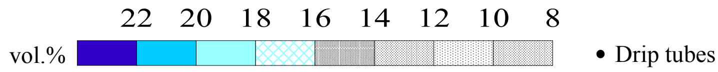


Figure 4.32: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 100 kPa under the fifth tower on 1 June



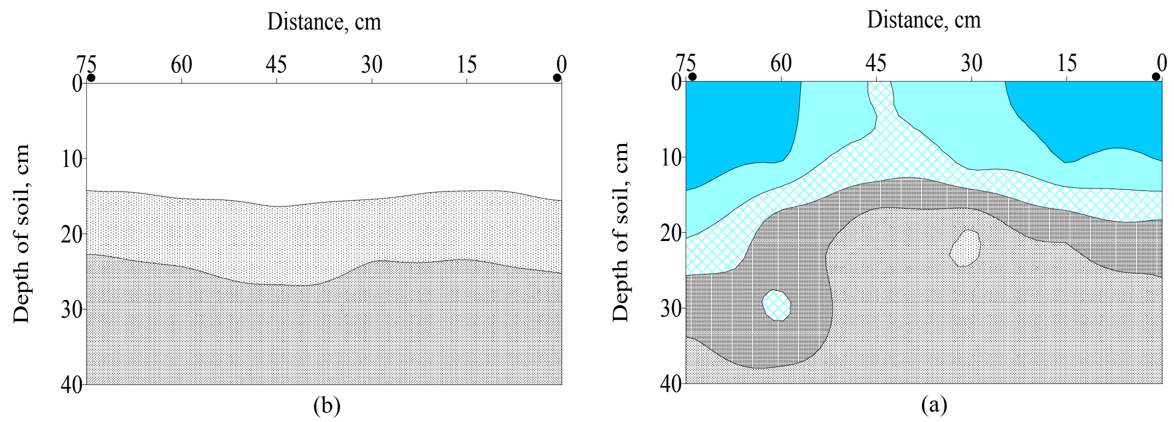


Figure 4.33: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 50 kPa under the ninth tower on 1 June

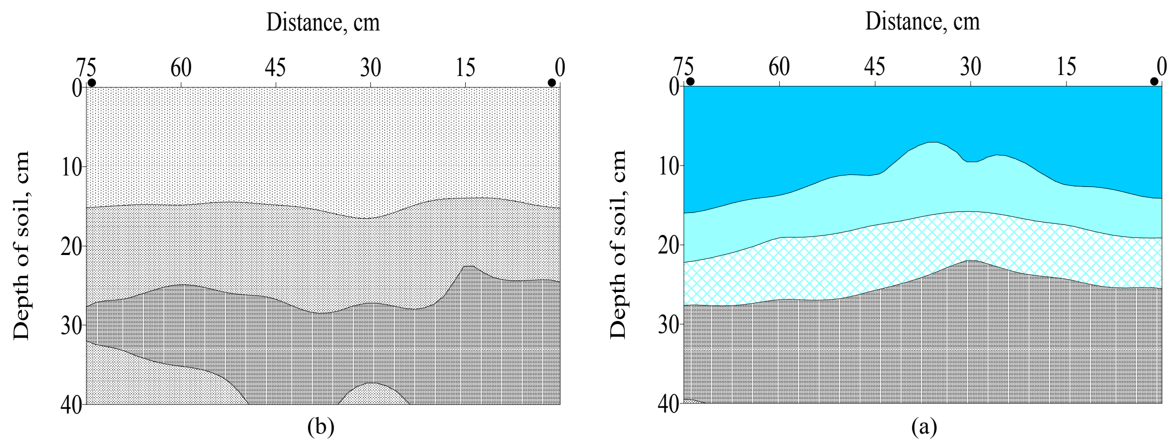


Figure 4.34: The soil water content between two drip tubes (b) before and (a) after irrigation at a pressure of 100 kPa under the ninth tower on 1 June

The previous figures also indicate that the wetted soil depth under the mobile drip irrigation at a pressure of 50 kPa was deeper than at an operating pressure of 100 kPa. That means that the use of high pressure with mobile drip irrigation may cause runoff. Generally, the soil water content after irrigation during the use of MDI was relatively similar under different pressures and different towers. At the same time, the distribution of the soil water content between drip tubes was sufficient to meet the plant requirements with great similarity. At 50 kPa on tower number nine, however, the wetted depth of soil after irrigation was lower than under both towers number one and five. The reason for this problem may be the insufficient efficiency of some emitters, or the number of emitters may lead to this difference. In all cases, the soil water content after irrigation was distributed similarly below and between the drip tubes. The previous figures are summarized in Figure 4.35. The quantity of water applied was 20 mm at all points of the center pivot lateral.

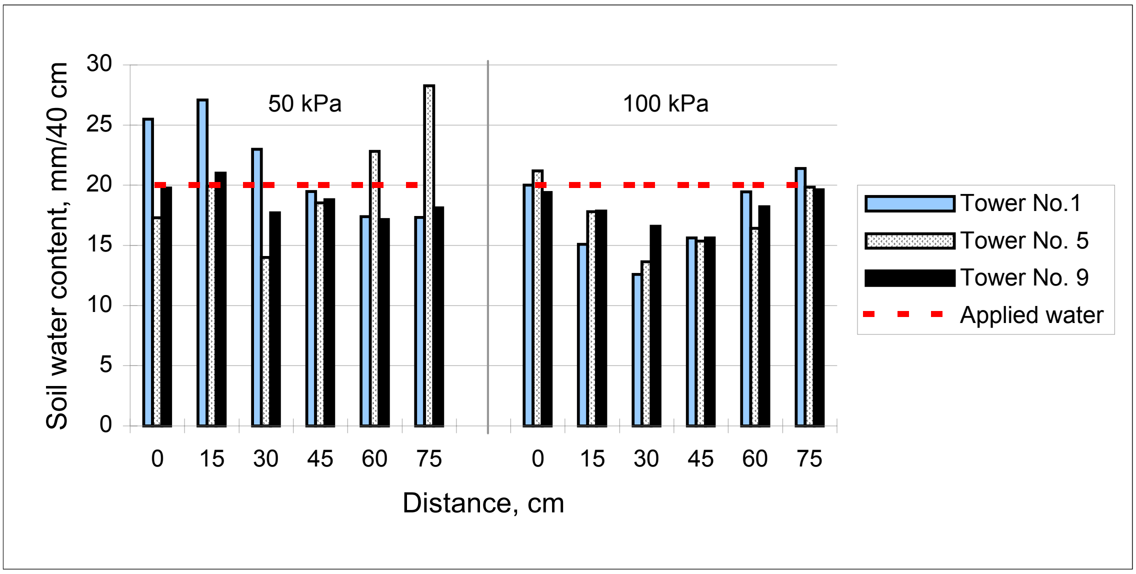


Figure 4.35: Soil water content between two drip tubes under the mobile drip irrigation with the center pivot machine

4.2.2.4 Irrigation depth

Figure 4.36 illustrates the relationship between the lateral length of the center pivot and both the applied and the measured irrigation depth by using the mobile drip irrigation with center pivot irrigation machines. Mean value of measured irrigation depth ranges from 18 to

22 mm at all tested towers and by using two operating pressures at the inlet of the drop tubes. The measured irrigation depth at the tower number one was relatively higher as the measured irrigation depth at both towers number five and number nine. The applied irrigation depth at the tower number one was relatively high too.

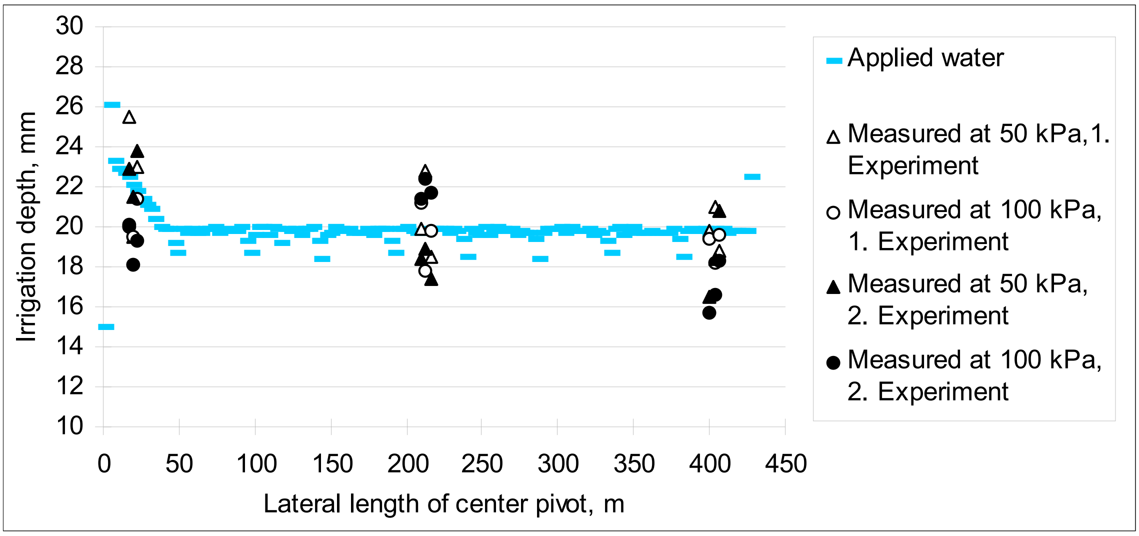


Figure 4.36: Irrigation depth at different pressures and under different towers by using the mobile drip irrigation with the center pivot machine

4.2.2.5 Instantaneous application rate (IAR)

In the design of a mobile irrigation system, the instantaneous application rate must be considered. If the instantaneous application rate from the drop tube is much higher than the intake rate of the soil, surface runoff is possible (Hanson et al., 1988).

The instantaneous application rate increased when the discharge rate increased, because both the distance between tubes is fixed (0.75 m) and the distance between emitters is fixed too (0.15 m). In this study, the discharge rate was about 10 L/h at 100 kPa and it was about 7 L/h at 50 kPa. Then the calculated value of IAR according equation 4.11 was 62 mm/h at 50 kPa and it was 89 mm/h at 100 kPa. The results indicate that high IAR increases the width and reduces the depth of the irrigated soil. In addition, a high IAR increases uniformity. However, runoff is possible. These results are in agreement with Amir and Dag (1993).

4.2.2.6 Distribution pattern efficiency (ε_p)

The mean of distribution pattern efficiency was calculated for all tested towers using mobile drip irrigation with the center pivot machine. Distribution pattern efficiency indicates the relationship between the quantity of water applied and the infiltrated water in the soil. At an operating pressure of 50 kPa, distribution pattern efficiency under tower number 1 was higher than under both towers 5 and 9, because in case of tower number 1 the length of the drip tubes was smaller than the length of the drip tubes under both towers 5 and 9. This means that under tower number 1 there was no runoff, but runoff is possible under both towers 5 and 9. Under the first tower, the water is better distributed and infiltrated in the soil than under the others. At an operating pressure of 100 kPa, distribution pattern efficiency under towers number 1, 5 and 9 in the first experiment was the same as shown in Figure 4.37. In the second experiment, however, it was relatively similar under tower number 1 and tower number 9 as shown in Figure 4.38. Under towers number 1, 5 and 9, distribution pattern efficiency at 50 kPa was higher than at 100 kPa, whereas the emitter discharge rate at 50 kPa is lower than the emitter discharge rate at 100 kPa. At the same time, the speed of the center pivot machine was constant under both pressures. The water was better infiltrated in the soil profile at 50 kPa than at 100 kPa. In addition, water runoff may easily occur at 100 kPa, because the water is moving more rapidly in the horizontal direction than in the vertical direction. At 50 kPa, however, the water moves more rapidly in the vertical direction than in the horizontal direction.

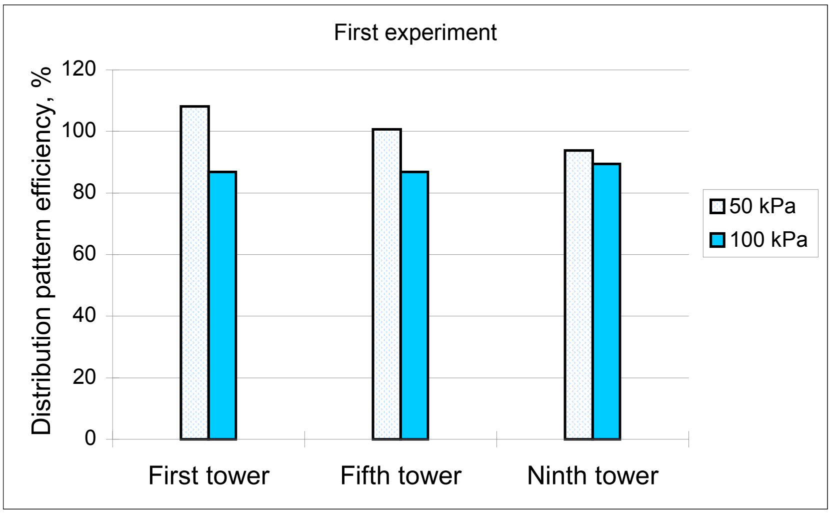


Figure 4.37: Water distribution pattern efficiency under different towers and at different pressures under the conditions of mobile drip irrigation with the center pivot machine (first experiment)

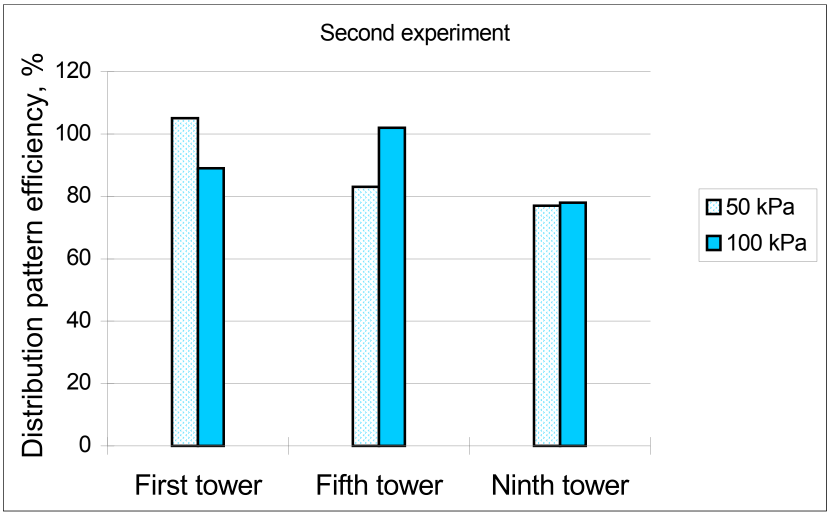


Figure 4.38: Water distribution pattern efficiency under different towers and at different pressures under the conditions of mobile drip irrigation with the center pivot machine (second experiment)

4.2.2.7 Friction force

The draft force required to drag a tube filled with water was 4.31 kg for a total tube length of 19 m (about 0.23 kg/m or 2.25 N/m). The drop tubes do not feature emitters, whereas the drip tubes are equipped with emitters.

Generally speaking, the water quantities at the inlets of the lateral increased with distance from the pivot when center pivot machines were used. This means that, the length of the tubes increased with distance from the pivot. Thus, the longest tubes will be at the end of the last tower. Friction forces can be calculated only for a length of 19 m. Division by the length allows the friction force for one meter to be calculated. The friction forces must be calculated for all tubes at the last tower. Then, these forces will be defined for the last tower. In this study, tower number nine is the last tower. The friction forces between the tubes and the surface at the last tube were about 128 N and 183 N at 100 kPa and 50 kPa, respectively as shown in Figure 4.39. The friction forces at 50 kPa were higher than the friction forces at 100 kPa, because the length of tube at 50 kPa was greater than the length of the tube at 100 kPa.

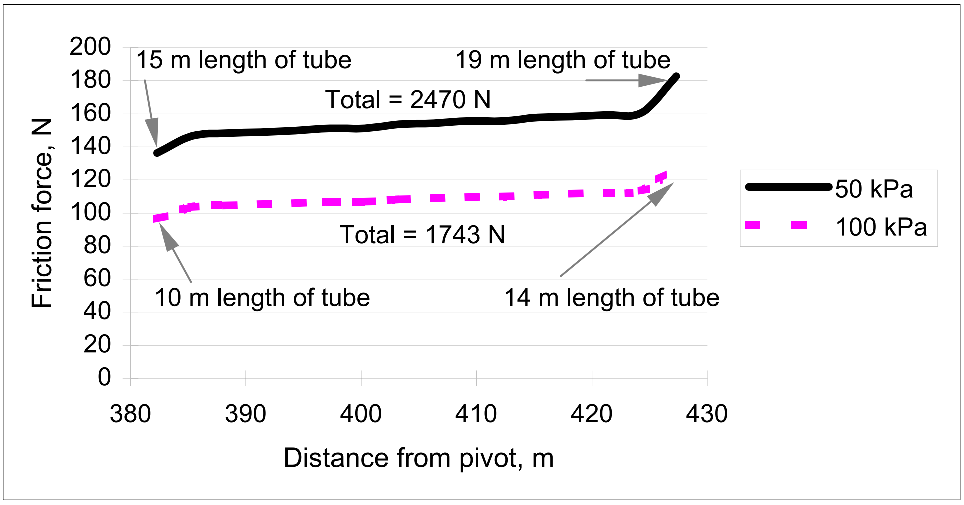


Figure 4.39: Friction forces for the tubes at the ninth tower under the conditions of mobile drip irrigation with the center pivot machine

4.2.3 Conclusions from the field experiments

The previous tables and figures indicated that the water distribution efficiency refers to the resulting stored soil moisture values and could differ from the coefficient of uniformity if runoff occurs as a result of water application. The change in moisture was not considered to be precisely accurate quantitatively. However, gave a good indication of relative moisture changes and was used to estimate distribution uniformity. These field experiments showed whether or not the water is well distributed in the soil. In this study, the runoff problem did not occur.

The previous figures showed that soil water distribution in the top 0.4 m of a loamy sand soil was very similar under the conditions of mobile drip irrigation. In addition, two levels of low pressure (50 kPa and 100 kPa) can be used under field conditions. Mobile drip irrigation can be improved further in order to achieve better water distribution if drop tubes longer than three meters are used on tower number one in order to prevent tube movement caused by wind. On the other hand, the designed distance between drip tubes (0.75 m) was excellent. Generally, the drip tubes were moved parallel, in particular on towers number 5 and 9. On the first tower, however, drop tube length should be 4 m instead of 3 m like on the another towers because the length of the drip tubes under the first tower was very short. In this case, the tubes can move from the right to the left, which means that water distribution under this tower may be not the same as under the other towers.

4.3 Design considerations of the MDI

After the basic data, the discharge of pivot lateral outlets, water distribution in the soil and the friction force requirements were examined for the interpretation of mobile drip irrigation with a center pivot machine. There are some design considerations that must be known to achieve better water distribution efficiency, such as the size of the machine, the filtration of water, flow rate adaptation and material requirements.

4.3.1 Size of the machine

Stationary drip irrigation systems are suitable for all differently shaped fields. In addition, these systems are suitable for many crops. However they are not suitable for some crops such as wheat and barley. Center pivot sprinkler machines are suitable for nearly all crops except paddy rice. The center pivot sprinkler machines are designed and available in different sizes (towers) from one tower to multiple towers, which can irrigate more than 200 ha.

For mobile drip irrigation with a center pivot machine, the total length of the last tube ranges from 11 to 19 m at 100 kPa and 50 kPa, respectively. In this case, the pivot consists of 9 towers (about 57.55 ha). Since this length of the tube is relatively complex, the size of the pivot machine (9 towers) with a mobile drip is sufficient in this case. At 50 kPa, however, the total friction force requirement is about 250 kg at the last tower. From the viewpoint of the manufacturers, this force is suitable for the electric motors which are mounted on each tower. This means that the mobile drip irrigation with a center pivot machine is suitable for 9 towers.

4.3.2 Filtration of water

The filtration of water in stationary drip irrigation is necessary to prevent emitter clogging. This process is not important in the case of center pivot sprinklers. In this study of mobile drip irrigation with a center pivot machine, non-filtrated groundwater was used without any problems for both the emitters and water distribution.

Generally, the water supply for most pivots is surface water such as a stream or a pond. Where high capacity wells are available, water can be pumped directly from the well. The water is pumped from the supply to the pivot point through a buried supply line, i.e. usually a polyvinyl chloride (PVC) plastic pipe. On center pivot machines, water can be filtered as shown in Figure 4.40. For the future application of mobile drip irrigation with center pivot machines, a filtration system can easily be installed between the supply and the pivot point.

