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Soil-Water-Plant Properties as Criteria for Mobile Irrigation System Design

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ABSTRACT

Drip irrigation and center pivot or linear move systems differ from the other conventional irrigation methods by making high frequency irrigation possible, and thus have the potential of producing higher yields. However expensive equipment and costly setting out of the system limit its expansions to large fields. High energy demands sensitivity to windy conditions and possible leaf burn where saline water are used are some limitation of the irrigation machine. The main objective of this research was to investigate the possibility to combine the advantages of these method as a mobile drip irrigation system. The main limitation of the mobile drip method seems to be the economical constraint to apply the water at high discharge rate to have sufficient area coverage, which may result in runoff and nonuniform water application. Methods to estimate the the size of the created ponded area as affected by the soil hydraulic conductivity, the dripper discharge, the irrigator velocity and the soil surface microtopography were developed and compared with field measurements. The methods to estimate the surface conditions were then served to determine the boundary conditions for the computation of the water and salt flow in the soil profile, and for estimating relative dry matter yield by adapting the Childs and Hanks (1975) methods. Field measurements and model results show good agreement. Yields obtained by the mobile drip method were slightly higher than yields obtained by the conventional methods, sprinkle for alfalfa and drip for onion. An economical feasibility study was made to define the machine discharge, velocity and area coverage which justify the mobile method and to compare performance of available irrigators.

1.0 INTRODUCTION - OBJECTIVES OF THE RESEARCH

Drip irrigation center pivot or linear move systems differ from the other traditional irrigation method (sprinklers, flood, furrow) by making high frequency irrigation possible, and thus reduce the matric and osmotic heads fluctuation, and have the potential of producing higher yields. However, drip irrigation of large, open fields of field crops or vegetables is limited due to the high price of drip equipment, high labor cost for setting out and collecting the laterals in critical time schedules and the clogging of emitters. High energy demand because of the high water pressure required by the center pivot and the linear move systems, and nonuniform water application due to winds and possible leaf burn, where saline waters are used, are some limitation of the irrigation machine systems.

The main objective of this research was to investigate the possibility of a low energy mobile drip system which moves slowly and continuously through a crop, creating a "line" water application with a uniform water application. However the economical constraint to apply water at a high discharge rate to have sufficient area coverage, may results in a possible runoff and nonuniform water application. Thus, there is a need for methods to predict the surface water ponding and water and salt flow in the soil profile which take in account the soil hydraulic properties, the applied discharge rate and the irrigator system characteristic.

To meet this need this research had the following objectives:

- 1) To develop a model of two-dimensional water flow for distribution of water and solutes under mobile drip conditions.

- 2) To determine the crop response to mobile drip irrigation, and to compare yields parameters of mobile drip irrigation and the conventional irrigation methods.

3) To develop criteria for designing the mobile drip irrigation system and to apply the criteria for engineering design of the mobile system.

Massive sampling is required to estimate the soil hydraulic properties which are the main input parameters needed for estimating the soil surface ponded area and thus, the possibility of nonuniform water application.

A simple field method for estimating the hydraulic properties, which will make the massive sampling possible was developed and is presented in Chapter 2.

Methods to estimate the ponded area and the water and salt flow in the soil as a function of the soil hydraulic properties and the systems characteristic are summarized in Chapter 3. Also in this chapter comparison of yield parameters between the mobile drip irrigation and the conventional methods.

An economical feasibility study based on possible discharge rate and irrigator velocity is presented in Chapter 4.

2.0 A SIMPLE FIELD METHOD FOR ESTIMATING THE HYDRAULIC CONDUCTIVITY AND MATRIC POTENTIAL-WATER CONTENT RELATIONS OF SOILS

Soil hydraulic conductivity-water content and matric head-water content functions are needed by many models to predict the factors that influence irrigation design, crop yield, or leaching requirements, etc. These measurements are not easily made. Moreover, laboratory and field measurements often differ due to the differences in soil conditions. Adequate field evaluation may also require many measurements to reflect spatial variability. Thus, relatively simple methods are needed to determine these functions in the field.