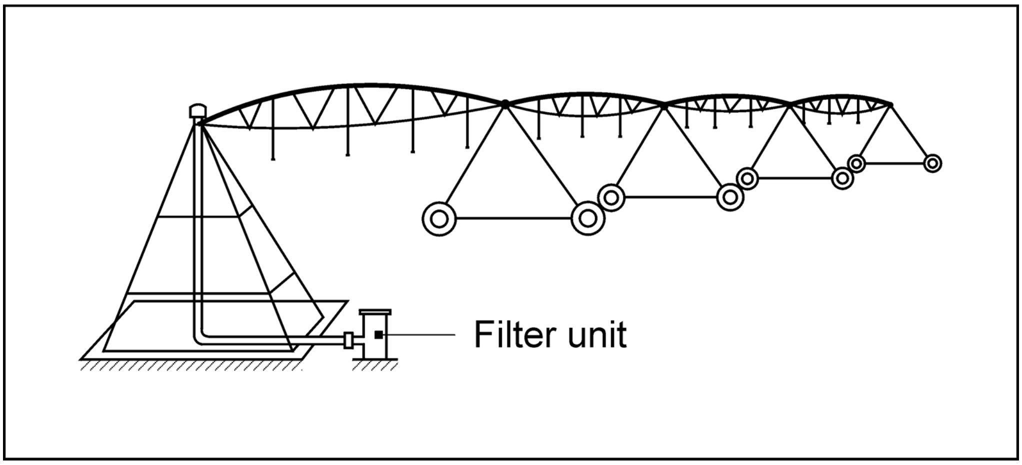


Figure 4.40: Possibility of water filtration on center pivot machines

4.3.3 Flow water adaptation

Pivots are best adapted to flat terrain, but units are also provide satisfactory results on slopes up to 15%. Sloping terrain may require towers to be located closer together so that the lateral line can more closely to follow the topography. Designing a center pivot for a particular field is rather routine since system length is normally determined by the radius of the field. On sloped fields, the pressure regulators are very important, in particular when mobile drip irrigation is employed. These regulators are used to achieve constant pressure at all drip tubes on the pivot and good water distribution on the surface of soil.

During mobile drip irrigation, the pressure regulators shown in Figure 4.41 must be used at all inlets of the drop tubes. This means that the pressure will be the same at all tubes. In this case, the emitter discharge will be constant and water distribution on the soil surface will be very good. Without pressure regulators, the pressure levels at all inlets of drip tubes will decrease when the distance from the pivot point grows. In this case, calculated water quantities at all tubes will be different from the actual quantities. Therefore the water quantities at different points will not be similarly distributed. The alternative would be the use of pressure compensating emitters like those described in Chapter (4.1). However, the discharge from these emitters was relatively small.

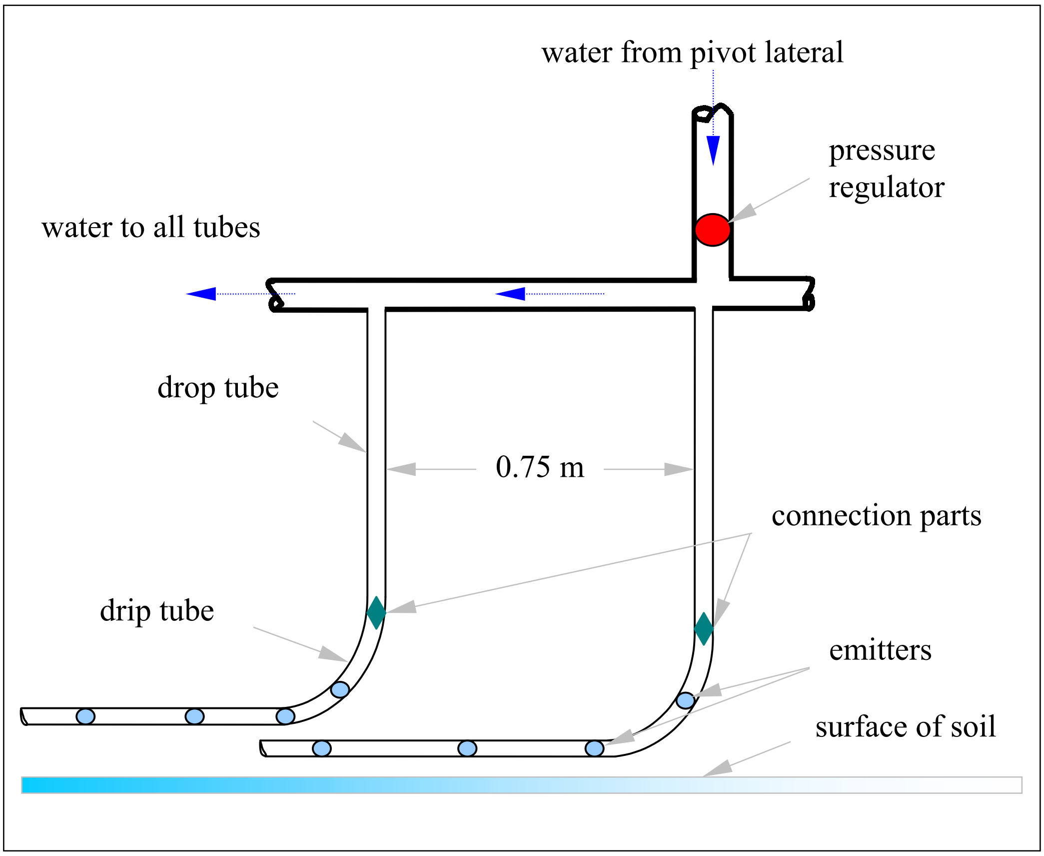


Figure 4.41: Schematic overview of mobile drip irrigation with a center pivot machine

The lateral line on most pivots will consist of several sizes of pipes, depending on system capacity. A system, equipped with pressure regulators or flow regulators at each outlet of the pivot, still has a uniform drip discharge. These pressure regulators are not installed at all drip tubes. Instead, they are fitted at the same place as the sprinklers. This means that the regulators are installed between the vertical aluminium tubes and the horizontal PE tube as shown in Figure 4.41. In this case, the flow water at all drip tubes can be simply adapted.

In the case of center pivot machines, the water quantities increased with distance from the pivot point as shown in Figure 4.42. Therefore, the number of emitters or the length of the drip tubes must increase as well. A water gauge can be simply installed at the supply inlet at the first tower. With the aid of this water gauge, the actual water quantities per irrigation cycle can be easily measured.

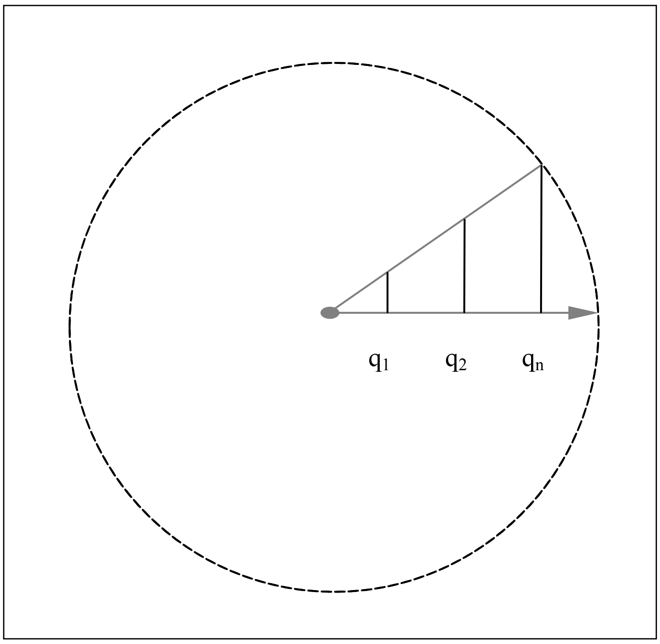


Figure 4.42: Schematic overview of water quantities on a lateral of a center pivot machine

4.3.4 Material requirements

For the design of MDI, everyone can use the traditional center pivot machines, which are available on the market. Some materials are required to modify the design of a center pivot machine with mobile drip irrigation. These materials include pressure regulators, horizontal PE tube, tubes without emitters (about 3 m) and tubes with emitters. The quantities or numbers of these materials are different from tower to tower. Some of them are fixed and do not differ from one tower to the next such as the length of the horizontal PE tube, the numbers of pressure regulators and the number of drop tubes. Others materials are different from tower to tower and vary depending on the water quantities at the drop tube inlets or the distance from the pivot point such as length of drip tubes and the number of emitters. The material requirements for the modification and design of the mobile drip irrigation with a center pivot machine operated at 100 kPa are indicated in Tables 4.9, 4.10, 4.11 and 4.12 at tower number one, tower number five, tower number nine and for all machines (9 towers), respectively. In agreement with the manufacturers of center pivot machines, the horizontal PE tube may be void in the future, but the outlets should all be made 1 m on the center pivot lateral.

Table 4.9: Material requirements for the design of mobile drip irrigation with center pivot irrigation machines, tower number 1

No.	**Tower number (1)** Material	Measurement of diameter	Length (m)	Number (piece)	**Total length of tubes (m)**
1	Reduce pieces	3/4″-1/2″		16	
2	Discharge control valve, Nelson, blue, low flow, 100 kPa	**IG3/4″**		16	
3	Duple nipple	3/4″		16	
4	PE bells	DN50 – IG3/4″		80	
5	Connecting screw	DN16 – AG3/4″		64	
6	PE tube as empty tube	DN16, PN4	about 3	64	**192**
7	Connection pieces from Plastro company	DN16		64	
8	Drip tubes Hydrogol 16/45 TA 15cm, 10 L/h	DN16	different	64	**46.5**
9	Plastro end fill pieces for drip tubes	DN16		64	
10	End fill pieces for horizontal PE tube	DN50		2	
11	PE-tube, outer diameter 50 mm	DN50, PN6	about 49	1	**49**
12	Metal pieces to brace PE tubes with towers	2 mm	3	16	48

Table 4.10: Material requirements for the design of mobile drip irrigation with center pivot irrigation machines, tower number 5

No.	**Tower number (5)** Material	Measurement of diameter	Length (m)	Number (piece)	**Total length of tubes (m)**
1	Reduce pieces	3/4″-1/2″		16	
2	Discharge control valve, Nelson, blue, low flow, 100 kPa	**IG3/4″**		16	
3	Duple nipple	3/4″		16	
4	PE bells	DN50 – IG3/4″		80	
5	Connecting screw	DN16 – AG3/4″		64	
6	PE tube as empty tube	DN16, PN4	about 3	64	**192**
7	Connection pieces from Plastro company	DN16		64	
8	Drip tubes Hydrogol 16/45 TA 15cm, 10 L/h	DN16	different	64	**381.15**
9	Plastro end fill pieces for drip tubes	DN16		64	
10	End fill pieces for horizontal PE tube	DN50		2	
11	PE-tube, outer diameter 50 mm	DN50, PN6	about 49	1	**49**
12	Metal pieces to brace PE tubes with towers	2 mm	3	16	48

Table 4.11: Material requirements for the design of mobile drip irrigation with center pivot irrigation machines, tower number 9

No.	**Tower number (9)** Material	Measurement of diameter	Length (m)	Number (piece)	**Total length of tubes (m)**
1	Reduce pieces	3/4″-1/2″		16	
2	Discharge control valve, Nelson, blue, low flow, 100 kPa	**IG3/4″**		16	
3	Duple nipple	3/4″		16	
4	PE bells	DN50 – IG3/4″		80	
5	Connecting screw	DN16 – AG3/4″		64	
6	PE tube as empty tube	DN16, PN4	about 3	64	**192**
7	Connection pieces from Plastro company	DN16		64	
8	Drip tubes Hydrogol 16/45 TA 15cm, 10 L/h	DN16	different	64	**724.80**
9	Plastro end fill pieces for drip tubes	DN16		64	
10	End fill pieces for horizontal PE tube	DN50		2	
11	PE-tube, outer diameter 50 mm	DN50, PN6	about 49	1	**49**
12	Metal pieces to brace PE tubes with towers	2 mm	3	16	48

Table 4.12: Material requirements for the design of mobile drip irrigation with center pivot irrigation machines (9 towers)

No.	**Pivot machine (9 towers)**	Measurement of diameter	Length (m)	Number (piece)	**Total length of tubes (m)**
	Material				
1	Reduce pieces	3/4″-1/2″		144	
2	Discharge control valve, Nelson, blue, low flow, 100 kPa	**IG3/4″**		144	
3	Duple nipple	3/4″		144	
4	PE bells	DN50 – IG3/4″		720	
5	Connecting screw	DN16 – AG3/4″		576	
6	PE tube as empty tube	DN16, PN4	about 3	576	**1728**
7	Connection pieces from Plastro company	DN16		576	
8	Drip tubes Hydrogol 16/45 TA 15cm, 10 L/h	DN16	different	576	**3435**
9	Plastro end fill pieces for drip tubes	DN16		576	
10	End fill pieces for horizontal PE tube	DN50		18	
11	PE-tube, outer diameter 50 mm	DN50, PN6	about 49	9	**441**
12	Metal pieces to brace PE tubes with towers	2 mm	3	144	432

5 TOTAL COST ANALYSIS

The economic side is considered an important factor not only in agricultural projects but in any project. The irrigation manager should be able to choose the proper irrigation system to keep costs to a minimum. The selection of an irrigation system cannot be done without considering the costs. The designer or manager will try to select the least costly system. The choice of irrigation system should involve both capital or fixed and operating or variable costs. Capital costs are easily identified sums of money which must be paid when installing a system. Operating costs are far less clear and spread over many years. The total costs are classified as capital and variable costs as illustrated in Mann et al. (1982), Sourell (1991) and FAO (1992).

There are several additional factors which affect irrigation system costs, which, however, are difficult to assess. Such factors are filtration and chlorination which are necessary to prevent clogging of low volume irrigation systems. Life expectancy of system components is unknown, and damage by field workers is a factor which must be considered. Depending upon system design, additional benefits can also result in terms of initial system and operating costs (Harrison and Smajstrla, 1982).

Johnson et al. (1987) developed a computer model to analyse the economics of center pivot irrigation systems at various soil intake rates. They concluded that the investment costs for all four sprinkler packages decreased as the system size increased. This decrease in cost reflects the economic effects which are dependent upon the size of the center pivot machine.

Persaud et al. (1988) calculated the yearly costs of a drip irrigation system as an alternative method of producing vegetable crops. They recommended that of the total initial cost of establishing an automatic drip irrigation system on a 4.36 ha farm 10.79% should be spent on pump house facilities; 3.1% on filter with accessories; 2.95% on chemigation facilities; 81.38% on field materials and 1.75% on installation. They also indicated that the cost of replacing the drip tubing is the most important cost in a drip irrigation system. The economic feasibility of the system will depend very much on this cost, among other production factors. They also mentioned that total annual costs can be reduced if the useful life of the drip tubing can be extended beyond 5 years.

In this study, an area of 57.55 ha was assumed for all irrigation systems. Cost estimates for system components were gathered from dealers and the farm managers in Germany based on the price of system installation in 2002. A manager must be able to calculate the cost of owning and operating a machine, as good irrigation system management requires knowledge of their costs and how they are related to irrigation system use.

5.1 The fixed costs

These are the costs of constructing the irrigation system to the point where it is ready for use. It may include pumps, pipes and field equipment. If the equipment is badly treated, it is obvious that its useful life will be considerably shortened. In this study, the fixed cost does not involve the costs of pumps. Fixed costs of an irrigation system are often called ownership costs. Irrigation system costs are one of the few costs that good management can minimise and learning how to accurately estimate irrigation system costs helps to cut costs. Fixed costs are those which depend on how long a system is owned rather than how much it is used, and include depreciation, interest and insurance. Depreciation is the major item in the cost of irrigation systems and farm machinery. There are many methods of estimating depreciation, in the calculations, the straight-line method was used. Annual depreciation (D) can be calculated as follows:

$$D = (P-S)/a \qquad (5.1)$$

where:
P = purchase or initial price, in €,
S = salvage value, in €, in this study, it is assumed to equal zero, and
a = life of system, in years.

Yearly fixed costs per hectare were calculated from the initial system costs using the capital recovery factor appropriate for the life of the system and the interest rate. Yearly insurance costs were assumed to be a percent of the initial capital costs of center pivot sprinkler, stationary drip irrigation and mobile drip irrigation systems. Interest on investment is the rate of interest which should reflect prevailing rates. In this study, the annual interest rate was 8%. Table 5.1 is a guideline to the useful life of equipment when it is properly used and maintained according to the manufacturer's recommendations. The capital requirements or the initial costs for used systems are indicated in Table 5.2.

Table 5.1: Useful life of irrigation system components according to FAO (1992)

Item	Years
Diesel-engined pump	10
Electrically-driven pump	10
Pipelines: • on the surface • buried	 4 – 7 10 – 20
Sprinkler and drip equipment	5 – 10
Center pivot	**12**
Drip pipes	**5**

5.2 The variable costs

The operating costs include the energy costs, repair, maintenance and labour. These costs are incurred regularly throughout the useful life of the system. Thus, a time period needs to be set over which the costs can be assessed. Usually the operation of a system is similar from one season or year to the next. Hence, a common approach is to consider the costs on the basis of one cropping season or over a full year as a suitable period.

The energy demand was 0.36, 0.16 and 0.26 kWh/m³ for center pivot sprinkler, stationary drip irrigation and the mobile drip irrigation, respectively. The annual maintenance costs were calculated on the basis of 1.5, 2 and 2% of the initial cost of the center pivot sprinkler, stationary drip irrigation and mobile drip irrigation, respectively based upon experiences in the field. Installation cost calculation was based on estimates made by the Institute of Production Engineering and Farm Building Research, FAL, Germany. Hourly rates were assumed to be € 13 for field labour and € 13 for a tractor with a driver. The maintenance cost is difficult to determine and will vary greatly depending upon the type of system.

On the other hand, labour is needed to operate irrigation systems, including such jobs as pump operation and the day-to-day irrigation of plots. The water fee was € 0.005 /m³ for all irrigation systems used. All irrigation considerations, the basis, the technical data, operating and cost data which were employed to calculate the total costs of the irrigation systems used are indicated in Table 5.2. The worksheet in Appendix (D) enables the fixed costs, the variable costs and the total costs of many irrigation systems to be easily calculated.

This study indicated that the high cost of stationary drip irrigation systems caused by the annual replacement of system components can be substantially reduced by using the mobile drip irrigation system. The variable cost of a center pivot sprinkler was a function of the water and energy requirements during the season. Maintenance, labour and tractor costs can be lower in center pivot sprinklers than in other irrigation systems. On the other hand, the electricity and the water costs may be lower in stationary drip and mobile drip irrigation systems. The fixed cost, variable cost and the total costs were calculated for the stationary drip, the center pivot sprinkler and mobile drip irrigation as illustrated in Tables 5.3, 5.4 and Figure 5.1.

Table 5.2: Irrigation considerations: basis, technical data, operating and cost data used to calculate the total costs of three different irrigation systems

Item	Unit	**Center pivot sprinkler**	**Stationary drip irrigation**	**Mobile drip irrigation**
Irrigated area	ha	57.55	57.55	57.55
Water required	m³/ha per season	1000	800	800
No. of irrigations	per season	5	12.5	5
Water required	**m³/ha**	**200**	**64**	**160**
Irrigation depth	mm	20	6.4	16
Evaporation	mm	4	4	4
Input pressure • at the pump • at pivot point • at main • at pivot point	 bar kPa kPa kPa	 8.59 300 ------ ------	 3.82 ------ 200 ------	 6.20 ------ ------ 200
Energy requirement	**kWh/m³**	**0.36**	**0.16**	**0.26**
Working time	h/ha per irrigation	0.10	0.174	0.15
Total working time	h/ha/season	**0.5**	**9.975**	**0.75**
Capital requirement (Initial cost)	**€**	**60,572**	**132,200**	56,225 # 15,497 * **71,722** (Total)
Interest rate	%	8	8	8
Useful life	a	12	5	12 # 5 *
Maintenance	% from initial	1.5	1.5	2
Electricity price	€/kWh	0.064	0.064	0.064
Water fee	€/m³	0.005	0.005	0.005
Labour cost	€/h	13	13	13
Tractor cost	€/h	13	13	13
No. of crops	per season	1 or 2	1 or 2	1 or 2

= Pivot machine without sprinklers
* = Only drip tubes, emitters and regulators

Table 5.3: Total yearly costs of different irrigation systems, (one season)

Item	Irrigation system		
	Stationary drip irrigation	Center pivot sprinkler	Mobile drip irrigation
Fixed costs, €/a			
-Depreciation	26440	5047.67	7784.81
-Interest	5288	2422.88	2868.88
-Insurance	2644	908.58	1434.44
-Total fixed costs	34372	8379.58	12088.48
Variable costs, €/a			
-Electricity	676.51	1702.43	1030.28
-Maintenance	1983	908.58	1434.44
-Labour	7462.80	374.08	561.11
-Tractor	7462.80	374.08	561.11
-Water	230.20	287.75	230.20
-Total variable costs	17815.31	3646.91	3817.14

Table 5.4: Total yearly costs of different irrigation systems, (two seasons)

Item	Irrigation system		
	Stationary drip irrigation	Center pivot sprinkler	Mobile drip irrigation
Fixed costs, €/a			
-Depreciation	26440	5047.67	7784.82
-Interest	5288	2422.88	2868.88
-Insurance	2644	908.58	1434.44
-Total fixed costs	34372	8379.58	12088.14
Variable costs, €/a			
-Electricity	1242.54	3294.37	1950.06
-Maintenance	1983	908.58	1434.44
-Labour	14925.59	748.15	1122.23
-Tractor	14925.59	748.15	1122.23
-Water	460.40	575.50	460.40
-Total variable costs	33537.12	6274.75	6089.35

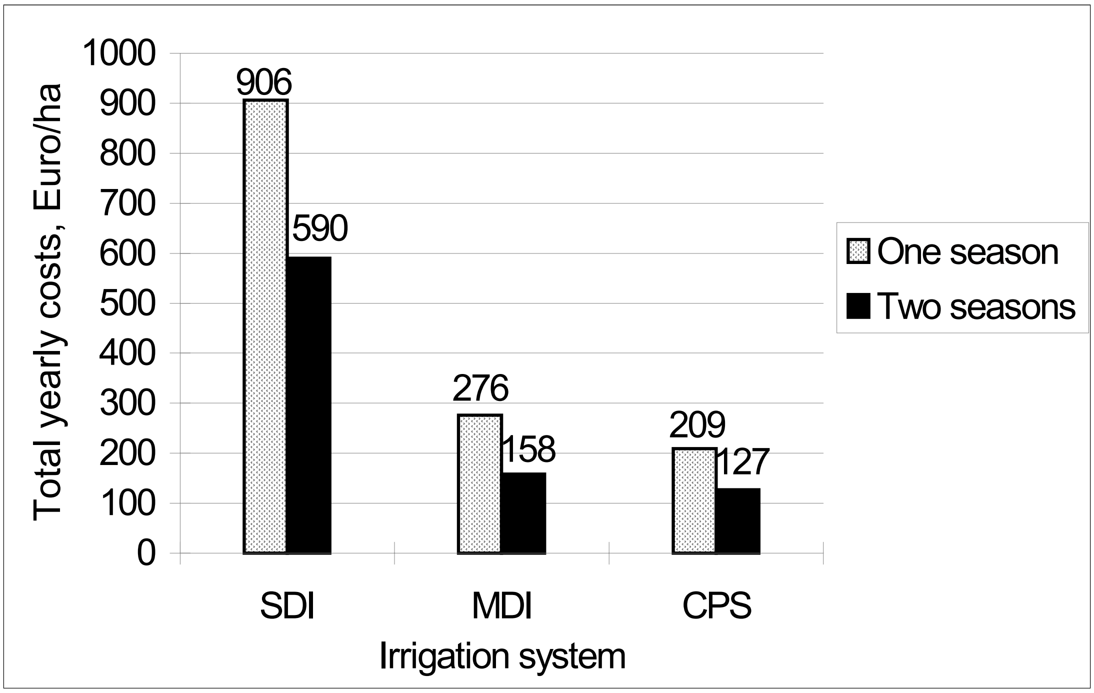


Figure 5.1: Total yearly costs of stationary drip irrigation (SDI), mobile drip irrigation (MDI) and a center pivot sprinkler (CPS)

The total costs of stationary drip irrigation were very high and they were very low in the case of the center pivot sprinkler. In the case of mobile drip irrigation, however, the total costs were nearly the same as the total costs caused by the center pivot sprinkler machine. In this economic evaluation of the different irrigation systems, the yield of the crop was not included. To achieve a complete economic analysis, the total yield from the area under each system should be included. However, this was impossible in this study.

In the case of stationary drip irrigation, the initial price comprises all components including the filtration system, whereas the expenses for the filtration system on a mobile irrigator were not included. Thus, the future use of filtration systems on mobile drip irrigators may increase the total costs of mobile drip irrigation. This comparison between irrigation systems shows that water and energy can be saved by using the MDI. Figure 5.2 illustrates the possibility of saving water and energy as well as the advantages of the mobile drip irrigation system.

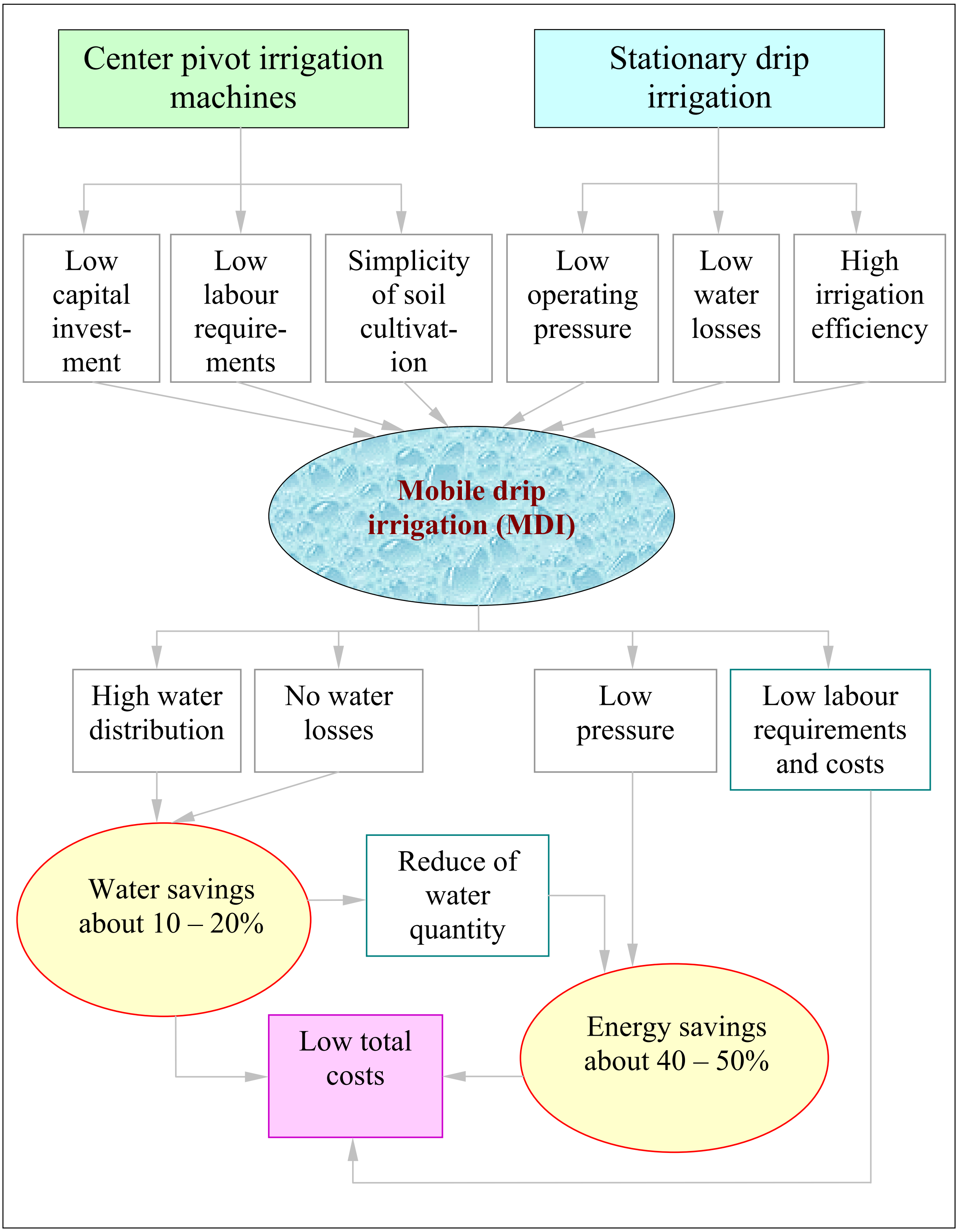


Figure 5.2: Water and energy savings and the advantages of the mobile drip irrigation system

5.3 Conclusions

The design of irrigation systems requires a complete study of each case to guarantee the most efficient use of water and energy. The of the type of irrigation system should depend on the soil properties, the topography, the crop to be grown, and the source and quality of water supply as well as initial costs, labour requirements and operating costs.

Mobile drip irrigation with a pivot machine can reduce water losses and save energy. The time requirements under both the mobile drip and the center pivot was lower than the time requirements under stationary drip irrigation. Total costs were very high in the case of stationary drip irrigation, but they were low in the case of the center pivot sprinkler. At the same time, the total costs were low in the case of mobile drip irrigation versus the stationary drip, because the capital requirements were very high in the case of stationary drip irrigation.

6 GENERAL DISCUSSION

The way to mobile drip irrigation consists of four stages. First, laboratory experiments to choose the better type of emitters and to achieve good water distribution. Second, calculation of both water quantities and the length of the drip tubes at all pivot points. Third, field experiments to study both water distribution in the soil and to measure the friction forces between the tubes and the surface. Fourth, a total cost comparison between mobile drip irrigation, stationary drip irrigation and the traditional center pivot machine.

This study illustrated that mobile drip irrigation with center pivot irrigation machines is a very appropriate solution under German conditions. The data and the approach of this study were applied in a pilot project in Brandenburg, Germany. In this project, three pivots were chosen, and one tower was selected from each pivot. The crops grown were two types of potatoes and sugar beet. The water quantities were reduced by 10 – 20% in the case of potatoes. No reduction was achieved for sugar beet under both mobile drip irrigation and the traditional center pivot with sprinklers. The yield was compared under both the MDI and the center pivot sprinkler. The yield under the MDI was higher than the yield under the center pivot sprinkler.

For the use of this system under Egyptian conditions, different crops should be chosen. Then this system can be applied, beginning with one or two towers. When this system provides good results, it can be used with more towers. Water filtration in this system is very important to avoid or reduce the risk of emitter clogging. In addition, runoff and the slope of the soil surface must be measured and adjusted if mobile drip irrigation is employed. In this study, the irrigation systems were evaluated and compared based on their work and economic characteristics, ecological influence, energy demand and cost analysis.

6.1 Work-Economic characteristics

The benefits and problems of any irrigation system must be investigated. Stationary drip irrigation is the frequent, slow application of water to the soil which, in turn, minimises percolation losses. In addition, drip irrigation maintains a soil moisture condition that keeps most of the soil well aerated (Goldberg et al., 1976). Today, the center pivot sprinkler machines are famous in the world. The farmer can use these machines to irrigate large-scale farms. The advantages of these machines are moderate capital requirement and the small work time requirement in comparison with the stationary drip irrigation.

Under the stationary drip irrigation system, the design of the irrigation system for the irrigated area (57.55 ha) is similar to the design shown in Figure 6.1. The total length of the lateral is about 300 m and the total length of the manifold is about 1918 m. Stationary drip irrigation systems are generally of the solid-set type. Manifolds and laterals are stationary, much the same as with sprinkler irrigation systems in which flow rate sprinklers (mini-sprinklers) are used to apply the water. The difference between drip and sprinkler irrigation mainly lies in the values of the various design variables.

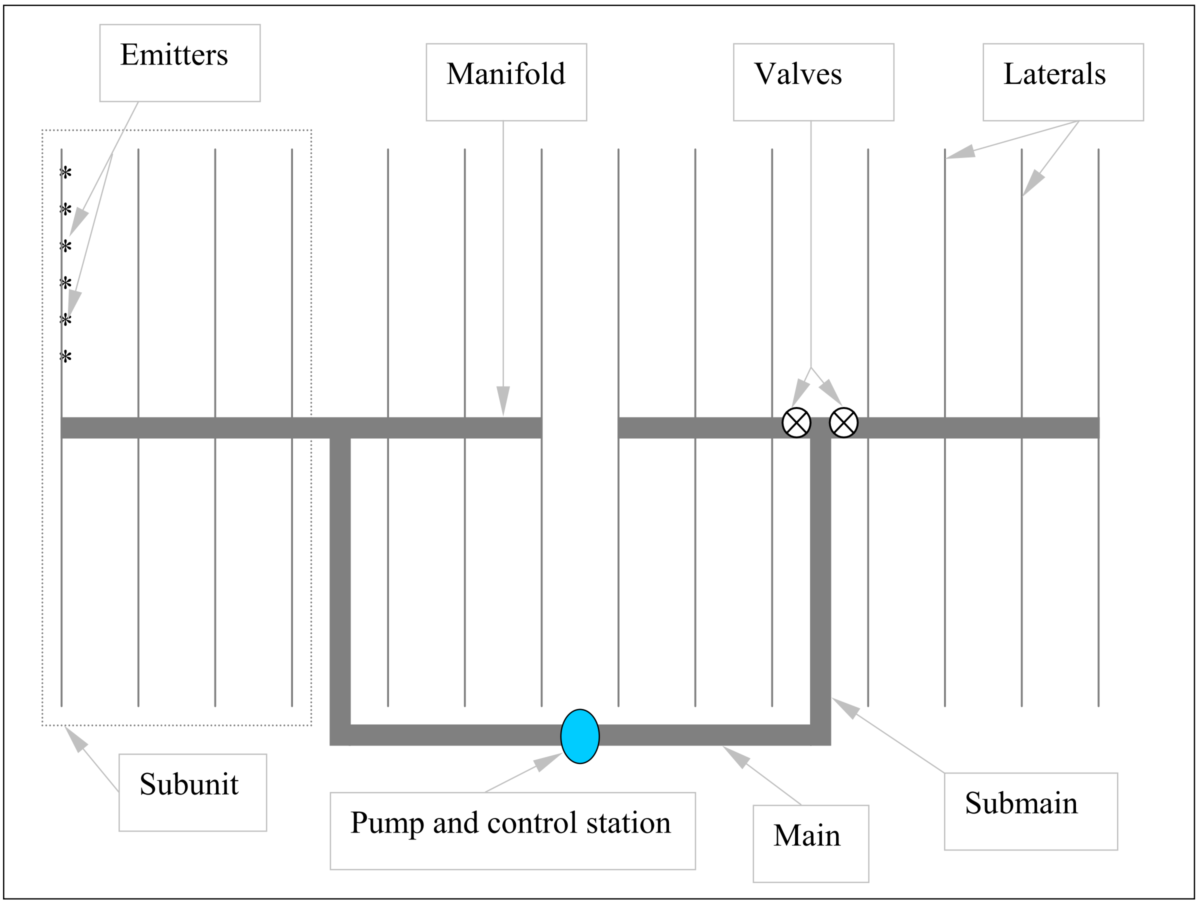


Figure 6.1: Basic configuration of the stationary drip irrigation system

For a full economic analysis of a sprinkler system, two main factors should be considered. First, the returns of the crop yields which result from the particular water distribution uniformity achieved in the irrigated field. Second, the costs of equipment, labour, water and energy resulting from the selected operating pressure head and sprinkler spacings.

6.2 Ecological and energy demand evaluation

Stationary drip irrigation consists of many components. The system may include water pumps, filters, manometers, valves, automatic timers, mainlines, submain lines, laterals, emitters and other accessory parts. Through static pressure or by a pump, the water is conveyed from the supply to the emitters through mainlines, the submain and laterals. The performance of stationary drip irrigation systems depends on many factors such as emitters, valves, pumps, filters, pipes, water and weather conditions, soil topography and management processes. The emitters must supply enough water to the plant root zone to meet the plant-water requirements. In the same manner, all components of design of a drip system must successfully work under field conditions.

The 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 application. The energy demand for all irrigation systems can be estimated based upon water use and the operating parameters of the irrigation system. The energy cost is the cost of providing fuel for the operation of the irrigation system. If diesel is the main fuel used, then the cost per litre can be determined from the market. Electricity, if available, will be costed at each unit of energy consumed (kWh). The energy cost is calculated from the seasonal energy demand using the method described in FAO (1992) as follows:

$$\text{Seasonal energy demand (kWh)} = \frac{\text{volume of water (m}^3\text{) x head (m)}}{\text{367 x pump efficiency}} \qquad (6.1)$$

Irrigation energy demands may be reduced by a) improving the pumping plant efficiencies; b) improving irrigation efficiency so that less water is required and c) lowering the pressure head of the irrigation system (Avlani and Chancellor, 1977). Water and energy requirements can be reduced by using both stationary drip and mobile drip irrigation systems rather than center pivot sprinkler machines as illustrated in Table 6.1.

Table 6.1: Water and energy demands of different irrigation systems

Irrigation system	Water demand, $m^3/(ha*a)$	Energy demand, kWh/(ha*a)
Stationary drip irrigation **(SDI)**	**800**	**128**
Center pivot sprinkler **(CPS)**	**1000**	**360**
Mobile drip irrigation **(MDI)**	**800**	**208**

However, runoff is possible under the MDI and the filtration of water is very important. The manager must consider that the runoff problem is not only caused by the design of the system but that it also occurs for other reasons, such as soil slope, soil infiltration rate and soil cultivation. The runoff problem under mobile drip irrigation can be reduced and avoided in many ways such as the application of 50 kPa instead of 100 kPa, enhancing the soil infiltration rate by improving soil cultivation. Additionally, the IAR value must be equal or smaller than the soil infiltration rate.

Generally, mobile drip irrigation with center pivot irrigation machines is possible and has many advantages such as high water distribution, no water losses due to wind drift and evaporation, energy savings of about (40 – 50%), water savings of about (10 – 20%) as compared with center pivot sprinklers, suitability for many crops, simplicity of use and soil operations, suitability for areas from 40 to 60 ha, possibility of chemigation and its relatively low total costs.

6.3 Total cost evaluation

The results of this study indicated that the total costs of mobile drip irrigation were lower than the total costs of stationary drip irrigation. At the same time, the total costs of MDI were relatively higher than the total costs of a center pivot sprinkler. In this case the cost was evaluated under German conditions. Therefore a new cost evaluation must be made under Egyptian market conditions. Then the total costs comparison between these systems may be different. Furthermore, the cost of a filtration system must be added to the total costs of mobile drip irrigation. Therefore this difference in the total costs must be known under Egyptian conditions.

However, the variable costs under Egyptian conditions may be lower than the variable costs under German conditions, whereas the cost of labour, tractor expenses, the cost of maintenance and the cost of water under Egyptian conditions are very different from the German conditions. At the same time, the fixed costs under Egyptian conditions may also be lower than the fixed costs under German conditions. Due to the interest rate, insurance and taxes are very different. Therefore the total costs under Egyptian conditions must be calculated for the MDI and the other systems.

6.4 Estimation of the new irrigation technique for Egyptian irrigation agriculture

Under a center pivot with sprinklers, the water is distributed on the entire soil surface through the sprinklers. In this case, evaporation will be higher than evaporation under the other systems (Addink et al., 1980). In Egypt, the center pivot sprinkler machines are used only in newly reclaimed areas. The weather in these areas is very hot. Therefore, the water losses due to evaporation are high if center pivot sprinklers are used. Under these conditions, additional water losses due to wind drift may occur. Mobile drip irrigation can be employed in these areas. However, the crop water requirements under Egyptian conditions and the length of the drip required need to be calculated. This length depends upon the water quantities at all outlets of the center pivot lateral and the emitter discharge rate. The distance of 0.75 m between the drip tubes is suitable for different crops, and the horizontal (PE) tube is available in the market. On the other hand, different types of emitters must be evaluated, and data for soil, crops, weather and the machine must be collected and calculated to design and install mobile drip irrigation with center pivot irrigation machines.

Many parameters will be used to evaluate the performance of emitters in the laboratory. At the same time, three or more towers from a center pivot machine will be chosen. The center pivot sprinklers will be replaced by the MDI parts. Soil samples must be taken from many places to measure the soil water content. Many advantages of this system can be exploited under the conditions of Egyptian irrigation agriculture. This system combines the advantages of both stationary drip irrigation and center pivot machines. Stationary drip irrigation has many advantages such as low soil water tension and the application of fertilisers through the drip system at frequent intervals, which helps increase yields. Moreover, diseases due to the wetting of the foliage during irrigation are reduced. The center pivot sprinkler provides many advantages such as low capital requirements, simplicity of use and ease of soil cultivation. The better irrigation system must apply water without causing physical damage to the crop.

7 SUMMARY AND CONCLUSIONS

In arid and semi-arid regions, center pivot systems experience a greater amount of evaporation than in other climates. Therefore improving irrigation efficiency is very important. Replacing the sprinklers on a center pivot machine by using polyethylene “PE” tubes with emitters to convey irrigation water directly to the soil surface converts a traditional center pivot to a mobile drip. In stationary drip irrigation, closed plastic tubes with emitters are used to deliver irrigation water to the plants using low pressure. No water losses due to wind drift and spray evaporation occur like in sprinkler systems such as center pivot machines. Climatic conditions also have a significant effect on the irrigation efficiency of sprinkler system. High wind conditions cause the distribution uniformity to be lowered considerably.

The idea of mobile drip irrigation is a combination of the advantages of stationary drip irrigation and center pivot machines. The advantages of the stationary drip irrigation are its low operating pressure, low water losses and high irrigation efficiency. The advantages of the center pivot machine are its low capital requirements and low labour requirements. In addition, soil cultivation under center pivot machines is easy. The tubes are connected to the lateral of the center pivot machine. The operating pressure of the drip tubes can be much lower than that of sprinkler systems. The operating pressure at the inlet of a traditional center pivot with sprinklers ranges from 400 to 500 kPa as compared with 175 to 225 kPa at the inlet of the pivot machine with MDI. Thus, pressure reduction in mobile drip irrigation enables energy to be conserved.