Most of the relatively simple field procedures developed so far are based on simplifying assumptions concerning the unsaturated hydraulic conductivity (k)-water content (θ) function or the diffusivity $D(\theta)$ function. Libardi et al. (1980) proposed a method to estimate k - θ from water content changes with time after steady infiltration, assuming a unit gradient. An exponential relationship between k - θ or a power function depending on the average θ in the profile with time, were also assumed. Russo and Bresler (1980) utilize the Brooks and Corey (1964) equations for the hydraulic properties and have applied the methods of Bouwer (1966) and Talsma (1969) to estimate the saturated hydraulic conductivity (K_s), the air entry matric head (h_w) and the sorptivity to develop those equations. However, these methods are still quite time-consuming, somewhat complicated and unreliable in

some situations (aggregated soils). Thus, there is a need for better and more usable methods.

This paper describes a reliable, quick and practical field method to estimate the matric head (h)- θ and the k-h functions, hereafter called the "dripper" method. Water is applied at a constant rate to a soil surface (originally quite dry), and the k-h and θ -h relations are estimated from measurements of the saturated area on the soil surface and the distance from the ponded radius to the wetting front as a function of dripper discharge rate for several rates. Water is applied with "drippers" used commercially in drip or trickle irrigation.

2.1 THEORY

When water is applied at a constant rate to a point on the soil surface, a ponded zone is created. The area of this ponded zone increases with time at the beginning, but later approaches a constant circular area (Brandt et al. 1971, Bresler 1977). When the radius of this ponded zone has approached a constant value, steady state conditions can be assumed and steady-state solutions of the two-dimensional equation can be applied to solve the flux "q" from the ponded zone. Wooding (1968) assumed the k-h relationship to be

$$K(h) = e^{-\alpha h} \quad [1]$$

and derived a solution as:

$$q = \frac{Q}{\pi r^2} = K_s + \frac{4}{\pi} \cdot \frac{1}{r} \cdot \psi \quad [2]$$

where " α " is a soil parameter, "q" is flux, " K_s " is the saturated hydraulic conductivity, "r" is the radius of the ponded zone at the

soil surface, "Q" is the dripper discharge rate and

$$\psi = \int_{h_0}^h K(h) dh = \int_{\theta_0}^{\theta} D(\theta) d\theta \quad [3]$$

where θ_0 is the initial water content of dry soil. The first term (K_s) in Eq. [2] represents the flux due to gravitational flow, whereas the second term arises from the flux due to matric head gradients only. The right term in the right hand side of Eq. [2] is similar to the solution (no pre-assumed K-h relationship) of the steady-state two-dimensional flow from a disk source on the soil surface as a result of absorption only (Philip 1969).

Eq. [2] is linear so estimates of K_s and ψ - the "matric flow function" can be determined from a linear regression of q vs $1/r$ if several discharge rates are used. This information is sufficient to develop explicit expression for the hydraulic function parameters where the $K(h)$ function type are known, or can be assumed.

Two of the most useful approaches to describe the hydraulic properties of a stable homogeneous unisotropic soils were examined. The first k-h functional relation assumed is that of Eq. [1]. By substituting (1) to (2):

$$q = K_s + \frac{4}{\pi} \cdot \frac{K_s}{\alpha} \cdot \frac{1}{r} \quad [4]$$

K_s is estimated from the intercept of the linear regression of q vs. $1/r$ (Eq. [2]), and α is then estimated from

$$\alpha = \frac{4 K_s}{b \pi} \quad [5]$$

where "b" is the slope of the linear regression equation.

The second set of functional relations between K and h and between h and θ was assumed by Brooks and Corey (1964) as:

$$k(h) = K_s \cdot \left[\frac{h_w}{h} \right]^\eta \quad ; h \leq h_w \quad [6]$$

$$\theta(h) = (\theta_s - \theta_o) \cdot \left[\frac{h_w}{h} \right]^\beta + \theta_o \quad ; h \leq h_w \quad [7]$$

$$K = K_s \quad \text{and} \quad \theta = \theta_s \quad ; h > h_w \quad [8]$$

where θ_s is the saturated water content of the ponded zone, h_w is the "bubbling" head (on-entry head) and the constants η and β are characteristics of the soil.

Since Eq.[6] contains one more parameter (h_w) than Eq. [1] an additional measurable soil parameter is required to obtain estimation of K_s , h_w , η and β . The sorptivity (S) can be estimated from the horizontal distance " x " from the ponded radius to the wetting front at any time as:

$$S(\theta_s, \theta_o) = \int_{\theta_o}^{\theta_s} x / t^{0.5} d\theta \approx x (\theta_s - \theta_o) / t^{0.5} \quad [9]$$

Philip (1969) defined a diffusivity function D^* which is related to S as

$$D^* = \pi S^2 / 4(\theta_s - \theta_o)^2 \quad [10]$$

Crank (1975) has suggested that D^* represents a nonlinear diffusivity function where $D(\theta)$ may change by 200-fold with little changes in D^* .

Crank has also defined D^* as

$$D^* = \frac{(1+\gamma)}{(\theta_s - \theta_o)^{(1+\gamma)}} + \int_{\theta_o}^{\theta_s} (\theta - \theta_o)^\gamma \cdot D(\theta) d\theta \quad [11]$$

where γ is a parameter having the value of about 0.67 for wetting conditions.

A relation involving these assumptions can be derived by substituting [6] into the left hand side of [3] and then into [2], integrating and taking the upper limits of the integral to be $h = 0$ and $\theta = \theta_s$ (due to the free water condition of the ponded zone).

$$q = K_s - \frac{4 h_w K_s}{\pi} \cdot \frac{\eta}{\eta-1} \cdot \frac{1}{r} \quad [12]$$

The above equation is only valid if $\eta > 2$ so $h_o^{1-\eta} \rightarrow 0$.

Russo and Bresler (1980) used Eqs. [10], [11] to develop an explicit expression to the soil parameter η , when the values of K_s , h_w , θ_s , θ_o , and S are known from independent measurements,

$$\eta = \frac{(n+2) [-20 K_s h_w (\theta_s - \theta_o)]}{(3n + 8) \pi S^2} + \frac{(3n + 8)}{(3n + 10)} \quad [13]$$

where n is an integer whose value depends on the model chosen to describe the size distribution and organization of soil pores. Russo and Bresler (1980) concluded that $n=0$, which is in accordance with the "series-parallel model" of Childs and Collis-George (1950), fits many soils.

If a series of measurements of different flux values are plotted vs. $1/r$, and regression parameters determined, h_w can be calculated from:

$$h_w = \frac{-b \pi (\eta-1)}{4 K_s \eta} \quad [14]$$

where "b" is the slope of the "q" vs. 1/r line. Eq. [14] can then be combined with Eq. [13] to give

$$\eta = 0.5 (C + C_1) + [(C + C_1)^2 - 4C]^{0.5} \quad [15]$$

$$\text{where } C = \frac{(n + 2) \cdot 5 \cdot b \cdot (\theta_s - \theta_o)}{(3n + 8) \cdot S^2} \quad ; \quad C = \frac{1.25}{S^2} \cdot b \cdot (\theta_s - \theta_o) \quad \text{for } n=0$$

$$\text{and } C_1 = \frac{3n + 10}{3n + 8} \quad ; \quad C_1 = 1.25 \quad \text{for } n=0$$

The value for β can be approximated from Brutaerts' (1967) relations as

$$\beta = (\eta - 2)/(n + 2) \quad [16]$$

2.2 PROCEDURES

The comparisons were carried out on three different soils in three locations:

- a) Sandy loam in Arava, Israel
- b) Coarse sand in Yotvata, Israel
- c) Millville silt loam in Logan, Utah.

Some properties of the soils are summarized in Table 1.

A water storage bottle with Marriott type burette was connected to drippers (used commercially for drip irrigation) to obtain different constant discharge rates. The drippers were located in the center of a leveled and relatively smooth plot about 0.8 x 0.8 m square. After water flow was started the ponded zone diameter was measured until it had reached a constant value, which usually occurred within 15 minutes. The border of the ponded area was determined visually as the point where the free-water (as indicated by "glistening" surface) zone ended. This is the same technique used to determine when a soil is saturated in determining the saturation percentage. An equivalent diameter was estimated by measuring the actual diameter in several directions.

Measurements of the wetting front distance as a function of time from the border of the ponded zone were made when the ponded zone reached its stable size. At the end of the run, measurements of water content were taken in the ponded zone θ_s and beyond the wetting front θ_o .