Several articles describe modifications of linear or center pivot design whose goal is the reduction of system pressure and evaporation losses. Many of these systems were designed for row crops. In some cases discussed in these publications, holes in pipes, similar length of hoses with different types of emitters and similar length of hoses with one type of emitters were used on linear and center pivot machines. In these cases, irrigation intensity was very high. At the same time, classic dripping irrigation materials for a center pivot were never used. Therefore the application of the MDI with center pivot machines will be important.

The objectives of this study were to:

1. develop and evaluate mobile drip irrigation with a center pivot machine,
2. save both water and energy by using the MDI system, and
3. compare the total costs of stationary drip, mobile drip and traditional center pivots with sprinklers.

To achieve these objectives, the study was accomplished in four stages. First, laboratory experiments to choose the better type of emitters to be connected to the center pivot machine. Second, calculation of both water quantities and the length of the drip tubes at all outlets of pivot. Third, field experiments for the measurement of both the soil water content and the friction forces between the tubes and the plant-covered soil. Fourth, preparation of a cost analysis for the stationary drip, mobile drip and traditional center pivot with sprinklers.

The laboratory experiments

Five different types of commercial In/On-line emitters were tested in the laboratory. These emitters were In-line 168, Hydrogol, Katif (two types) and Matic. All tests were performed at six operating pressures (25, 50, 100, 150, 200 and 225 kPa). These pressures were chosen because they are within the manufacturers operating pressure range. The water temperature ranged from 22 to 24 °C. It was measured using a mercury thermometer with an accuracy of 1 °C. These emitters were selected because of their wide acceptance and availability. There are many parameters for emitter evaluation such as emitter discharge (q), the discharge coefficient of variation (CV) and emission uniformity (EU). The coefficient of variation is one of the significant parameters which influence the overall uniformity and efficiency of the system. Emission uniformity (EU) values of 94% or more are desirable, and in no case should the design's EU be below 90%.

The emitter discharge exponent (x) is a very important factor in hydraulic emitter performance. The hydraulic characteristics of all tested emitters were calculated with the aid of regression analysis. The emitter discharge exponent values for On-line emitters were very small in both the negative and positive range. Small negative values suggested that discharge gradually decreased as pressure was increased. In the case of In-line emitters, however, the emitter exponent values were higher than 0.5. This means that the flow type is turbulent and, therefore classified as non-pressure compensating (NPC). Correlation coefficients (r) are also reported for each emitter type. Values of (r) very close to one indicate that pressure and discharge highly correlate. Positive values of (r) mean that the discharge will increase as pressure is increased. Negative values mean that the discharge is reduced as pressure is increased.

The results of this stage indicated that the discharge of On-line emitters (Katif and Matic) was the same at all pressure levels. In the case of In-line emitters (In-line 168 and Hydrogol), however, the discharge exhibited a linear increase. In addition, the discharge coefficient of variation values for In-line emitters followed a normal distribution at each operating pressure (about 5%). In the case of On-line emitters, however, it was distributed normally only for Katif emitters. In the Matic type, the discharge coefficient of variation was relatively high (12.5%). The manufacturer's coefficient of variation should be ≤ 15% to achieve reasonable uniformity of water application. The results showed that an increasing value of the discharge coefficient of variation has the effect of decreasing emission uniformity for all tested emitters. The average of emission uniformity was ≥ 95% in the range of pressure from 25 to 225 kPa for all emitter types except for Matic. In the case of Matic emitters, emission uniformity was about 80% at the same range of pressure.

Mobile drip irrigation needs emitters that have high discharge, high emission uniformity, a low coefficient of variation, low distance between them and which are easy to install. High discharge is needed to reduce both the length of drip tubes and the number of emitters. High emission uniformity and the lowest coefficient of variation enhance irrigation water distribution on the soil surface. Based on the laboratory experiments, Hydrogol emitters were chosen for installation with a center pivot machine to continue the field experiments. Hydrogol emitters were chosen because they have many advantages such as a high rate of discharge (about 10 L/h at 100 kPa), small distance between the emitters (0.15 m). In other types, distance was 0.20 m or 0.25 m. However, the advantages of these systems were high emission uniformity (over 95%), a low coefficient of variation (lower than 5%) and easy installation.

Calculation of drip tube length

In the center pivot machine, the water quantities at the pivot outlets are increased when the distance from pivot point grows. Water quantities at all pivot outlets were calculated using Chu´s and Moe´s (1972) equations and the pivot flow chart from the companies Nelson (2001) and Valmont (2001). Irrigation depth was 20 mm and the irrigation time was 48 h. The actual emitter discharge was measured and calculated based on the laboratory experiments. The emitter discharges were about 10 L/h and 7 L/h at 100 kPa and 50 kPa, respectively. The length of the drip tubes at any outlets on the pivot lateral can be simply calculated by dividing water quantity at any point on the emitter discharge. Normally, the length of the drip tube at the first tower is smaller than the length of the drip tube at the last tower. The length of the drip tube at an operating pressure of 50 kPa was about 1 m at the first and 16 m at the last tower.

The field experiments

Three towers of the pivot machine were chosen to study water distribution under it. These towers were tower number 1, number 5, and number 9. The better type of emitters was chosen and installed at the center of these towers. Drop tubes (without emitters) were installed between the horizontal PE tube and the drip tubes (with emitter). The length of one drop tube was about 3 m at all outlets and the distance between drip tubes was 0.75 m. The soil water contents between drip tubes under the mobile drip with a center pivot machine before and after irrigation were calculated for the soil samples. The results indicated that soil water distribution in the top 0.4 m below the soil surface under loamy sand soil was very similar for mobile drip irrigation at two lower levels of pressure.

The soil water content was measured and calculated before and after irrigation in the area between the drip tubes. The results showed that soil water distribution was very good under mobile drip irrigation at all towers. Two levels of pressure (50 and 100 kPa) can be used at the inlet of the drop tubes without any significant difference (3 – 5 mm) between the applied and the measured soil water content. This means that the soil water content under the MDI at 50 kPa and 100 kPa is very good and the distance between the drip tubes is very suitable for use. However, when the soil water content in the area between two drip tubes is nearly the same, mobile drip irrigation can be used to irrigate both row and grain crops.

Distribution pattern efficiency indicates the relationship between the water quantities applied and the infiltrated water in the soil. The average value of distribution pattern efficiency was the same under the first, fifth and ninth towers. Distribution pattern efficiency ranged from 85% to 100%. In all cases, distribution pattern efficiency at 50 kPa was higher than at 100 kPa. This means that water runoff may occur at 100 kPa because water moves more rapidly in the horizontal direction than in the vertical direction. The draft force was measured and the friction forces were calculated only at the last tower (tower No. 9), because the length of the drip tubes under this tower was greater than the length of the tube at any other position. The friction forces at 50 kPa were higher than the friction forces at 100 kPa, because the length of tube at 50 kPa was greater than at 100 kPa. The maximum values of friction force at the last tube under tower number 9 were 183 N and 128 N at 50 kPa and 100 kPa, respectively.

The cost analysis

The economic side is considered an important factor in the evaluation of irrigation systems and any other project. The choice of irrigation system should involve both fixed and variable costs. Fixed costs are easily identified sums which must be paid when installing a system. Variable costs are far less clear and spread over many years. The costs of irrigation systems consist of depreciation, interest, operation, maintenance and installation.

The results indicated that the total costs were € 906 /ha∗a, € 209 /ha∗a and € 276 /ha∗a for stationary drip irrigation, traditional center pivot sprinklers and mobile drip irrigation, respectively. These costs were calculated for one season per year. However, they were € 590 /ha∗a, € 127 /ha∗a and € 158 /ha∗a for stationary drip irrigation, traditional center pivot sprinklers and mobile drip irrigation, respectively. These costs were calculated for two seasons per year. The results indicated that the total costs of stationary drip irrigation (SDI) were very high and that they were low for the center pivot sprinkler (CPS). In the case of mobile drip irrigation (MDI), however, the total costs were close to the total costs of a center pivot sprinkler machine. To achieve a complete economic analysis, the total yield of the area under each system should be included. In this study, however, this was impossible.

For the same area and at 50 kPa and 100 kPa, the mobile drip irrigation system needs about 1.35 to 1.74%, respectively of the polyethylene tubes that would be needed for a stationary drip irrigation system. On the other hand, the center pivot sprinkler machine can be adapted to provide the mobility and the water supply for such a concept. Mobile drip irrigation with a center pivot irrigation machine can save about 10 – 20% water and about 40 – 50% energy.

8 ZUSAMMENFASSUNG

Die Verdunstungsraten sind in ariden und semi ariden Gebieten erheblich höher als in den humiden Klimazonen. Daher ist es wichtig die vorhandene Beregnungs- und Bewässerungstechnik in Bezug auf Wassereinsparung zu verbessern. Für den wasser- und energiesparenden Einsatz bietet sich die stationäre Tropfbewässerung an. Mit der Tropfbewässerung kann das Wasser den Pflanzen mit geringem Energieaufwand gezielt zugeführt werden. Verluste durch Windabdrift und Verdunstung des Bewässerungswassers sind nahezu ausgeschlossen.

Den Vorteilen stehen allerdings auch die Nachteile des sehr hohen Kapital- und Arbeitszeitbedarfes entgegen. Auf Grund der Nachteile, besonders auf großen Einsatzflächen, entstand die Idee, die stationäre Tropfbewässerung mit einem beweglichen Beregnungsverfahren, das auf Großflächen eingesetzt werden kann, zu kombinieren. Der geringe flächenbezogene Kapitalbedarf und der sehr niedrige Arbeitszeitbedarf der Kreisberegnungsmaschine führten dazu, diese Technik als Träger- und Wasserzuführungs-system für die Tropfrohre zu verwenden.

Das neu entwickelte Bewässerungsverfahren „die mobile Tropfbewässerung“ verbindet die genannten Vorteile der Kreisberegnung und die der Tropfbewässerung nahezu ideal.

Das Ziel der Arbeit ist:

1. Entwicklung und Bewertung der mobilen Tropfbewässerung,
2. Einsparung von Wasser und Energie gegenüber den herkömmlichen Beregnungsverfahren, und
3. Vergleich der Gesamtkosten zwischen der stationären Tropfbewässerung, der Kreisberegnungsmaschine mit Düsen und der mobilen Tropfbewässerung.

Um die gestellten Ziele zu erreichen, wurde die Arbeit in vier Teile gegliedert:

A. Laborversuche zur Auswahl der geeigneten Tropfer.
B. Berechnung der Durchflüsse der einzelnen Tropfrohre auf der gesamten Länge der Kreisberegnungsmaschine, Berechnung der Tropfrohrlänge und Berechnung des Tropfrohr-abstandes.
C. Feldversuche wurden auf dem Versuchsfeld der FAL durchgeführt. Messung der Wasserverteilung im Boden und des Zugkraftbedarfes der Tropfrohre bei der Bewässerung.
D. Kapitalbedarfs- und Verfahrenskostenberechnung.

Laborversuche

Für die Laborversuche wurden aus der Literatur und den Herstellerprospekten fünf verschiedene Tropfer ausgewählt. Dieses sind die In-line Tropfer: In-line 168, Hydrogol und die On-line Tropfer: Matic, Katif 4 L/h und Katif 8 L/h.

Die Volumendurchflußversuche wurden auf dem Laborprüfstand mit 25, 50, 100, 150, 200 und 225 kPa durchgeführt. Die Wassertemperatur betrug 22 bis 24° C. Ausgewertet wurden der Volumendurchfluß (q), der Variationskoeffizient (CV) und die Gleichförmigkeit (EU). Um eine gute Gleichförmigkeit der Wasserverteilung zu erreichen, muß der EU-Wert bei 94% oder höher liegen. Die hydraulischen Kenndaten aller untersuchten Tropfer wurden einer Regressionsanalyse unterzogen. Ein wichtiger Faktor für die hydraulische Tropferleistung ist der Tropfer Exponent (x).

Die Tropfer für den Einsatz bei der mobilen Tropfbewässerung müssen folgende Voraussetzungen erfüllen: eine hohe Gleichförmigkeit, einen niedrigen Variationskoeffizient, einen geringen Tropferabstand auf dem Tropfrohr und eine einfache Handhabung bei der Montage an der Kreisberegnungsmaschine. Ein hoher Volumendurchfluß der Tropfer ist erforderlich, damit die Tropfrohrlänge nicht zu lang wird und sich dadurch der Zugkraftbedarf nicht unnötig erhöht. Die hohe Gleichförmigkeit und der niedrige Variationskoeffizient des Durchflusses geben Auskunft über die Gleichmäßigkeit der Wasserverteilung.

Von den untersuchten Tropfern erfüllt der Hydrogol Tropfer, mit einem Volumendurchfluß von 10 L/h, einer hohen Gleichförmigkeit von über 95% und einem Variationskoeffizient von weniger als 5% die geforderten Bedingungen am besten, so dass er für die weiteren Feldversuche ausgewählt wurde. Auch der Abstand der Tropfer auf dem Tropfrohr ist mit 0,15 m um 0,05 bis 0,10 m geringer als von vergleichbaren Tropfrohren anderer Hersteller. Die Montage der Tropfrohre ist relativ einfach, so dass sie auch von Hilfskräften durchgeführt werden kann. Wenn die Wassermenge an der Kreisberegnungsmaschine und die Durchflüsse der Tropfer bekannt sind, kann die Tropfrohrlänge berechnet werden.

Feldversuche

Im Feldversuch wurden die ausgewählten Tropfrohre an drei Traversen einer Kreisberegnungsmaschine montiert. Die Beregnungshöhe beim Versuch betrug 20 mm. Als Grundlage diente hierbei die Umdrehungszeit der Maschine von 48 h, eine Verdunstung von ca. 10 mm/Tag in Ägypten und die Gesamtlänge der Maschine von 428 m (entspricht einer Beregnungsfläche von 57,55 ha).

Der Montageabstand der Tropfrohre betrug 0,75 m. Die Länge der Tropfrohre wurde mit Hilfe des Volumendurchflusses der Tropfer für jede Position berechnet, so dass an der ersten Traverse die Tropfrohrlänge mindestens 1 m und an der letzten Traverse 16 m bei 50 kPa betrug. Damit das Wasser der Tropfrohre direkt auf dem Boden verteilt wird, wurde vor jedem Tropfrohr ein 3,0 m langes Leerrohr (ohne Tropfer) montiert. Der Versuch wurde auf den Versuchsflächen der FAL durchgeführt. Die Kenndaten der Versuchsfläche waren, Bewuchs: Gras, Bodenart: lS 3D 46/49, Bodenoberflächengefälle: 1 – 2%.

Für die Versuche wurde der Druck am Tropfrohranfang von 50 kPa und 100 kPa vorgegeben. Um die gleiche, berechnete Wassermenge auszubringen, sind die Tropfrohre bei 50 kPa Druck länger und bei 100 kPa Druck kürzer. Der Bodenwassergehalt wurde mit Hilfe der gravimetrischen Methode direkt vor und 24 h nach der Bewässerung gemessen. Um die Querverteilung des Wasser genau zu bestimmen, wurden nebeneinander 6 Bohrstockproben im

Abstand von 0,15 m, in vier Tiefen bis 0,40 m entnommen. Für eine gute statistische Absicherung wurde jede Beprobung 4 fach wiederholt.

Trotz des unterschiedlichen Durchflusses, bedingt durch den Eingangsdruck, konnten bei der Querverteilung im Boden keine großen Unterschiede beim Bodenwassergehalt festgestellt werden. Die gemessene Bodenwassermenge im Abstand von 0,30 und 0,45 m vom Tropfrohr war nur um 3 bzw. 5 mm geringer als die verteilte Wassermenge. Diese Ergebnisse bedeuten, dass bei einem Tropfrohrabstand von 0,75 m mit der mobilen Tropfbewässerung das Wasser sowohl bei 50 kPa als auch bei 100 kPa sehr gut quer verteilt werden kann.

Das Verhältnis zwischen der Bewässerungshöhe und dem tatsächlich den Pflanzen im Boden zur Verfügung stehenden Wasser bezeichnet man als Wasserverteilungseffizient. Der Durchschnittswert unter den drei Traversen war gleich und lag zwischen 85% und 100%. Beim Eingangsdruck von 50 kPa lag der Wert höher als bei einem Eingangsdruck von 100 kPa. Bei größeren Geländeneigungen ist es möglich, dass bei dem Eingangsdruck von 100 kPa ein Abfluß entsteht.

Die Reibungskraft wurde nur an der letzten Traverse (längste Tropfrohre) gemessen. Durch das längere Tropfrohr bei der 50 kPa Variante betrug die Reibungskraft 183 N. Das kürzere Tropfrohr bei der 100 kPa Variante benötigte dagegen nur 128 N.

Kapitalbedarf- und Verfahrenskostenvergleich

Ein wichtiger Faktor für den Verfahrensvergleich ist die ökonomische Bewertung der Bewässerungsverfahren. Dieser Vergleich gibt vielfach den Ausschlag darüber, in welchem Projekt welches Verfahren eingesetzt werden kann.

In dieser Arbeit wurden die drei Verfahren Kreisberegnung, stationäre Tropf-bewässerung und die mobile Tropfbewässerung gegenübergestellt. Der Kapitalbedarf wurde nach Angaben der Hersteller ermittelt und die Verfahrenskosten berechnet.

Das teuerste Verfahren bei einer Vegetationsperiode im Jahr war mit Gesamtkosten von 906 €/ha∗a die stationäre Tropfbewässerung. Die geringsten Gesamtkosten verursacht die Kreisberegnung mit 209 €/ha∗a. Zwischen den beiden Extremen liegt die mobile Tropfbewässerung mit 276 €/ha∗a. Die Verfahrenskosten können erheblich gesenkt werden, wenn zwei Vegetationsperioden im Jahr wie z.B. in Ägypten möglich sind. Die Gesamtkosten der stationären Tropfbewässerung betragen dann je Jahr 590 €/ha∗a, die der Kreisberegnung 127 €/ha∗a und die der mobilen Tropfbewässerung 158 €/ha∗a.

Bewertung der mobilen Tropfbewässerung

Dem Nachteil der höheren Verfahrenskosten der mobilen Tropfbewässerung im Vergleich mit der Kreisberegnungsmaschine, stehen erhebliche Vorteile der mobilen Tropfbewässerung gegenüber. Gegenüber einer stationären Tropfbewässerung wird für die mobile Tropfbewässerung nur ein Rohrmaterialaufwand von ca. 1,6% benötigt.

So wird durch die Senkung des Betriebsdruckes am Tropfrohr auf 50 kPa gegenüber der Düsenwasserverteilung 40 – 50% Energie eingespart. Durch die gleichmäßige Wasserverteilung, der nahezu ausgeschlossenen Windbeeinflussung und der geringen Verdunstung bei der Bewässerung kann bei Ertragsstabilität 10 – 20% Wasser eingespart werden.

Die Vorteile der Wasser- und Energieeinsparung werden besonders in ariden und semiariden Gebieten dazu beitragen, dass das neue Bewässerungsverfahren in Zukunft zur Ressourcenschonung beitragen kann. Je nach Wasserbereitstellung ist an eine Filterung des Wassers zu denken. Die Wirksamkeit der Filterung muß der einer stationären Tropfbewässerungsanlage entsprechen.