Thus, this method is simple, requiring only surface measurements of area of the ponded zone, distance from the ponded zone to the wetting front and dripper discharge rate. It is nondestructive except for the small area required for measurements of θ_s and θ_o and readily

adapted to many field situations. It also requires a small amount of water so the method can be used in areas remote from a water source. Thus this method requires only a set of drippers with different discharge rates, a large <25 liter/water storage bottle, a scale for measuring distances, a timer and a calibrated container for measuring dripper discharge rate.

Field measurements of the θ -h function were taken in Arava and Yotvata soils using 12 mercury tensiometers placed at depths from 0.15 to 0.4 m in a 3 x 3 m square plot. Eight plots were established randomly in a 0.3 hectare field on the Arava soil and six plots were randomly chosen in a 0.15 hectare field in Yotvata soil. The soil was then wetted and covered by a sheet of white polyethylene and an additional 0.05m soil added to minimize soil temperature fluctuations. At different tensiometer readings a soil sample was taken from the immediate vicinity of the tensiometer cup, and the corresponding gravimetric water content was determined. Bulk density was also measured at the same spot using a non-destructive soil sampler (Blake 1965). Saturated water content, θ_s , was taken gravimetrically immediately after wetting.

Field measurements of the k- θ function for a drained profile were made on 6 replicates in Arava soil. Three mercury tensiometers were located at 0.10, 0.20, 0.30 and 0.40 m, in a 5.4 x 5.4 m square plot. The plot was then flooded. White polyethylene sheet was covered with about 0.05 m soil to minimize evaporation and temperature effects. Time interval increments of tensiometer readings ranged from 30 minutes at the beginning to several hours when changes were slower. Total time for each measurement was about 5 days. Soil water content was estimated using the water retention curve measured previously. The

hydraulic conductivity for each depth increment was determined from Eq. [3] of Bresler and Kemper (1970).

The values of K_s and h_w , for the Arava and Yotvata soils were determined using the "air-entry-permeameter" method of Russo and Bresler (1980). Three locations were randomly chosen for each soil with 6 replicates in each location.

For purposes of comparison, the h - θ relation for Millville silt loam was measured using a pressure plate method.

A cylinder was used for field measurements of infiltration at Logan and to measure K_s (which was assumed to be equal to the steady state infiltration rate after a long time). The sorptivity "S" was estimated on the same sites used for infiltrometer tests where $S = I/t^{0.5}$ where "I" is cumulative infiltration. A cylinder 0.3 m in diameter and 0.3 m high was forced into the soil to a depth of 0.2 m. The water was applied onto a dense screen to minimize soil surface changes.

2.3 RESULTS AND DISCUSSION

The ponded zone radius as a function of time and dripper discharge is shown in Figures 1-3 for Yotvata, Arava, and Logan soils respectively, to check on the assumption of steady value after a few minutes. The radius of the ponded zone increased rapidly initially, but approached a constant value after about 10 minutes. The ponded radius increased as the discharge rate increased or as the hydraulic conductivity decreased. About the same final ponded radius was measured for 4.6 l/h discharge rate at Logan, 40 l/h at Arava and 100 l/h at Yotvata soils where the K_s values are .0071, .0561 and .2092 mm/sec (Table 2)

respectively. The length of the time to approach steady state also increased as the discharge rate increased.

Figure 4 shows a plot of the relationship between flux and $1/r$ for the three soils. Note that a wide range of discharge rates is needed to cause the data to "spread out". It can be seen from Figure 4 that both the saturated hydraulic conductivity " K_s ", (the intercept) and the matric flow function " ψ " (the slope) decrease as the soil texture is finer, Yotvata > Arava > Logan.

Values of K_s and α as estimated by the several methods are shown in Table 2. There was good agreement between K_s values measured by the "dripper" method and those determined by the conventional one-dimensional infiltrometer methods (differences of 3, 2 and 11 percent for Arava, Yotvata and Logan soils respectively). There was also good agreement between values estimated by the "dripper" method and the "drainage profile" method (6 percent difference for both Arava and Yotvata soils).