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10 APPENDIX

Appendix A

Calculated data from the laboratory experiments

Table A1: The mean of discharge from In-line 168 emitters at different pressures

Emitter No.	Emitter discharge, L/h					
	25 kPa	50 kPa	100 kPa	150 kPa	200 kPa	225 kPa
1	3.88	5.80	8.28	10.20	12.24	12.72
2	3.88	5.80	8.40	10.32	12.08	12.56
3	3.88	5.84	8.32	10.32	12.16	12.72
4	3.80	6.04	8.72	10.96	12.16	12.72
5	3.88	5.92	8.56	10.64	12.16	12.72
6	3.76	5.92	8.56	10.52	11.84	12.48
7	3.88	5.96	8.84	10.84	12.40	12.96
8	3.80	5.80	8.24	10.12	12.16	12.48
9	3.76	5.84	8.56	10.60	11.84	12.24
10	3.80	5.68	8.12	10.00	12.40	12.64
11	3.76	6.04	8.88	11.04	12.08	12.56
12	3.92	5.84	8.32	10.40	12.16	12.80
13	3.76	5.80	8.24	10.12	11.92	12.40
14	3.88	5.96	8.96	10.96	12.48	13.20
15	3.76	5.80	8.20	10.16	11.92	12.48
16	3.76	5.72	8.20	10.12	12.00	12.56
17	3.96	6.16	8.88	11.00	12.56	13.20
18	3.76	5.68	8.20	10.04	11.84	12.48
19	3.76	5.52	8.40	10.28	11.76	12.48
20	3.88	5.68	7.88	10.12	12.16	12.80
21	3.72	5.68	8.48	10.28	11.76	12.32
22	3.76	5.56	8.08	10.00	12.08	12.56
23	3.72	5.56	8.12	10.04	11.92	12.40
24	4.00	5.68	8.36	10.20	12.56	13.20
25	3.80	5.56	8.08	9.92	12.08	12.80
26	3.88	5.72	8.28	10.32	12.48	12.72
27	3.88	5.68	8.28	10.24	11.92	12.80
28	3.68	5.80	8.44	10.32	11.84	12.40
29	3.76	5.80	8.32	10.24	11.84	12.40
30	3.76	5.76	8.40	10.20	11.92	12.40
Mean, L/h	3.82	5.79	8.39	10.35	12.09	12.64

Table A2: The mean of discharge from Hydrogol emitters at different pressures

Emitter No.	Emitter discharge, L/h					
	25 kPa	50 kPa	100 kPa	150 kPa	200 kPa	225 kPa
1	4.92	7.32	10.80	13.32	15.56	16.40
2	4.84	7.28	10.68	13.20	15.48	16.40
3	4.72	7.08	10.32	12.84	15.16	16.04
4	5.12	7.72	11.12	13.64	16.00	16.88
5	4.68	6.92	9.80	12.84	14.92	15.80
6	4.76	7.00	10.28	12.80	15.16	16.04
7	5.00	7.36	10.76	13.24	15.52	16.40
8	5.08	7.60	10.96	13.56	15.88	16.80
9	4.72	6.84	10.16	12.44	14.76	15.72
10	4.84	7.20	10.28	12.72	14.80	15.64
11	4.84	7.16	10.76	13.32	15.68	16.64
12	4.84	7.28	10.72	13.20	15.52	16.40
13	4.92	7.36	10.96	13.56	14.72	15.64
14	4.96	7.56	10.76	13.20	15.44	16.40
15	4.72	6.96	9.80	12.00	14.12	14.92
16	4.72	7.12	10.36	12.84	15.08	15.96
17	4.84	7.24	10.24	12.72	14.72	15.52
18	4.72	7.00	10.08	12.36	14.44	15.20
19	4.72	7.24	10.52	12.96	15.36	16.32
20	5.20	7.88	11.24	13.68	16.00	16.92
21	5.24	8.16	11.68	14.40	16.64	17.76
22	4.60	7.00	9.84	12.04	14.00	14.76
23	4.92	7.32	10.80	13.32	15.96	16.56
24	4.72	6.92	9.68	12.00	14.04	14.76
25	4.60	6.92	10.00	12.36	14.48	15.36
26	4.76	7.44	10.56	12.68	15.04	15.44
27	5.00	7.16	10.16	12.60	13.88	14.84
28	4.72	7.16	10.44	12.68	15.40	16.40
29	4.92	7.44	10.72	13.00	15.32	16.04
30	4.72	7.00	10.24	12.80	15.12	15.96
Mean, L/h	4.85	7.25	10.49	12.94	15.13	16.00

Table A3: The mean of discharge from Matic emitters at different pressures

Emitter No.	Emitter discharge, L/h					
	25 kPa	50 kPa	100 kPa	150 kPa	200 kPa	225 kPa
1	1.92	3.24	3.84	4.12	2.56	2.64
2	4.56	3.04	3.64	4.44	4.80	4.80
3	2.08	2.92	3.40	3.80	2.40	2.48
4	3.12	2.72	3.24	3.72	4.64	4.72
5	2.48	3.92	4.24	4.52	4.32	4.16
6	2.32	2.88	3.60	4.24	3.12	3.04
7	2.40	3.48	3.84	4.12	3.84	3.92
8	4.08	3.48	3.84	4.04	4.32	4.32
9	4.08	3.00	3.36	3.64	4.08	4.16
10	3.36	3.84	4.52	5.10	3.92	3.84
11	3.04	3.84	4.52	5.00	4.00	3.92
12	3.84	3.60	4.04	4.36	4.32	4.32
13	3.84	3.36	3.84	4.16	4.08	4.08
14	2.64	3.52	3.80	3.88	4.80	4.88
15	2.24	4.16	4.72	5.16	4.24	4.16
16	2.32	3.08	3.60	3.80	4.32	4.32
17	2.64	2.64	3.12	3.48	3.92	4.00
18	3.28	3.00	3.32	3.48	5.20	5.20
19	3.52	2.60	2.92	3.36	5.28	5.36
20	4.56	3.44	3.92	4.32	5.28	5.12
21	2.64	2.64	2.92	4.16	4.80	4.64
22	2.16	3.48	3.84	4.04	3.36	3.36
23	2.64	2.76	3.40	3.92	4.08	4.08
24	4.32	3.12	3.48	3.80	4.80	4.88
25	2.96	3.44	4.16	4.80	5.12	5.28
26	2.56	3.80	4.20	4.40	3.12	3.36
27	3.12	3.24	3.56	3.80	5.36	5.44
28	2.32	3.64	3.68	3.64	3.84	4.40
29	3.76	2.76	3.12	3.52	4.08	4.00
30	2.16	3.12	3.64	3.88	2.48	2.64
Mean, L/h	3.03	3.26	3.71	4.09	4.15	4.18

Table A4: The mean of discharge from Katif (4 L/h) emitters at different pressures

Emitter No.	Emitter discharge, L/h					
	25 kPa	50 kPa	100 kPa	150 kPa	200 kPa	225 kPa
1	5.32	3.64	3.68	3.64	3.68	3.60
2	5.24	3.92	3.84	3.80	3.72	3.64
3	4.84	3.80	3.84	3.84	4.00	4.20
4	5.36	3.68	3.84	3.96	4.00	4.48
5	4.88	3.80	3.84	3.92	4.36	4.56
6	4.92	3.80	3.72	3.76	3.72	3.64
7	4.44	3.76	3.84	3.76	4.04	3.92
8	5.28	3.92	3.84	3.96	3.96	3.96
9	5.04	3.56	3.72	3.92	3.80	3.84
10	4.80	3.84	3.84	3.96	3.76	3.80
11	4.80	3.92	3.84	3.84	3.80	3.80
12	4.80	3.80	3.84	4.08	3.72	3.72
13	5.28	3.84	3.76	3.72	3.92	3.96
14	4.44	3.84	3.80	3.84	3.56	3.52
15	5.32	3.96	3.80	4.00	4.08	4.16
16	4.96	3.84	3.84	4.04	3.88	3.88
17	5.32	3.56	3.60	3.44	4.32	4.36
18	5.32	3.96	3.88	3.92	3.92	4.04
19	4.60	3.60	3.84	3.76	3.44	3.56
20	4.84	3.72	3.76	3.64	3.76	3.76
21	4.88	3.84	3.80	3.76	3.80	3.88
22	5.04	3.60	3.68	3.68	3.80	3.76
23	5.24	3.96	3.84	3.96	3.68	3.64
24	5.52	3.76	3.76	3.64	3.96	4.00
25	4.76	3.84	3.76	3.88	3.60	3.64
26	5.32	3.92	3.80	3.72	4.00	4.16
27	4.68	3.52	3.64	3.64	3.60	3.60
28	5.16	3.80	3.80	3.68	3.84	3.84
29	4.80	3.72	3.72	3.80	3.64	3.64
30	5.12	3.68	3.64	3.60	4.08	4.24
Mean, L/h	5.01	3.78	3.78	3.81	3.85	3.89

Table A5: The mean of discharge from Katif (8 L/h) emitters at different pressures

Emitter No.	Emitter discharge, L/h					
	25 kPa	50 kPa	100 kPa	150 kPa	200 kPa	225 kPa
1	10.56	8.44	8.56	8.48	8.40	8.64
2	10.64	8.40	8.60	8.56	8.88	9.20
3	10.56	8.44	8.44	8.12	9.04	9.76
4	9.60	7.80	7.92	7.72	9.04	9.52
5	10.56	8.72	8.60	8.52	8.72	8.96
6	10.00	8.40	8.44	8.60	8.40	8.40
7	9.68	8.40	8.48	8.68	9.44	9.68
8	10.40	8.36	8.52	8.72	9.92	10.32
9	10.24	8.16	8.40	7.88	9.84	10.16
10	10.72	8.76	8.76	8.52	9.92	10.08
11	10.64	8.64	8.68	8.72	9.12	8.80
12	10.48	8.40	8.52	8.76	8.40	8.40
13	10.64	8.12	7.92	8.04	8.40	8.56
14	9.84	8.60	8.56	8.76	9.52	9.84
15	10.00	8.44	8.64	8.76	8.72	8.88
16	10.40	8.84	8.68	8.64	8.88	8.96
17	10.72	7.92	8.08	8.00	9.60	9.76
18	9.60	8.36	8.40	8.60	8.80	8.96
19	10.48	8.16	8.24	8.68	8.72	9.28
20	10.56	8.28	8.44	8.64	9.04	9.04
21	9.68	8.24	8.52	8.80	9.84	9.84
22	10.00	8.24	8.24	8.20	8.64	8.80
23	10.16	8.32	8.32	8.52	8.40	8.56
24	10.48	7.88	7.84	8.68	8.96	9.04
25	10.48	8.08	8.30	8.12	8.96	9.92
26	10.72	8.44	8.56	8.76	8.72	8.96
27	10.48	8.52	8.64	8.76	8.80	8.48
28	10.64	8.32	8.24	8.72	9.36	9.60
29	10.24	8.28	8.36	8.80	8.80	8.96
30	10.56	8.08	8.28	8.60	8.72	8.64
Mean, L/h	10.33	8.33	8.41	8.51	9.00	9.20

Appendix B

Calculated data by using Chu and Moe, (1972), Nelson, (2001) and Valmont, (2001)

Table B1: Mean of water quantity at all outlets on the center pivot using different sources

Sprink. No.	Distance from pivot, (m)	Nelson Q, L/min	Chu,1972 Q, L/min	Dis. from pivot, (m)	Valmont Q, L/min	Mean Q, L/min
1	1.90	0.40	0.16	1.83	....	0.28
2	4.90	1.00	0.64	4.80	0.87	0.84
3	7.90	1.60	1.03	7.77	0.98	1.20
4	10.90	2.10	1.43	10.74	1.36	1.63
5	13.90	2.60	1.82	13.70	1.78	2.07
6	16.90	3.10	2.21	16.67	2.16	2.49
7	19.90	3.50	2.60	19.64	2.54	2.88
8	22.90	3.90	3.00	22.60	2.91	3.27
9	25.90	4.20	3.39	25.57	3.29	3.63
10	28.90	4.50	3.78	28.54	3.67	3.98
11	31.90	4.90	4.18	31.50	4.01	4.36
12	34.90	5.00	4.57	34.47	4.43	4.67
13	37.90	5.10	4.96	37.44	4.81	4.96
14	40.90	5.40	5.35	40.41	5.19	5.31
15	43.90	5.80	5.75	43.38	5.56	5.70
16	46.90	5.50	6.14	46.34	6.06	5.90
Total	46.90	58.60	51.01	46.34	49.62	53.17
17	49.40	6.10	5.60	49.39	6.43	6.04
18	52.40	6.90	6.86	52.36	6.73	6.83
19	55.40	7.10	7.25	55.33	7.11	7.15
20	58.40	7.70	7.64	58.29	7.49	7.61
21	61.40	7.80	8.04	61.26	7.87	7.90
22	64.40	8.20	8.43	64.23	8.25	8.29
23	67.40	8.90	8.82	67.20	8.63	8.78
24	70.40	9.20	9.22	70.16	9.00	9.14
25	73.40	9.80	9.61	73.13	9.39	9.60
26	76.40	9.80	10.00	76.10	9.80	9.87
27	79.40	10.30	10.39	79.07	10.18	10.29
28	82.40	10.90	10.79	82.03	10.56	10.75
29	85.40	11.00	11.18	85.00	10.94	11.04
30	88.40	11.40	11.57	87.97	11.32	11.43
31	91.40	12.20	11.96	90.94	11.70	11.95
32	94.40	11.20	12.36	93.90	12.23	11.93
Total	94.40	148.50	149.72	93.90	141.20	148.60
33	97.00	11.90	11.00	96.95	12.64	11.85
34	100.00	12.60	13.09	99.92	12.83	12.84
35	103.00	13.70	13.48	102.89	13.25	13.48
36	106.00	14.10	13.88	105.85	13.63	13.87
37	109.00	13.70	14.27	108.82	14.00	13.99
38	112.00	14.90	14.66	111.79	14.38	14.65
39	115.00	15.20	15.05	114.76	14.76	15.00
40	118.00	14.80	15.45	117.72	14.15	14.80
41	121.00	15.90	15.84	120.69	15.52	15.75
42	124.00	16.10	16.23	123.66	15.90	16.08
43	127.00	16.80	16.62	126.63	16.28	16.57
44	130.00	16.30	17.02	129.60	16.65	16.66
45	133.00	17.60	17.41	132.56	17.03	17.35
46	136.00	17.90	17.80	135.53	17.41	17.70
47	139.00	18.50	18.20	138.50	17.79	18.16
48	142.00	16.80	18.59	141.46	18.43	17.94
Total	142.00	246.80	248.59	141.46	232.01	246.69

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Table B1: (*Continued*)

Sprink. No.	Distance from pivot, (m)	Nelson Q, L/min	Chu,1972 Q, L/min	Dis. from pivot, (m)	Valmont Q, L/min	Mean Q, L/min
49	144.50	16.80	16.39	144.51	18.84	17.34
50	147.50	18.50	19.31	147.48	18.96	18.92
51	150.50	19.30	19.70	150.45	19.34	19.45
52	153.50	20.40	20.10	153.42	19.72	20.07
53	156.50	20.40	20.49	156.38	20.10	20.33
54	159.50	20.70	20.88	159.35	20.48	20.69
55	162.50	21.50	21.27	162.32	20.86	21.21
56	165.50	21.20	21.66	165.28	21.23	21.36
57	168.50	21.40	22.06	168.25	21.65	21.70
58	171.50	21.90	22.45	171.22	22.03	22.13
59	174.50	22.80	22.84	174.19	22.41	22.68
60	177.50	22.20	23.23	177.16	22.79	22.74
61	180.50	23.90	23.56	180.12	23.16	23.54
62	183.50	24.10	24.02	183.09	23.54	23.89
63	186.50	24.70	24.35	186.06	23.92	24.32
64	189.50	22.30	24.81	189.03	24.64	23.92
Total	189.50	342.10	347.12	189.03	324.83	344.29
65	192.10	23.70	21.79	192.07	25.02	23.50
66	195.10	25.40	25.54	195.04	25.10	25.35
67	198.10	25.90	25.93	198.01	25.47	25.77
68	201.10	26.70	26.32	200.98	25.85	26.29
69	204.10	26.30	26.72	203.94	26.23	26.42
70	207.10	26.30	27.11	206.91	26.61	26.67
71	210.10	26.60	27.50	209.88	26.99	27.03
72	213.10	27.40	27.89	212.85	27.37	27.55
73	216.10	28.60	28.29	215.82	27.74	28.21
74	219.10	28.60	28.68	218.78	28.12	28.47
75	222.10	29.00	29.07	221.75	28.50	28.86
76	225.10	29.80	29.47	224.72	28.88	29.38
77	228.10	28.90	29.86	227.68	29.26	29.34
78	231.10	30.50	30.25	230.65	29.67	30.14
79	234.10	30.40	30.64	233.62	30.05	30.36
80	237.10	28.40	31.04	236.59	30.85	30.10
Total	237.10	442.50	446.10	236.59	416.69	443.44
81	239.60	28.80	27.18	239.64	31.23	29.07
82	242.60	31.90	31.68	242.60	31.19	31.59
83	245.60	31.40	32.15	245.57	31.57	31.71
84	248.60	31.20	32.54	248.54	31.95	31.90
85	251.60	33.40	32.93	251.50	32.32	32.88
86	254.60	32.10	33.33	254.47	32.70	32.71
87	257.60	33.10	33.72	257.44	33.12	33.31
88	260.60	34.50	34.11	260.41	33.50	34.04
89	263.60	34.30	34.50	263.38	33.88	34.23
90	266.60	34.60	34.89	266.34	34.25	34.58
91	269.60	35.20	35.29	269.31	34.63	35.04
92	272.60	34.40	35.68	272.28	35.01	35.03
93	275.60	35.70	36.08	275.25	35.39	35.72
94	278.60	35.70	36.47	278.21	35.77	35.98
95	281.60	36.10	36.86	281.18	36.15	36.37
96	284.60	33.90	37.25	284.15	37.06	36.07
Total	284.60	536.30	544.66	284.15	508.49	540.23

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Table B1: (*Continued*)

Sprink. No.	Distance from pivot, (m)	Nelson Q, L/min	Chu,1972 Q, L/min	Dis. from pivot, (m)	Valmont Q, L/min	Mean Q, L/min
97	287.20	33.80	32.58	287.20	37.43	34.60
98	290.20	36.70	37.99	290.16	37.32	37.34
99	293.20	38.30	38.38	293.13	37.70	38.13
100	296.20	38.60	38.77	296.10	38.08	38.48
101	299.20	39.20	39.17	299.07	38.46	38.94
102	302.20	40.20	39.53	302.03	38.83	39.52
103	305.20	39.10	39.95	305.00	39.21	39.42
104	308.20	40.90	40.34	307.97	39.59	40.28
105	311.20	40.50	40.71	310.94	39.97	40.39
106	314.20	40.60	41.13	313.90	40.35	40.69
107	317.20	41.00	41.52	316.87	40.73	41.08
108	320.20	41.90	41.91	319.84	41.14	41.65
109	323.20	40.80	42.31	322.81	41.52	41.54
110	326.20	42.40	42.70	325.77	41.90	42.33
111	329.20	42.20	43.10	328.74	42.28	42.53
112	332.20	39.10	43.48	331.71	43.22	41.93
Total	332.20	635.30	643.57	331.71	600.30	638.85
113	334.70	41.20	37.97	334.76	43.64	40.94
114	337.70	44.30	44.20	337.72	43.41	43.97
115	340.70	45.30	44.60	340.69	43.79	44.56
116	343.70	43.00	44.99	343.66	44.17	44.05
117	346.70	45.00	45.38	346.63	44.59	44.99
118	349.70	46.50	45.78	349.60	44.97	45.75
119	352.70	44.80	46.17	352.56	45.34	45.44
120	355.70	45.20	46.56	355.53	45.72	45.83
121	358.70	45.90	46.95	358.50	46.10	46.32
122	361.70	47.00	47.25	361.46	46.48	46.91
123	364.70	46.60	47.74	364.43	46.86	47.07
124	367.70	46.70	48.13	367.40	47.24	47.36
125	370.70	47.10	48.52	370.37	47.62	47.75
126	373.70	47.90	48.92	373.33	47.99	48.27
127	376.70	49.10	49.31	376.30	48.37	48.93
128	379.70	45.50	49.70	379.27	49.43	48.21
Total	379.70	731.10	742.17	379.27	692.08	736.35
129	382.30	45.70	43.37	382.32	49.81	46.29
130	385.30	49.80	50.44	385.28	49.55	49.93
131	388.30	50.90	50.83	388.25	49.92	50.55
132	391.30	50.80	51.22	391.22	50.30	50.77
133	394.30	51.10	51.61	394.19	50.68	51.13
134	397.30	51.90	52.00	397.16	51.06	51.65
135	400.30	51.20	52.40	400.12	51.44	51.68
136	403.30	52.70	52.79	403.09	51.82	52.44
137	406.30	52.80	53.18	406.06	52.20	52.73
138	409.30	53.40	53.58	409.03	52.57	53.18
139	412.30	52.60	53.97	411.99	52.99	53.19
140	415.30	53.90	54.36	414.96	53.37	53.88
141	418.30	53.90	54.75	417.93	53.75	54.13
142	421.30	54.30	55.15	420.89	54.13	54.53
143	424.30	55.10	55.54	423.86	54.50	55.05
144	427.30	71.60	55.93	426.83	61.28	62.94
Total	427.30	851.70	841.12	426.83	789.56	844.07

Table B2: Total number of emitters on the center pivot at 50 and 100 kPa with mobile drip irrigation by using Hydrogol emitters