Comparison of the hydraulic parameters as estimated for the "Brooks-Corey" $K-h$ and $\theta-h$ functions (Equations 6-8) by the different methods is summarized in Table 3. Values of sorptivity that were estimated by the "air-entry-permeameter" are also summarized in Table 3. Similar values of the soil parameter η were determined by the three different methods (5, 8 and 2 percent differences for Arava, Yotvata and Logan soils respectively). Similar estimations for the parameters β , by the different methods were obtained also. The variations in the estimation of the air-entry-head h_w are low for Arava soil but are higher for the two other soils. The difference in h_w determined by the "drainage -profile" and by the "drip" methods are 32 and 50 percent for

Yotvata and Logan soils respectively. However the physical difference between the above mentioned values of h_w is very small (≈ 40 mm H_2O). About the same values of sorptivity were found at Logan when the measurements were made from cumulative infiltration or from wetting front distance with time.

It should be noted that since this new "dripper" method for estimating the soil water hydraulic properties is based on "pre-assumed" K - h and θ - h functions, the limitations of those functions should be considered. These functions are fitted mostly to the wetter region of soil water properties. We have found considerable error when we tried to extrapolate these functions to the wilting point and air-dry water content range. Thus, when using them for evapotranspiration simulation we have had to adjust those functions on the dry end.

Also, when applying the steady-state solution for the flux from a steady ponded area, a homogenous soil with uniform water content is assumed. The "dripper" method actually senses some kind of average of the surface hydraulic properties. Under field conditions the above assumptions are not always met. The soil surface often changes upon wetting regardless of the method used. Thus, additional research may be needed to evaluate the importance of this factor. Preliminary results indicate that drippers' ponding may be very useful to evaluate such changes on surface crusting as a function of time.

2.4 SUMMARY AND CONCLUSIONS

The "dripper" method proposed herein gives estimates of the saturated hydraulic conductivity and the matric flux potential from measurements of the ponded radius and water flux, for several flux

rates on the soil surface. Measurements of the sorptivity can also be made as the horizontal distance from the ponded area to the wetting front as a function of time. Other hydraulic relations such as water content-matric head ($\theta-h$), and hydraulic conductivity-matric head ($K-h$) can be derived according to the hydraulic function assumed. Good agreement was obtained for K_s , $K-h$ and $\theta-h$ relations for the "dripper" method and direct field and laboratory measurements.

The "dripper" method is simple and applicable to a wide range of soils. The system requires only a set of drippers with different discharge rates, a large (25 liter) bottle, a scale for measuring distances, a timer and a calibrated container for measuring the dripper discharge. Measurements can be taken in remote locations where the water supply is limited because very little water is required. Since the time required for measuring is about an hour, the method can be used for extensive sampling for spatially heterogeneous fields. The "dripper" method is not destructive (except for ponded and unwet water content sampling) so it can be adapted to measuring changes in soil hydraulic properties with time at about the same sampling site.

Derivations of soil hydraulic properties by this dripper method are, of course, no better than the pre-assumed hydraulic functions. Also, the soil in the sampling site (about 1 m square) is assumed to be homogenous with uniform initial water content in the wetted area, which may not always be true under field conditions.

Table - 1: Soils' Properties.

Soil	Sand (%)	Silt (%)	Clay (%)	θ_s	θ_o
Arava	83	8	9	.36	.031
Yotvata	94	3	3	.331	.026
Logan	29	16	55	.46	.05

Table - 2: Comparison of K_s and α , of soils under study, as measured by a different method, assuming Equation 1.

Soil	Method	K_s mm/sec	α 1/mm
Arava	Direct		0.0068*
			0.0192**
	Air entr permeam.	.0543 (.003)	
	Field dripper	.0561 (.005)	0.0072
	Direct		0.0052*
Yotvata	Air entr permeam.	.2056 (.025)	
	Field dripper	.2092 (.039)	0.0055
	Infiltrometer	.0063 (.0032)	
Logan	Field dripper	.0071	0.0075

( ) - standard error of the number above

Table - 3: Comparison of the hydraulic properties of soils under study, as measured by different methods, assuming Equations 6-8.