Sprink. No.	Distance from pivot, (m)	Mean Q, L/h	No. of emitters at **50 kPa**,7.26 L/h	No. of emitters at **100 kPa**, 10.49 L/h	Tower No.
1	1.90	16.80	3	2	1
2	4.90	50.20	7	5	1
3	7.90	72.20	10	7	1
4	10.90	97.80	14	10	1
5	13.90	124.00	17	12	1
6	16.90	149.40	21	15	1
7	19.90	172.80	24	17	1
8	22.90	196.20	27	19	1
9	25.90	217.60	30	21	1
10	28.90	239.00	33	23	1
11	31.90	261.80	36	25	1
12	34.90	280.00	39	27	1
13	37.90	297.40	41	29	1
14	40.90	318.80	44	31	1
15	43.90	342.20	47	33	1
16	46.90	354.00	49	34	1
Total	46.90	3190.20	442	310	
17	49.40	362.60	50	35	2
18	52.40	409.80	57	39	2
19	55.40	429.20	59	41	2
20	58.40	456.60	63	44	2
21	61.40	474.20	66	46	2
22	64.40	497.60	69	48	2
23	67.40	527.00	73	51	2
24	70.40	548.40	76	53	2
25	73.40	576.00	80	55	2
26	76.40	592.00	82	57	2
27	79.40	617.40	85	59	2
28	82.40	645.00	89	62	2
29	85.40	662.40	92	63	2
30	88.40	685.80	95	66	2
31	91.40	717.20	99	69	2
32	94.40	715.80	99	69	2
Total	94.40	8917.00	1234	857	
33	97.00	710.80	98	68	3
34	100.00	770.40	106	74	3
35	103.00	808.60	112	77	3
36	106.00	832.20	115	80	3
37	109.00	839.40	116	80	3
38	112.00	878.80	121	84	3
39	115.00	900.20	124	86	3
40	118.00	888.00	123	85	3
41	121.00	945.20	130	90	3
42	124.00	964.60	133	92	3
43	127.00	994.00	137	95	3
44	130.00	999.40	138	96	3
45	133.00	1040.80	144	100	3
46	136.00	1062.20	147	102	3
47	139.00	1089.80	150	104	3
48	142.00	1076.40	149	103	3
Total	142.00	14800.80	2043	1416	

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Table B2: (*Continued*)

Sprink. No.	Distance from pivot, (m)	Mean Q, L/h	No. of emitters at **50 kPa**,7.26 L/h	No. of emitters at **100 kPa**, 10.49 L/h	Tower No.
49	144.50	1040.60	144	100	4
50	147.50	1135.40	157	109	4
51	150.50	1166.80	161	112	4
52	153.50	1204.40	166	115	4
53	156.50	1219.80	168	117	4
54	159.50	1241.20	171	119	4
55	162.50	1272.60	176	122	4
56	165.50	1281.80	177	122	4
57	168.50	1302.20	180	124	4
58	171.50	1327.60	183	127	4
59	174.50	1361.00	188	130	4
60	177.50	1364.40	188	130	4
61	180.50	1412.40	195	135	4
62	183.50	1433.20	198	137	4
63	186.50	1459.40	201	139	4
64	189.50	1435.00	198	137	4
Total	189.50	20657.80	2851	1975	
65	192.10	1410.20	195	135	5
66	195.10	1520.80	210	145	5
67	198.10	1546.00	213	148	5
68	201.10	1577.40	218	151	5
69	204.10	1585.00	219	151	5
70	207.10	1600.40	221	153	5
71	210.10	1621.80	224	155	5
72	213.10	1653.20	228	158	5
73	216.10	1692.60	233	162	5
74	219.10	1708.00	236	163	5
75	222.10	1731.40	239	165	5
76	225.10	1763.00	243	168	5
77	228.10	1760.40	243	168	5
78	231.10	1808.40	249	173	5
79	234.10	1821.80	251	174	5
80	237.10	1805.80	249	172	5
Total	237.10	26606.20	3671	2541	
81	239.60	1744.20	241	167	6
82	242.60	1895.40	261	181	6
83	245.60	1902.40	262	182	6
84	248.60	1913.80	264	183	6
85	251.60	1973.00	272	188	6
86	254.60	1962.60	271	187	6
87	257.60	1998.80	276	191	6
88	260.60	2042.20	282	195	6
89	263.60	2053.60	283	196	6
90	266.60	2074.80	286	198	6
91	269.60	2102.40	290	201	6
92	272.60	2101.80	290	201	6
93	275.60	2143.40	296	205	6
94	278.60	2158.80	298	206	6
95	281.60	2182.20	301	208	6
96	284.60	2164.20	298	207	6
Total	284.60	32413.60	4471	3096	

(Continued on next page)

Table B2 (*Continued*)

Sprink. No.	Distance from pivot, (m)	Mean Q, L/h	No. of emitters at **50 kPa**,7.26 L/h	No. of emitters at **100 kPa**, 10.49 L/h	Tower No.
97	287.20	2076.20	286	198	7
98	290.20	2240.20	309	214	7
99	293.20	2287.60	315	218	7
100	296.20	2309.00	318	220	7
101	299.20	2336.60	322	223	7
102	302.20	2371.20	327	226	7
103	305.20	2365.20	326	226	7
104	308.20	2416.60	333	231	7
105	311.20	2423.60	334	231	7
106	314.20	2441.60	337	233	7
107	317.20	2465.00	340	235	7
108	320.20	2499.00	345	239	7
109	323.20	2492.60	344	238	7
110	326.20	2540.00	350	242	7
111	329.20	2551.60	352	244	7
112	332.20	2516.00	347	240	7
Total	332.20	38332.00	5285	3658	
113	334.70	2456.20	339	234	8
114	337.70	2638.20	364	252	8
115	340.70	2673.80	369	255	8
116	343.70	2643.20	364	252	8
117	346.70	2699.40	372	258	8
118	349.70	2745.00	378	262	8
119	352.70	2726.20	376	260	8
120	355.70	2749.60	379	262	8
121	358.70	2779.00	383	265	8
122	361.70	2814.60	388	269	8
123	364.70	2824.00	389	270	8
124	367.70	2841.40	392	271	8
125	370.70	2864.80	395	273	8
126	373.70	2896.20	399	276	8
127	376.70	2935.60	405	280	8
128	379.70	2892.60	399	276	8
Total	379.70	44179.80	6091	4215	
129	382.30	2777.60	383	265	9
130	385.30	2995.80	413	286	9
131	388.30	3033.00	418	289	9
132	391.30	3046.40	420	291	9
133	394.30	3067.80	423	293	9
134	397.30	3099.20	427	296	9
135	400.30	3100.80	427	296	9
136	403.30	3146.20	434	300	9
137	406.30	3163.60	436	302	9
138	409.30	3191.00	440	304	9
139	412.30	3191.20	440	305	9
140	415.30	3232.66	446	308	9
141	418.30	3248.00	448	310	9
142	421.30	3271.60	451	312	9
143	424.30	3302.80	455	315	9
144	427.30	3776.20	520	360	9
Total	427.30	50643.86	6981	4832	

Table B3: Total number and length of drip tubes on the center pivot by using Hydrogol emitters

Distance from pivot, (m)	**50 kPa**			**100 kPa**		
	Total length (m)	Numbers of tubes	Length of one tube, (m)	Total length (m)	Numbers of tubes	Length of one tube, (m)
1.90	0.45	4	0.11	0.30	4	0.08
4.90	1.05	4	0.26	0.75	4	0.19
7.90	1.50	4	0.38	1.05	4	0.26
10.90	2.10	4	0.53	1.50	4	0.38
13.90	2.55	4	0.64	1.80	4	0.45
16.90	3.15	4	0.79	2.25	4	0.56
19.90	3.60	4	0.90	2.55	4	0.64
22.90	4.05	4	1.01	2.85	4	0.71
25.90	4.50	4	1.13	3.15	4	0.79
28.90	4.95	4	1.24	3.45	4	0.86
31.90	5.40	4	1.35	3.75	4	0.94
34.90	5.85	4	1.46	4.05	4	1.01
37.90	6.15	4	1.54	4.35	4	1.09
40.90	6.60	4	1.65	4.65	4	1.16
43.90	7.05	4	1.76	4.95	4	1.24
46.90	7.35	4	1.84	5.10	4	1.28
Total = 46.9	66.30	64		46.50	64	
49.40	7.50	4	1.88	5.25	4	1.31
52.40	8.55	4	2.14	5.85	4	1.46
55.40	8.85	4	2.21	6.15	4	1.54
58.40	9.45	4	2.36	6.60	4	1.65
61.40	9.90	4	2.48	6.90	4	1.73
64.40	10.35	4	2.59	7.20	4	1.80
67.40	10.95	4	2.74	7.65	4	1.91
70.40	11.40	4	2.85	7.95	4	1.99
73.40	12.00	4	3.00	8.25	4	2.06
76.40	12.30	4	3.08	8.55	4	2.14
79.40	12.75	4	3.19	8.85	4	2.21
82.40	13.35	4	3.34	9.30	4	2.33
85.40	13.80	4	3.45	9.45	4	2.36
88.40	14.25	4	3.56	9.90	4	2.48
91.40	14.85	4	3.71	10.35	4	2.59
94.40	14.85	4	3.71	10.35	4	2.59
Total = 94.4	185.10	64		128.55	64	
97.00	14.70	4	3.68	10.20	4	2.55
100.00	15.90	4	3.98	11.10	4	2.78
103.00	16.80	4	4.20	11.55	4	2.89
106.00	17.25	4	4.31	12.00	4	3.00
109.00	17.40	4	4.35	12.00	4	3.00
112.00	18.15	4	4.54	12.60	4	3.15
115.00	18.60	4	4.65	12.90	4	3.23
118.00	18.45	4	4.61	12.75	4	3.19
121.00	19.50	4	4.88	13.50	4	3.38
124.00	19.95	4	4.99	13.80	4	3.45
127.00	20.55	4	5.14	14.25	4	3.56
130.00	20.70	4	5.18	14.40	4	3.60
133.00	21.60	4	5.40	15.00	4	3.75
136.00	22.05	4	5.51	15.30	4	3.83
139.00	22.50	4	5.63	15.60	4	3.90
142.00	22.35	4	5.59	15.45	4	3.86
Total = 142	306.45	64		212.40	64	

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Table B3: (*Continued*)

Distance from pivot, (m)	50 kPa			100 kPa		
	Total length (m)	Numbers of tubes	Length of one tube, (m)	Total length (m)	Numbers of tubes	Length of one tube, (m)
144.50	21.60	4	5.40	15.00	4	3.75
147.50	23.55	4	5.89	16.35	4	4.09
150.50	24.15	4	6.04	16.80	4	4.20
153.50	24.90	4	6.23	17.25	4	4.31
156.50	25.20	4	6.30	17.55	4	4.39
159.50	25.65	4	6.41	17.85	4	4.46
162.50	26.40	4	6.60	18.30	4	4.58
165.50	26.55	4	6.64	18.30	4	4.58
168.50	27.00	4	6.75	18.60	4	4.65
171.50	27.45	4	6.86	19.05	4	4.76
174.50	28.20	4	7.05	19.50	4	4.88
177.50	28.20	4	7.05	19.50	4	4.88
180.50	29.25	4	7.31	20.25	4	5.06
183.50	29.70	4	7.43	20.55	4	5.14
186.50	30.15	4	7.54	20.85	4	5.21
189.50	29.70	4	7.43	20.55	4	5.14
Total = 189.5	427.65	64		296.25	64	
192.10	29.25	4	7.31	20.25	4	5.06
195.10	31.50	4	7.88	21.75	4	5.44
198.10	31.95	4	7.99	22.20	4	5.55
201.10	32.70	4	8.18	22.65	4	5.66
204.10	32.85	4	8.21	22.65	4	5.66
207.10	33.15	4	8.29	22.95	4	5.74
210.10	33.60	4	8.40	23.25	4	5.81
213.10	34.20	4	8.55	23.70	4	5.93
216.10	34.95	4	8.74	24.30	4	6.08
219.10	35.40	4	8.85	24.45	4	6.11
222.10	35.85	4	8.96	24.75	4	6.19
225.10	36.45	4	9.11	25.20	4	6.30
228.10	36.45	4	9.11	25.20	4	6.30
231.10	37.35	4	9.34	25.95	4	6.49
234.10	37.65	4	9.41	26.10	4	6.53
237.10	37.35	4	9.34	25.80	4	6.45
Total = 237.1	550.65	64		381.15	64	
239.60	36.15	4	9.04	25.05	4	6.26
242.60	39.15	4	9.79	27.15	4	6.79
245.60	39.30	4	9.83	27.30	4	6.83
248.60	39.60	4	9.90	27.45	4	6.86
251.60	40.80	4	10.20	28.20	4	7.05
254.60	40.65	4	10.16	28.05	4	7.01
257.60	41.40	4	10.35	28.65	4	7.16
260.60	42.30	4	10.58	29.25	4	7.31
263.60	42.45	4	10.61	29.40	4	7.35
266.60	42.90	4	10.73	29.70	4	7.43
269.60	43.50	4	10.88	30.15	4	7.54
272.60	43.50	4	10.88	30.15	4	7.54
275.60	44.40	4	11.10	30.75	4	7.69
278.60	44.70	4	11.18	30.90	4	7.73
281.60	45.15	4	11.29	31.20	4	7.80
284.60	44.70	4	11.18	31.05	4	7.76
Total = 284.6	670.65	64		464.40	64	

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Table B3: (*Continued*)

Distance from pivot, (m)	50 kPa			100 kPa		
	Total length (m)	Numbers of tubes	Length of one tube, (m)	Total length (m)	Numbers of tubes	Length of one tube, (m)
287.20	42.90	4	10.73	29.70	4	7.43
290.20	46.35	4	11.59	32.10	4	8.03
293.20	47.25	4	11.81	32.70	4	8.18
296.20	47.70	4	11.93	33.00	4	8.25
299.20	48.30	4	12.08	33.45	4	8.36
302.20	49.05	4	12.26	33.90	4	8.48
305.20	48.90	4	12.23	33.90	4	8.48
308.20	49.95	4	12.49	34.65	4	8.66
311.20	50.10	4	12.53	34.65	4	8.66
314.20	50.55	4	12.64	34.95	4	8.74
317.20	51.00	4	12.75	35.25	4	8.81
320.20	51.75	4	12.94	35.85	4	8.96
323.20	51.60	4	12.90	35.70	4	8.93
326.20	52.50	4	13.13	36.30	4	9.08
329.20	52.80	4	13.20	36.60	4	9.15
332.20	52.05	4	13.01	36.00	4	9.00
Total = 332.2	792.75	64		548.70	64	
334.70	50.85	4	12.71	35.10	4	8.78
337.70	54.60	4	13.65	37.80	4	9.45
340.70	55.35	4	13.84	38.25	4	9.56
343.70	54.60	4	13.65	37.80	4	9.45
346.70	55.80	4	13.95	38.70	4	9.68
349.70	56.70	4	14.18	39.30	4	9.83
352.70	56.40	4	14.10	39.00	4	9.75
355.70	56.85	4	14.21	39.30	4	9.83
358.70	57.45	4	14.36	39.75	4	9.94
361.70	58.20	4	14.55	40.35	4	10.09
364.70	58.35	4	14.59	40.50	4	10.13
367.70	58.80	4	14.70	40.65	4	10.16
370.70	59.25	4	14.81	40.95	4	10.24
373.70	59.85	4	14.96	41.40	4	10.35
376.70	60.75	4	15.19	42.00	4	10.50
379.70	59.85	4	14.96	41.40	4	10.35
Total = 379.7	913.65	64		632.25	64	
382.30	57.45	4	14.36	39.75	4	9.94
385.30	61.95	4	15.49	42.90	4	10.73
388.30	62.70	4	15.68	43.35	4	10.84
391.30	63.00	4	15.75	43.65	4	10.91
394.30	63.45	4	15.86	43.95	4	10.99
397.30	64.05	4	16.01	44.40	4	11.10
400.30	64.05	4	16.01	44.40	4	11.10
403.30	65.10	4	16.28	45.00	4	11.25
406.30	65.40	4	16.35	45.30	4	11.33
409.30	66.00	4	16.50	45.60	4	11.40
412.30	66.00	4	16.50	45.75	4	11.44
415.30	66.90	4	16.73	46.20	4	11.55
418.30	67.20	4	16.80	46.50	4	11.63
421.30	67.65	4	16.91	46.80	4	11.70
424.30	68.25	4	17.06	47.25	4	11.81
427.30	78.00	4	19.50	54.00	4	13.50
Total = 427.3	1047.15	64		724.80	64	

Table B4: Mean of calculated irrigation depth at all outlets on the center pivot machine

Sprink. No.	Distance from pivot, (m)	Mean of discharge, (m)³	Irrigated area, (m)²	Irrig. depth (calculated), (mm)	Irrig. depth (needed), (mm)	Tower No.
1	1.90	0.81	40.57	19.97	20	1
2	4.90	2.41	92.32	26.10	20	1
3	7.90	3.47	148.84	23.31	20	1
4	10.90	4.69	205.36	22.84	20	1
5	13.90	5.95	261.88	22.72	20	1
6	16.90	7.17	318.40	22.52	20	1
7	19.90	8.29	374.92	22.11	20	1
8	22.90	9.42	431.44	21.83	20	1
9	25.90	10.44	487.96	21.40	20	1
10	28.90	11.47	544.48	21.07	20	1
11	31.90	12.57	601.00	20.92	20	1
12	34.90	13.44	657.52	20.44	20	1
13	37.90	14.28	714.04	20.00	20	1
14	40.90	15.3	770.56	19.86	20	1
15	43.90	16.43	827.08	19.87	20	1
16	46.90	16.99	883.60	19.23	20	1
Total	46.90	153.13	7359.97	mean = 21.51	20	
17	49.40	17.4	930.70	18.70	20	2
18	52.40	19.67	987.22	19.92	20	2
19	55.40	20.6	1043.74	19.74	20	2
20	58.40	21.92	1100.26	19.92	20	2
21	61.40	22.76	1156.78	19.68	20	2
22	64.40	23.88	1213.30	19.68	20	2
23	67.40	25.3	1269.82	19.92	20	2
24	70.40	26.32	1326.34	19.84	20	2
25	73.40	27.65	1382.86	19.99	20	2
26	76.40	28.42	1439.38	19.74	20	2
27	79.40	29.64	1495.90	19.81	20	2
28	82.40	30.96	1552.42	19.94	20	2
29	85.40	31.8	1608.94	19.76	20	2
30	88.40	32.92	1665.46	19.77	20	2
31	91.40	34.43	1721.98	19.99	20	2
32	94.40	34.36	1778.50	19.32	20	2
Total	94.40	428.02	21673.60	mean = 19.73	20	
33	97.00	34.12	1827.48	18.67	20	3
34	100.00	36.98	1884.00	19.63	20	3
35	103.00	38.81	1940.52	20.00	20	3
36	106.00	39.95	1997.04	20.00	20	3
37	109.00	40.29	2053.56	19.62	20	3
38	112.00	42.18	2110.08	19.99	20	3
39	115.00	43.21	2166.60	19.94	20	3
40	118.00	42.62	2223.12	19.17	20	3
41	121.00	45.37	2279.64	19.90	20	3
42	124.00	46.3	2336.16	19.82	20	3
43	127.00	47.71	2392.68	19.94	20	3
44	130.00	47.97	2449.20	19.59	20	3
45	133.00	49.96	2505.72	19.94	20	3
46	136.00	50.99	2562.24	19.90	20	3
47	139.00	52.31	2618.76	19.98	20	3
48	142.00	51.67	2675.28	19.31	20	3
Total	142.00	710.44	36022.08	mean = 19.71	20	

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Table B4: (*Continued*)

Sprink. No.	Distance from pivot, (m)	Mean of discharge, (m)³	Irrigated area, (m)²	Irrig. depth (calculated), (mm)	Irrig. depth (needed), (mm)	Tower No.
49	144.50	49.95	2722.38	18.35	20	4
50	147.50	54.5	2778.90	19.61	20	4
51	150.50	56.01	2835.42	19.75	20	4
52	153.50	57.81	2891.94	19.99	20	4
53	156.50	58.55	2948.46	19.86	20	4
54	159.50	59.58	3004.98	19.83	20	4
55	162.50	61.08	3061.50	19.95	20	4
56	165.50	61.53	3118.02	19.73	20	4
57	168.50	62.51	3174.54	19.69	20	4
58	171.50	63.72	3231.06	19.72	20	4
59	174.50	65.33	3287.58	19.87	20	4
60	177.50	65.49	3344.10	19.58	20	4
61	180.50	67.8	3400.62	19.94	20	4
62	183.50	68.79	3457.14	19.90	20	4
63	186.50	70.05	3513.66	19.94	20	4
64	189.50	68.88	3570.18	19.29	20	4
Total	189.50	991.57	50340.48	mean = 19.69	20	
65	192.10	67.69	3619.16	18.70	20	5
66	195.10	73	3675.68	19.86	20	5
67	198.10	74.21	3732.20	19.88	20	5
68	201.10	75.72	3788.72	19.99	20	5
69	204.10	76.08	3845.24	19.79	20	5
70	207.10	76.82	3901.76	19.69	20	5
71	210.10	77.85	3958.28	19.67	20	5
72	213.10	79.35	4014.80	19.76	20	5
73	216.10	81.24	4071.32	19.95	20	5
74	219.10	81.98	4127.84	19.86	20	5
75	222.10	83.11	4184.36	19.86	20	5
76	225.10	84.62	4240.88	19.95	20	5
77	228.10	84.5	4297.40	19.66	20	5
78	231.10	86.8	4353.92	19.94	20	5
79	234.10	87.45	4410.44	19.83	20	5
80	237.10	86.68	4466.96	19.40	20	5
Total	237.10	1277.1	64688.96	mean = 19.74	20	
81	239.60	83.72	4514.06	18.55	20	6
82	242.60	90.98	4570.58	19.91	20	6
83	245.60	91.32	4627.10	19.74	20	6
84	248.60	91.86	4683.62	19.61	20	6
85	251.60	94.7	4740.14	19.98	20	6
86	254.60	94.2	4796.66	19.64	20	6
87	257.60	95.94	4853.18	19.77	20	6
88	260.60	98.03	4909.70	19.97	20	6
89	263.60	98.57	4966.22	19.85	20	6
90	266.60	99.59	5022.74	19.83	20	6
91	269.60	100.92	5079.26	19.87	20	6
92	272.60	100.89	5135.78	19.64	20	6
93	275.60	102.88	5192.30	19.81	20	6
94	278.60	103.62	5248.82	19.74	20	6
95	281.60	104.75	5305.34	19.74	20	6
96	284.60	103.88	5361.86	19.37	20	6
Total	284.60	1555.85	79007.36	mean = 19.69	20	

(Continued on next page)

Table B4: (*Continued*)

Sprink. No.	Distance from pivot, (m)	Mean of discharge, (m)³	Irrigated area, (m)²	Irrig. depth (calculated), (mm)	Irrig. depth (needed), (mm)	Tower No.
97	287.20	99.66	5410.85	18.42	20	7
98	290.20	107.53	5467.37	19.67	20	7
99	293.20	109.8	5523.89	19.88	20	7
100	296.20	110.83	5580.41	19.86	20	7
101	299.20	112.16	5636.93	19.90	20	7
102	302.20	113.82	5693.45	19.99	20	7
103	305.20	113.53	5749.97	19.74	20	7
104	308.20	116	5806.49	19.98	20	7
105	311.20	116.33	5863.01	19.84	20	7
106	314.20	117.2	5919.53	19.80	20	7
107	317.20	118.32	5976.05	19.80	20	7
108	320.20	119.95	6032.57	19.88	20	7
109	323.20	119.64	6089.09	19.65	20	7
110	326.20	121.92	6145.61	19.84	20	7
111	329.20	122.48	6202.13	19.75	20	7
112	332.20	120.77	6258.65	19.30	20	7
Total	332.20	1839.94	93356.00	mean = 19.71	20	
113	334.70	117.9	6305.75	18.70	20	8
114	337.70	126.63	6362.27	19.90	20	8
115	340.70	128.34	6418.79	19.99	20	8
116	343.70	126.87	6475.31	19.59	20	8
117	346.70	129.57	6531.83	19.84	20	8
118	349.70	131.76	6588.35	20.00	20	8
119	352.70	130.86	6644.87	19.69	20	8
120	355.70	131.98	6701.39	19.69	20	8
121	358.70	133.39	6757.91	19.74	20	8
122	361.70	135.1	6814.43	19.83	20	8
123	364.70	135.55	6870.95	19.73	20	8
124	367.70	136.39	6927.47	19.69	20	8
125	370.70	137.51	6983.99	19.69	20	8
126	373.70	139.02	7040.51	19.75	20	8
127	376.70	140.91	7097.03	19.85	20	8
128	379.70	138.84	7153.55	19.41	20	8
Total	379.70	2120.63	107674.40	mean = 19.69	20	
129	382.30	133.32	7202.53	18.51	20	9
130	385.30	143.8	7259.05	19.81	20	9
131	388.30	145.58	7315.57	19.90	20	9
132	391.30	146.23	7372.09	19.84	20	9
133	394.30	147.25	7428.61	19.82	20	9
134	397.30	148.76	7485.13	19.87	20	9
135	400.30	148.84	7541.65	19.74	20	9
136	403.30	151.02	7598.17	19.88	20	9
137	406.30	151.85	7654.69	19.84	20	9
138	409.30	153.17	7711.21	19.86	20	9
139	412.30	153.18	7767.73	19.72	20	9
140	415.30	155.17	7824.25	19.83	20	9
141	418.30	155.9	7880.77	19.78	20	9
142	421.30	157.04	7937.29	19.79	20	9
143	424.30	158.53	7993.81	19.83	20	9
144	427.30	181.26	8050.33	22.52	20	9
Total	427.30	2430.91	122022.88	mean = 19.91	20	

Appendix C

Calculated data from the field experiments

Table C1: The soil water content under tower number one before and after irrigation at 50 kPa with mobile drip irrigation (first experiment, 15 May 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	36.59	34.35	6.54	9.28	37.13	32.03	15.92	22.61
	10-20	40.60	37.53	8.19	11.64	41.40	36.42	13.67	19.42
	20-30	44.37	40.27	10.19	14.48	42.09	37.41	15.50	17.76
	30-40	45.44	40.97	10.90	15.48	45.11	40.39	11.67	16.58
15	0-10	32.84	30.97	6.03	8.56	40.76	35.14	16.00	22.71
	10-20	38.66	35.83	7.89	11.21	38.90	33.96	14.55	20.67
	20-30	40.55	36.68	10.57	15.01	42.45	37.75	12.45	17.68
	30-40	43.97	39.57	11.11	15.78	45.06	40.35	11.68	16.59
30	0-10	35.41	33.32	6.27	8.91	39.66	34.46	15.11	21.46
	10-20	41.99	38.75	8.36	11.87	39.93	35.17	13.55	19.24
	20-30	46.15	41.65	10.79	15.32	41.86	37.18	12.58	17.87
	30-40	47.37	42.57	11.29	16.03	44.46	39.81	11.66	16.56
45	0-10	34.88	32.86	6.15	8.73	39.93	34.87	14.51	20.61
	10-20	36.71	33.98	8.04	11.41	38.70	34.65	11.70	16.61
	20-30	45.58	41.27	10.45	14.84	41.60	37.21	11.82	16.78
	30-40	46.08	41.47	11.12	15.80	43.14	38.70	11.46	16.27
60	0-10	35.74	33.50	6.69	9.50	41.62	36.34	14.51	20.61
	10-20	38.13	35.17	8.41	11.94	39.61	35.51	11.53	16.37
	20-30	44.09	40.06	10.07	14.29	39.79	35.78	11.22	15.94
	30-40	43.52	39.15	11.17	15.86	38.30	34.40	11.31	16.07
75	0-10	40.14	37.55	6.88	9.77	38.30	33.23	15.24	21.64
	10-20	40.38	37.12	8.80	12.50	43.09	38.44	12.08	17.16
	20-30	46.30	41.87	10.57	15.01	41.38	37.28	11.00	15.62
	30-40	41.59	37.46	11.04	15.68	43.03	38.71	11.17	15.87

-Soil moisture content (weight, %) = [(humid weight – dry weight)/ dry weight] x 100
-Soil moisture content (vol. %) = (weight, %) x soil density
-Soil density in this experiment was 1.42 g/cm^3

Table C2: The soil water content under tower number one before and after irrigation at 50 kPa with mobile drip irrigation (second experiment, 1 June 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	35.53	32.31	9.98	14.17	42.55	36.67	16.04	22.78
	10-20	37.08	33.62	10.28	14.59	40.61	35.42	14.66	20.82
	20-30	44.74	40.88	9.43	13.39	43.96	39.16	12.27	17.42
	30-40	47.41	43.44	9.15	12.99	43.34	38.98	11.18	15.87
15	0-10	43.39	39.93	8.66	12.29	51.10	44.84	13.95	19.81
	10-20	37.61	34.26	9.77	13.88	45.78	40.48	13.08	18.57
	20-30	45.30	41.13	10.13	14.39	45.65	40.61	12.42	17.64
	30-40	45.27	41.51	9.05	12.85	43.20	38.69	11.66	16.55
30	0-10	40.02	36.82	8.71	12.36	40.67	35.65	14.09	20.01
	10-20	40.84	37.37	9.30	13.21	42.63	37.63	13.31	18.90
	20-30	41.00	37.37	9.70	13.77	46.86	41.55	12.78	18.15
	30-40	46.35	42.48	9.10	12.92	39.53	35.38	11.72	16.64
45	0-10	39.19	36.12	8.51	12.08	43.52	37.77	15.25	21.65
	10-20	39.00	35.79	8.99	12.77	40.17	35.48	13.20	18.75
	20-30	49.05	45.05	8.90	12.63	44.70	39.91	12.00	17.04
	30-40	43.12	39.43	9.35	13.27	42.35	37.94	11.62	16.50
60	0-10	37.14	34.05	9.08	12.90	43.99	38.16	15.28	21.69
	10-20	42.57	39.37	8.58	12.18	45.02	40.04	12.43	17.64
	20-30	46.40	42.73	8.60	12.21	41.72	37.52	11.22	15.93
	30-40	45.02	41.38	8.80	12.49	46.06	41.39	11.30	16.05
75	0-10	37.47	34.41	8.92	12.66	40.17	34.46	16.56	23.52
	10-20	40.91	37.50	9.08	12.89	44.54	38.81	14.75	20.95
	20-30	43.58	39.86	9.35	13.28	46.50	41.55	11.91	16.91
	30-40	45.41	41.46	9.51	13.51	43.78	39.44	11.00	15.63

Table C3: The soil water content under tower number one before and after irrigation at 100 kPa with mobile drip irrigation (first experiment, 15 May 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	37.58	35.25	6.59	9.36	43.01	37.00	16.24	23.07
	10-20	38.38	35.54	7.98	11.34	39.73	35.62	11.55	16.40
	20-30	44.02	39.93	10.23	14.53	45.17	40.85	10.57	15.01
	30-40	46.96	42.35	10.89	15.46	47.78	42.88	11.43	16.23
15	0-10	46.76	43.87	6.58	9.35	38.74	33.82	14.54	20.65
	10-20	41.61	38.28	8.69	12.33	35.30	31.74	11.23	15.95
	20-30	45.36	41.10	10.35	14.69	35.57	32.22	10.41	14.79
	30-40	44.31	39.88	11.11	15.77	46.67	41.98	11.17	15.85
30	0-10	40.12	37.74	6.31	8.96	37.13	33.02	12.45	17.67
	10-20	40.04	37.17	7.73	10.97	37.87	34.46	9.90	14.05
	20-30	44.22	40.25	9.88	14.03	44.23	40.01	10.55	14.99
	30-40	46.62	42.08	10.78	15.31	44.96	40.62	10.67	15.14
45	0-10	39.03	36.65	6.49	9.22	46.00	40.65	13.16	18.68
	10-20	45.37	42.16	7.61	10.81	40.40	36.41	10.98	15.59
	20-30	46.15	42.11	9.60	13.62	44.38	40.19	10.41	14.79
	30-40	45.21	40.83	10.73	15.24	46.14	41.61	10.89	15.46
60	0-10	43.60	41.02	6.30	8.94	39.82	35.00	13.78	19.57
	10-20	41.96	38.99	7.62	10.83	40.47	36.05	12.26	17.41
	20-30	45.30	41.46	9.25	13.13	43.77	39.57	10.61	15.06
	30-40	45.20	40.88	10.55	14.98	46.00	41.52	10.78	15.30
75	0-10	41.19	38.73	6.36	9.03	41.95	36.28	15.63	22.19
	10-20	43.05	39.90	7.90	11.22	40.50	35.94	12.67	18.00
	20-30	45.71	41.70	9.62	13.66	45.26	40.94	10.56	14.99
	30-40	46.14	41.66	10.74	15.24	45.42	40.98	10.82	15.37

Table C4: The soil water content under tower number one before and after irrigation at 100 kPa with mobile drip irrigation (second experiment, 1 June 2001)

Distance from drip tubes (cm)	Samples depth (cm)	**Before irrigation**				**After irrigation**			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	37.53	34.59	8.51	12.09	39.84	34.31	16.13	22.91
	10-20	42.09	38.78	8.55	12.14	39.22	34.65	13.19	18.73
	20-30	43.73	39.52	10.66	15.14	40.53	36.37	11.45	16.26
	30-40	41.23	37.40	10.24	14.54	45.13	40.53	11.35	16.12
15	0-10	33.15	30.45	8.88	12.62	39.08	33.99	14.95	21.23
	10-20	40.51	37.26	8.73	12.40	34.03	30.37	12.03	17.09
	20-30	41.71	37.81	10.31	14.64	42.87	38.38	11.70	16.61
	30-40	46.73	42.45	10.07	14.30	40.16	36.12	11.19	15.88
30	0-10	37.65	34.83	8.09	11.49	41.79	36.40	14.81	21.03
	10-20	39.87	36.40	9.52	13.52	38.40	34.18	12.35	17.54
	20-30	44.07	39.93	10.36	14.70	42.81	38.28	11.83	16.80
	30-40	44.82	40.69	10.115	14.41	43.07	38.69	11.32	16.08
45	0-10	34.67	32.09	8.05	11.43	41.92	36.32	15.42	21.90
	10-20	44.14	40.61	8.69	12.34	40.88	36.42	12.25	17.40
	20-30	44.02	39.97	10.15	14.41	43.05	38.78	11.02	15.65
	30-40	46.80	42.45	10.25	14.56	41.15	37.01	11.19	15.88
60	0-10	38.50	35.62	8.09	11.49	39.13	33.87	15.55	22.08
	10-20	41.00	37.62	8.98	12.75	36.38	32.22	12.89	18.30
	20-30	45.32	41.10	10.27	14.58	44.27	39.62	11.74	16.68
	30-40	44.37	40.23	10.28	14.59	46.24	41.64	11.04	15.68
75	0-10	37.83	34.97	8.17	11.60	38.73	33.77	14.69	20.86
	10-20	41.53	38.01	9.25	13.14	37.49	33.37	12.33	17.51
	20-30	44.15	40.06	10.19	14.47	43.15	38.80	11.21	15.92
	30-40	44.69	40.46	10.46	14.85	42.81	38.63	10.83	15.37

Table C5: The soil water content under tower number five before and after irrigation at 50 kPa with mobile drip irrigation (first experiment, 15 May 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	35.38	32.36	9.34	13.27	37.75	32.44	16.37	23.24
	10-20	38.57	34.79	10.87	15.44	39.93	34.91	14.37	20.40
	20-30	41.93	37.56	11.64	16.53	43.42	38.56	12.62	17.93
	30-40	43.64	39.04	11.79	16.74	46.65	41.48	12.46	17.70
15	0-10	37.70	35.01	7.68	10.90	45.81	39.59	15.70	22.29
	10-20	40.59	36.79	10.32	14.66	42.28	37.27	13.46	19.11
	20-30	42.57	38.24	11.34	16.11	47.59	42.16	12.89	18.30
	30-40	44.07	39.43	11.79	16.74	46.54	41.15	13.12	18.63
30	0-10	35.38	32.64	8.39	11.92	42.70	37.25	14.62	20.76
	10-20	41.29	37.38	10.46	14.85	40.52	35.93	12.77	18.14
	20-30	41.23	37.08	11.20	15.90	48.07	43.00	11.78	16.73
	30-40	43.44	38.98	11.46	16.27	46.40	41.36	12.19	17.30
45	0-10	35.30	32.77	7.72	10.96	40.71	35.26	15.46	21.96
	10-20	36.89	33.49	10.17	14.44	43.27	37.85	14.31	20.32
	20-30	43.06	38.71	11.22	15.93	44.24	39.41	12.28	17.43
	30-40	44.80	40.05	11.86	16.84	45.72	40.83	11.98	17.01
60	0-10	36.02	33.68	6.93	9.84	45.70	39.33	16.21	23.02
	10-20	37.24	33.97	9.62	13.66	45.07	39.35	14.53	20.63
	20-30	42.91	38.64	11.05	15.69	48.40	43.01	12.53	17.80
	30-40	45.37	40.75	11.32	16.08	47.49	42.51	11.71	16.64
75	0-10	38.04	35.71	6.53	9.28	41.21	35.53	15.97	22.68
	10-20	38.38	34.96	9.78	13.89	42.59	36.70	16.06	22.81
	20-30	42.25	38.03	11.09	15.75	45.92	40.26	14.05	19.95
	30-40	44.05	39.48	11.59	16.46	52.94	46.93	12.82	18.21

Table C6: The soil water content under tower number five before and after irrigation at 50 kPa with mobile drip irrigation (second experiment, 1 June 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	38.31	35.81	7.00	9.94	45.62	39.33	16.00	22.72
	10-20	40.18	36.91	8.87	12.59	43.62	38.79	12.44	17.66
	20-30	44.33	40.01	10.79	15.32	44.93	40.49	10.95	15.55
	30-40	44.33	40.28	10.07	14.30	43.69	39.61	10.32	14.66
15	0-10	37.80	35.36	6.90	9.80	46.24	39.87	15.98	22.69
	10-20	42.45	38.93	9.04	12.83	45.64	40.42	12.92	18.35
	20-30	43.93	39.62	10.89	15.47	44.69	40.28	10.94	15.54
	30-40	44.15	40.06	10.23	14.53	43.16	39.06	10.51	14.92
30	0-10	47.68	44.37	7.47	10.60	39.64	34.20	15.88	22.55
	10-20	45.23	41.26	9.63	13.68	42.42	37.76	12.34	17.53
	20-30	47.64	43.10	10.53	14.96	44.88	40.46	10.94	15.53
	30-40	45.43	40.94	10.96	15.57	44.63	40.53	10.10	14.35
45	0-10	44.54	41.39	7.62	10.82	46.93	40.64	15.48	21.98
	10-20	44.23	40.31	9.71	13.78	45.09	40.13	12.38	17.58
	20-30	47.73	43.17	10.56	14.99	43.64	39.35	10.90	15.48
	30-40	44.31	40.23	10.14	14.40	43.21	39.22	10.19	14.48
60	0-10	44.28	40.89	8.29	11.77	41.41	35.68	16.06	22.80
	10-20	46.06	41.72	10.40	14.77	44.11	39.14	12.70	18.03
	20-30	45.70	41.25	10.78	15.30	47.19	42.47	11.12	15.79
	30-40	48.62	44.12	10.21	14.50	44.00	39.91	10.24	14.53
75	0-10	43.04	39.94	7.76	11.02	47.26	40.62	16.35	23.21
	10-20	45.32	41.41	9.46	13.43	44.62	39.52	12.90	18.32
	20-30	49.11	44.15	11.25	15.98	46.16	41.47	11.32	16.07
	30-40	45.98	41.78	10.03	14.25	44.60	40.46	10.23	14.53

-Soil moisture content (weight, %) = [(humid weight – dry weight)/ dry weight] x 100
-Soil moisture content (vol. %) = (weight, %) x soil density
-Soil density in this experiment was 1.42 g/cm^3

Table C7: The soil water content under tower number five before and after irrigation at 100 kPa with mobile drip irrigation (first experiment, 15 May 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	36.15	33.34	8.42	11.96	44.01	37.84	16.29	23.14
	10-20	37.83	34.30	10.29	14.62	43.20	37.89	14.02	19.90
	20-30	43.36	39.05	11.02	15.64	48.02	42.28	13.58	19.29
	30-40	42.31	37.99	11.39	16.18	52.73	47.02	12.14	17.25
15	0-10	38.39	35.30	8.75	12.42	38.73	33.22	16.60	23.57
	10-20	38.98	35.12	10.99	15.61	46.98	41.17	14.11	20.04
	20-30	39.16	35.07	11.68	16.58	49.13	43.80	12.15	17.25
	30-40	44.87	40.23	11.55	16.41	48.48	43.04	12.64	17.95
30	0-10	36.66	34.15	7.34	10.43	48.01	42.09	14.07	19.97
	10-20	40.02	36.25	10.41	14.78	43.31	38.73	11.84	16.81
	20-30	42.39	37.94	11.73	16.66	45.57	40.42	12.75	18.10
	30-40	44.63	39.96	11.69	16.60	48.38	43.15	12.13	17.23
45	0-10	31.43	29.06	8.15	11.57	45.39	39.37	15.28	21.69
	10-20	38.50	35.20	9.39	13.33	44.65	40.08	11.40	16.19
	20-30	41.46	37.18	11.50	16.33	47.03	41.95	12.09	17.17
	30-40	42.74	38.23	11.79	16.74	46.91	41.56	12.87	18.27
60	0-10	36.52	33.64	8.56	12.16	44.80	39.03	14.78	20.98
	10-20	40.36	36.55	10.44	14.82	44.69	39.52	13.10	18.60
	20-30	42.18	37.86	11.41	16.20	48.06	42.57	12.90	18.31
	30-40	41.68	37.45	11.28	16.02	50.73	45.10	12.47	17.71
75	0-10	38.21	35.08	8.91	12.65	50.17	43.03	16.59	23.56
	10-20	41.34	37.34	10.70	15.19	46.68	40.73	14.63	20.77
	20-30	42.28	37.70	12.14	17.24	48.81	42.93	13.70	19.46
	30-40	44.52	39.77	11.94	16.96	52.17	46.28	12.73	18.07

Table C8: The soil water content under tower number five before and after irrigation at 100 kPa with mobile drip irrigation (second experiment, 1 June 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	32.28	30.13	7.15	10.16	43.60	37.63	15.86	22.52
	10-20	42.77	39.31	8.82	12.53	45.22	39.84	13.48	19.15
	20-30	45.25	41.05	10.24	14.54	48.95	43.99	11.27	16.00
	30-40	48.81	44.24	10.34	14.69	44.79	40.59	10.35	14.70
15	0-10	30.72	28.55	7.58	10.77	40.20	34.77	15.63	22.20
	10-20	33.27	30.54	8.97	12.73	42.06	34.01	13.63	19.36
	20-30	45.15	40.98	10.17	14.44	47.07	42.33	11.20	15.90
	30-40	49.50	44.88	10.28	14.59	44.10	39.97	10.31	14.64
30	0-10	32.86	30.59	7.40	10.50	38.80	33.39	16.21	23.02
	10-20	39.24	36.07	8.80	12.49	42.32	37.11	14.02	19.92
	20-30	44.86	40.54	10.65	15.12	46.52	41.70	11.55	16.41
	30-40	49.04	44.41	10.43	14.80	45.00	40.70	10.57	15.00
45	0-10	35.93	33.53	7.17	10.17	37.79	32.48	16.33	23.19
	10-20	44.01	40.42	8.89	12.62	42.91	37.81	13.50	19.16
	20-30	46.56	42.17	10.43	14.81	45.50	40.64	11.94	16.95
	30-40	46.37	42.00	10.41	14.78	47.15	42.53	10.86	15.42
60	0-10	30.41	28.39	7.13	10.13	38.80	33.34	16.39	23.28
	10-20	38.17	35.12	8.68	12.32	43.18	38.06	13.43	19.07
	20-30	49.05	44.39	10.51	14.92	46.00	41.19	11.66	16.56
	30-40	51.68	46.80	10.43	14.81	43.54	39.38	10.58	15.02
75	0-10	33.51	31.09	7.79	11.07	40.05	34.45	16.25	23.08
	10-20	42.23	38.77	8.92	12.67	42.57	37.72	12.84	18.24
	20-30	50.66	45.65	10.98	15.59	44.40	39.99	11.03	15.67
	30-40	47.13	42.68	10.41	14.79	45.16	40.86	10.51	14.94

Table C9: The soil water content under tower number nine before and after irrigation at 50 kPa with mobile drip irrigation (first experiment, 15 May 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	39.11	36.96	5.83	8.28	44.40	38.98	13.92	19.76
	10-20	42.32	39.36	7.53	10.69	41.31	36.98	11.69	16.61
	20-30	47.62	43.08	10.53	14.96	46.90	42.05	11.53	16.38
	30-40	47.91	43.36	10.51	14.92	43.09	38.76	11.18	15.87
15	0-10	37.70	35.56	6.00	8.52	40.74	35.71	14.08	19.99
	10-20	41.67	38.77	7.46	10.59	38.99	34.69	12.40	17.60
	20-30	46.14	41.88	10.17	14.44	41.99	37.61	11.64	16.53
	30-40	44.60	40.23	10.88	15.45	46.44	41.77	11.19	15.88
30	0-10	44.31	41.86	5.86	8.32	49.89	44.32	12.56	17.84
	10-20	43.78	40.72	7.53	10.69	39.17	35.06	11.72	16.65
	20-30	48.03	43.63	10.07	14.30	49.27	44.28	11.28	16.02
	30-40	42.33	38.25	10.66	15.14	43.62	39.29	11.01	15.64
45	0-10	40.86	38.60	5.86	8.31	44.52	39.48	12.77	18.14
	10-20	40.21	37.38	7.57	10.75	39.94	35.79	11.60	16.48
	20-30	48.12	43.73	10.06	14.28	44.40	39.78	11.61	16.49
	30-40	43.53	39.32	10.71	15.21	45.79	41.09	11.45	16.25
60	0-10	36.31	34.32	5.80	8.23	45.24	40.01	13.07	18.56
	10-20	40.95	38.14	7.37	10.47	36.47	32.78	11.26	15.98
	20-30	46.29	42.08	9.99	14.19	47.50	42.83	10.90	15.48
	30-40	44.66	40.41	10.52	14.94	46.26	41.85	10.54	14.96
75	0-10	44.37	41.75	6.26	8.89	47.05	41.28	13.97	19.84
	10-20	39.30	36.49	7.71	10.94	44.85	40.17	11.67	16.57
	20-30	47.45	43.03	10.26	14.57	46.03	41.47	10.99	15.60
	30-40	40.16	36.43	10.22	14.51	45.32	40.99	10.58	15.02

Table C10: The soil water content under tower number nine before and after irrigation at 50 kPa with mobile drip irrigation (second experiment, 1 June 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	36.27	34.12	6.30	8.95	36.36	31.80	14.31	20.33
	10-20	42.19	39.19	7.64	10.85	35.13	31.75	10.65	15.12
	20-30	46.13	42.27	9.13	12.96	41.19	37.64	9.42	13.37
	30-40	44.09	40.47	8.95	12.71	41.77	38.22	9.28	13.18
15	0-10	37.79	35.51	6.41	9.11	32.49	28.39	14.44	20.51
	10-20	40.57	37.56	8.00	11.36	34.72	31.55	10.04	14.26
	20-30	47.79	43.76	9.21	13.08	42.15	38.57	9.28	13.18
	30-40	44.79	41.09	9.02	12.81	43.07	39.37	9.39	13.34
30	0-10	36.32	34.32	5.82	8.26	37.85	33.32	13.60	19.31
	10-20	39.89	36.90	8.12	11.53	33.95	30.63	10.83	15.38
	20-30	48.11	44.17	8.91	12.66	42.61	39.04	9.13	12.97
	30-40	42.78	39.32	8.80	12.49	39.25	35.97	9.13	12.97
45	0-10	37.13	34.89	6.43	9.13	35.00	31.12	12.47	17.71
	10-20	43.52	40.51	7.44	10.56	33.70	30.74	9.63	13.67
	20-30	45.39	41.70	8.85	12.57	45.00	41.26	9.08	12.89
	30-40	44.12	40.51	8.90	12.64	41.21	37.82	8.94	12.70
60	0-10	37.34	35.14	6.27	8.90	33.56	29.34	14.40	20.45
	10-20	43.47	40.33	7.80	11.07	32.53	29.58	9.97	14.16
	20-30	46.29	42.38	9.21	13.08	41.98	38.35	9.47	13.44
	30-40	46.28	42.35	9.28	13.18	35.99	32.90	9.39	13.34
75	0-10	36.83	34.64	6.31	8.97	36.31	31.55	15.08	21.41
	10-20	44.44	41.12	8.09	11.48	37.34	33.71	10.78	15.31
	20-30	46.36	42.39	9.37	13.31	43.85	39.84	10.06	14.29
	30-40	44.85	41.13	9.04	12.84	44.03	40.24	9.42	13.38

Table C11: The soil water content under tower number nine before and after irrigation at 100 kPa with mobile drip irrigation (first experiment, 15 May 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	41.93	39.28	6.75	9.59	41.65	36.14	15.25	21.66
	10-20	38.48	35.59	8.14	11.56	40.73	36.16	12.65	17.96
	20-30	48.88	44.21	10.57	15.01	44.62	40.24	10.87	15.43
	30-40	44.20	39.96	10.61	15.06	43.32	39.05	10.96	15.56
15	0-10	38.23	35.76	6.89	9.79	43.21	37.66	14.74	20.93
	10-20	41.40	38.18	8.42	11.96	42.33	37.61	12.54	17.81
	20-30	44.43	40.24	10.43	14.80	47.36	42.79	10.70	15.19
	30-40	41.23	37.40	10.23	14.53	39.82	36.01	10.57	15.00
30	0-10	41.53	38.83	6.96	9.88	45.07	39.63	13.71	19.47
	10-20	39.42	36.22	8.83	12.54	44.75	40.04	11.75	16.69
	20-30	46.29	41.94	10.37	14.72	45.03	40.46	11.28	16.01
	30-40	41.85	37.83	10.64	15.11	40.40	36.15	11.74	16.67
45	0-10	38.99	36.44	6.99	9.93	41.12	35.92	14.46	20.54
	10-20	38.70	35.58	8.79	12.48	43.06	38.74	11.17	15.86
	20-30	44.90	40.61	10.58	15.03	44.77	40.30	11.09	15.75
	30-40	39.69	35.80	10.86	15.42	44.73	40.12	11.50	16.33
60	0-10	38.44	35.93	6.99	9.92	45.09	39.37	14.54	20.65
	10-20	37.47	34.53	8.52	12.10	41.65	36.94	12.76	18.13
	20-30	44.65	40.34	10.70	15.20	47.10	42.43	11.02	15.65
	30-40	37.04	33.45	10.72	15.22	48.50	43.52	11.43	16.23
75	0-10	39.21	36.71	6.81	9.67	36.69	32.17	14.03	19.92
	10-20	37.43	34.57	8.26	11.73	43.24	38.36	12.73	18.07
	20-30	43.68	39.68	10.07	14.31	44.70	39.99	11.77	16.71
	30-40	40.41	36.54	10.58	15.03	45.94	41.37	11.04	15.68

Table C12: The soil water content under tower number nine before and after irrigation at 100 kPa with mobile drip irrigation (second experiment, 1 June 2001)

Distance from drip tubes (cm)	Samples depth (cm)	Before irrigation				After irrigation			
		Wet weight (g)	Dry weight (g)	Soil moisture content		Wet weight (g)	Dry weight (g)	Soil moisture content	
				Weight (%)	Vol. (%)			Weight (%)	Vol. (%)
0	0-10	38.35	35.74	7.32	10.39	40.03	34.74	15.23	21.63
	10-20	44.41	40.57	9.46	13.43	42.72	38.00	12.43	17.65
	20-30	48.96	44.41	10.26	14.57	42.80	38.78	10.39	14.75
	30-40	45.87	41.71	9.99	14.19	43.46	39.48	10.07	14.31
15	0-10	35.54	33.02	7.63	10.84	43.89	38.25	14.72	20.91
	10-20	41.60	37.89	9.80	13.92	43.13	38.51	11.98	17.02
	20-30	49.36	44.91	9.91	14.08	43.97	39.77	10.55	14.98
	30-40	45.22	41.13	9.93	14.10	45.44	41.17	10.36	14.71
30	0-10	36.47	33.89	7.61	10.80	37.16	32.57	14.12	20.05
	10-20	40.99	37.65	8.87	12.60	43.40	38.91	11.52	16.36
	20-30	46.69	42.38	10.15	14.42	45.30	41.08	10.27	14.59
	30-40	47.83	43.60	9.71	13.78	42.81	38.85	10.19	14.46
45	0-10	33.97	31.60	7.51	10.66	37.27	32.60	14.34	20.37
	10-20	41.62	38.01	9.52	13.52	39.43	35.18	12.10	17.19
	20-30	45.33	41.23	9.95	14.13	42.53	38.39	10.78	15.31
	30-40	45.94	41.78	9.96	14.15	44.77	40.53	10.46	14.85
60	0-10	36.01	33.43	7.73	10.97	39.24	34.13	14.97	21.26
	10-20	41.17	37.68	9.26	13.14	39.03	34.72	12.42	17.64
	20-30	48.09	43.58	10.35	14.70	44.43	40.10	10.80	15.34
	30-40	42.32	38.71	9.32	13.23	45.74	41.53	10.14	14.40
75	0-10	37.70	35.09	7.45	10.57	36.76	31.89	15.27	21.69
	10-20	43.82	40.05	9.40	13.35	41.00	36.19	13.27	18.84
	20-30	45.97	41.81	9.96	14.14	47.53	42.94	10.68	15.17
	30-40	45.42	41.53	9.37	13.31	45.52	41.45	9.82	13.94

-Soil moisture content (weight, %) = [(humid weight – dry weight)/ dry weight] x 100
-Soil moisture content (vol. %) = (weight, %) x soil density
-Soil density in this experiment was 1.42 g/cm³

Appendix D- Worksheet for estimating the total costs of different irrigation systems

	-Information	**Irrigation systems**			
		C.P.S	**S.D.I**	**M.D.I**	
a-	Initial cost, €	....	....	....	#
				....	*
				....	
b-	Depreciation rate, %	....	....	....	#
					*
c-	Useful life, years	....	....	....	#
				....	*
d-	Interest rate, %	....	....	....	
e-	Total irrigated area, ha	....	....	....	
f-	Source of energy	....	....	....	
g-	Electricity price, €/kWh	....	....	....	
h-	Water price, €/m³	....	....	....	
i-	Maintenance, % from (a)	....	....	....	
j-	Labour cost, €/h	....	....	....	
k-	Tractor cost, €/h	....	....	....	
l-	No. of irrigations per season	....	....	....	
m-	Water required per irrigation, m³/ha	....	....	....	
n-	No. of crops per year	....	....	....	
o-	Yearly volume of water, m³ = (m)(e)(l)(n)	....	....	....	
p-	Energy requirement, kWh/(ha.a)	....	....	....	
q-	Yearly energy requirement, kWh = (e)(n)(p)	....	....	....	
r-	Total working time, h/ha	....	....	....	
	-Fixed costs				
1-	Depreciation per year = (a)/(c)	....	....	....	#
				....	*
				....	
2-	Interest = [(a)/2](d)	....	....	....	#
				....	*
				....	
3-	Insurance [1.5, 2 and 2% from (a), respectively], €	....	....	....	
4-	Total fixed costs, € = (1) + (2) + (3)	....	....	....	
5-	Fixed costs, €/(ha.a) = (4)/[(e)(n)]	....	....	....	
	-Variable costs				
6-	Charges of electricity equipment, €	....	....	....	
7-	Electricity cost, € = (g)(q)	....	....	....	
8-	Electricity taxes, € = 3.5% from (6) + (7)	....	....	....	
9-	Electricity added taxes, € = 16% from [(6) + (7) + (8)]	....	....	....	
10-	Total electricity cost, € = (6) + (7) + (8) + (9)	....	....	....	
11-	Maintenance, € = (a)(i)	....	....	....	
12-	Labour cost, € = (e)(j)(n)(r)	....	....	....	
13-	Tractor cost, € = (e)(k)(n)(r)	....	....	....	
14-	Water cost, € = (h)(o)	....	....	....	
15-	Total variable costs, € = (10) + (11) + (12) + (13) + (14)	....	....	....	
16-	Variable costs, €/(ha.a) = (15)/[(e)(n)]	....	....	....	
17-	Total costs, € = (4) + (15)	....	....	....	
	-Total costs, €/ha = (17)/[(e)(n)] or (5) + (16)	....	....	....	

= Pivot machine without sprinklers

* = Drip tubes, emitters and regulators

Worksheet for estimating the total costs of different irrigation systems (one season/year)

	-Information	**Irrigation systems**			
		C.P.S	**S.D.I**	**M.D.I**	
a-	Initial cost, €	60572	132200	56225	#
				15497	*
				71722	
b-	Depreciation rate, %	100/12	100/5	100/12	#
				100/5	*
c-	Useful life, years	12	5	12	#
				5	*
d-	Interest rate, %	0.08	0.08	0.08	
e-	Total irrigated area, ha	57.55	57.55	57.55	
f-	Source of energy	Elect.	Elect.	Elect.	
g-	Electricity price, €/kWh	0.064	0.064	0.064	
h-	Water price, €/m³	0.005	0.005	0.005	
i-	Maintenance, % from (a)	1.5	1.5	2	
j-	Labour cost, €/h	13	13	13	
k-	Tractor cost, €/h	13	13	13	
l-	No. of irrigations per season	5	12.5	5	
m-	Water required per irrigation, m³/ha	200	64	160	
n-	No. of crops per year	1	1	1	
o-	Yearly volume of water, m³ = (m)(e)(l)(n)	57550	46040	46040	
p-	Energy requirement, kWh/(ha.a)	360	128	208	
q-	Yearly energy requirement, kWh = (e)(n)(p)	20718	7366.4	11970.4	
r-	Total working time, h/ha	0.5	9.975	0.75	
	-Fixed costs				
1-	Depreciation per year = (a)/(c)	5047.67	26440.00	4685.42	#
				3099.40	*
				7784.82	
2-	Interest = [(a)/2](d)	2422.88	5288	2249	#
				619.88	*
				2868.88	
3-	Insurance [1.5, 2 and 2% from (a), respectively], €	908.58	2644	1434.44	
4-	Total fixed costs, € = (1) + (2) + (3)	8379.13	34372.00	12088.14	
5-	Fixed costs, €/(ha.a) = (4)/[(e)(n)]	**145.60**	**597.25**	**210.05**	
	-Variable costs				
6-	Charges of electricity equipment, €	92.03	92.03	92.03	
7-	Electricity cost, € = (g)(q)	1325.95	471.45	766.11	
8-	Electricity taxes, € = 3.5% from (6) + (7)	49.63	19.72	30.03	
9-	Electricity added taxes, € = 16% from [(6) + (7) + (8)]	234.82	93.31	142.11	
10-	Total electricity cost, € = (6) + (7) + (8) + (9)	1702.43	676.51	1030.28	
11-	Maintenance, € = (a)(i)	908.58	1983	1434.44	
12-	Labour cost, € = (e)(j)(n)(r)	374.08	7462.80	561.11	
13-	Tractor cost, € = (e)(k)(n)(r)	374.08	7462.80	561.11	
14-	Water cost, € = (h)(o)	287.75	230.20	230.20	
15-	Total variable costs, € = (10) + (11) + (12) + (13) + (14)	3646.91	17815.13	3817.14	
16-	Variable costs, €/(ha.a) = (15)/[(e)(n)]	**63.37**	**309.56**	**66.33**	
17-	Total costs, € = (4) + (15)	12026.04	52187.31	15905.28	
	-Total costs, €/ha = (17)/[(e)(n)] or (5) + (16)	**208.97**	**906.82**	**276.37**	

= Pivot machine without sprinklers

* = Drip tubes, emitters and regulators

Worksheet for estimating the total costs of different irrigation systems (two seasons/year)

	-Information	Irrigation systems C.P.S	S.D.I	M.D.I	
a-	Initial cost, €	60572	132200	56225	#
				15497	*
				71722	
b-	Depreciation rate, %	100/12	100/5	100/12	#
				100/5	*
c-	Useful life, years	12	5	12	#
				5	*
d-	Interest rate, %	0.08	0.08	0.08	
e-	Total irrigated area, ha	57.55	57.55	57.55	
f-	Source of energy	Elect.	Elect.	Elect.	
g-	Electricity price, €/kWh	0.064	0.064	0.064	
h-	Water price, €/m³	0.005	0.005	0.005	
i-	Maintenance, % from (a)	1.5	1.5	2	
j-	Labour cost, €/h	13	13	13	
k-	Tractor cost, €/h	13	13	13	
l-	No. of irrigations per season	5	12.5	5	
m-	Water required per irrigation, m³/ha	200	64	160	
n-	No. of crops per year	2	2	2	
o-	Yearly volume of water, m³ = (m)(e)(l)(n)	115100	92080	92080	
p-	Energy requirement, kWh/(ha.a)	360	128	208	
q-	Yearly energy requirement, kWh = (e)(n)(p)	41436	14732.8	23940.8	
r-	Total working time, h/ha	0.5	9.975	0.75	
	-Fixed costs				
1-	Depreciation per year = (a)/(c)	5047.67	26440.00	4685.42	#
				3099.40	*
				7784.82	
2-	Interest = [(a)/2](d)	2422.88	5288	2249	#
				619.88	*
				2868.88	
3-	Insurance [1.5, 2 and 2% from (a), respectively], €	908.58	2644	1434.44	
4-	Total fixed costs, € = (1) + (2) + (3)	8379.13	34372.00	12088.14	
5-	Fixed costs, €/(ha.a) = (4)/[(e)(n)]	**72.80**	**298.63**	**105.02**	
	-Variable costs				
6-	Charges of electricity equipment, €	92.03	92.03	92.03	
7-	Electricity cost, € = (g)(q)	2651.9	942.9	1532.12	
8-	Electricity taxes, € = 3.5% from (6) + (7)	96.04	36.22	56.85	
9-	Electricity added taxes, € = 16% from [(6) + (7) + (8)]	454.4	171.38	268.97	
10-	Total electricity cost, € = (6) + (7) + (8) + (9)	3294.37	1242.54	1950.06	
11-	Maintenance, € = (a)(i)	908.58	1983	1434.44	
12-	Labour cost, € = (e)(j)(n)(r)	748.15	14925.59	1122.23	
13-	Tractor cost, € = (e)(k)(n)(r)	748.15	14925.59	1122.23	
14-	Water cost, € = (h)(o)	575.50	460.40	460.40	
15-	Total variable costs, € = (10) + (11) + (12) + (13) + (14)	6274.75	33537.12	6089.35	
16-	Variable costs, €/(ha.a) = (15)/[(e)(n)]	**54.52**	**291.37**	**52.90**	
17-	Total costs, € = (4) + (15)	14653.87	67909.12	18177.49	
	-Total costs, €/ha = (17)/[(e)(n)] or (5) + (16)	**127.31**	**590.00**	**157.93**	

= Pivot machine without sprinklers

* = Drip tubes, emitters and regulators

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