Soil	Method	K_s mm/sec	η	β	h_w mm	S mm/sec
Arava	Drainage profile		3.55 (0.16)	.611	-93.3	
	Air entr permeam.	.0543 (.003)	3.51	.836	-108.5 (21.0)	1.2 (.43)
	Field dripper	.0561 (.005)	3.36 (0.08)	.681 (.015)	-98.3 (2.2)	1.2*
Yotvata	Drainage profile		4.90**	1.448	-94.4	
	Air entr permeam.	.2056 (.025)	4.47	1.234	-112.0 (32)	2.08 (.48)
	Field dripper	.2092 (.039)	4.52 (0.26)	1.258 (0.085)	-139.1 (6.60)	2.08*
	pressure plate		2.48**	.239	-40.0	
Logan	Infiltr.	.0063 (.0032)				
	Field dripper	.0071	2.528	0.264	80.0	.55

() - standard error of the number above

* - values of sorptivity from the cylinder method

** - values of η from water retention curve (Eq. 16, $n=0$)

Figure 1. Radius of the ponded zone versus time at several trickle discharges -- Yolvata soil.

Figure 2. Radius of the ponded zone versus time at several trickle discharge -- Arava soil.

Figure 4. Flux density as related to $1/\text{radius}$ of the ponded zone.

3.0 WATER AND SALT FLOW FROM A MOBILE DRIP SOURCE

The economical constraint to emit at a relatively high discharge rate results in a possible runoff and non-homogeneous water application. Thus, emphasizes the need for methods to predict the size of the ponded zone created in the vicinity of an emitter, and to compute the result water and salt flow in the soil profile.

This chapter describes quantitative methods to evaluate the water flow from mobile drip irrigator which consist on:

- a) A model to determine the ponded area on the soil surface as a function of the soil hydraulic properties, the irrigator discharge rate and velocity and the field surface structure (elevated rows, furrows etc.).
- b) A model to compute water and salt flow in the soil profile. The model of Childs and Hanks (1975) was adapted to the conditions of mobile drip source.

Field experiments were conducted for evaluation of the models results and for comparison of the high frequency mobile drip irrigation method with two common irrigation method, sprinklers for alfalfa and drippers for onion.

3.1 A MODEL TO DETERMINE THE PONDED AREA

Unlike the common stationary drip irrigation where a circular ponded area is created around the dripper on the soil surface (Brandt et al. 1971), a different geometry and consequently physical boundary conditions are developed when moving the water source (dripper) along the field. Where the water source is a single (a cluster of drippers with certain discharge rate), a ponded strip is created (Figures 5a). This zone is then moving with the irrigator along the field. If, instead, there are multiple drippers along the irrigator wing (Figure 5b), spread in such a distance

from each other so it create a mutual ponding zone, a "plane" ponded area is created and is moving with the irrigator along the field.

Figure 5a - Ponded area on the soil surface from single moving sources.

Figure 5b - Ponded area on the soil surface from multiple moving sources.

The single source will probably be applied where the seed-bed is prepared as an elevated rows. Then, the geometry (microtopography) of the soil surface is another factor involved in the shape and dimension of the ponded area. The multiple source will be probably applied to forages or grains. For both cases multiple and single sources it is more convenient to express the discharge rate per unit length Q/l . For the multiple sources "l" is unit length of the irrigator wing. For the single sources where the ponded strip width is limited by the soil surface, "furrows" like, it is

convenient to set "1" as the width of furrow base.

The basic assumption of the proposed method to estimate the ponded zone is that for certain discharge rate and soil surface hydraulic properties, the same ponded area is created, regardless of the actual geometry of this ponded area.

The size of the final ponded area, usually obtained after about 10 minutes of irrigation (Figures 1-3) can be derived from Equation 2. Bresler (1977) derived for the exponential K-h relations

$$r = \left\{ \left[\frac{2}{\alpha \pi} \right]^2 + \frac{Q}{\pi K_S} \right\}^{0.5} - \frac{2}{\alpha \pi}$$

$$A = \pi \cdot r^2 \quad [17]$$

r can be derived, also, from equation 13 where the "Brooks-Corey" K-h and H-h relations are assumed:

$$r = \left\{ \left[\frac{2 h_w}{(1-\eta)} \right]^2 + \frac{Q}{\pi K_S} \right\}^{0.5} - \frac{2 h_w}{\pi (1-\eta)}$$

$$A = \pi \cdot r^2 \quad [18]$$

The above assumption was checked and evaluated in this research.

Another assumption is that where the ponded area is large enough so the influence of the borders of this zone on water absorption is small relative to that of the central ponded area, a one-dimensional infiltration and water flow theory can be applied. This assumption is usually met for the case of the high discharge rate involved in the mobile drip irrigation.

Computation of the ponded area A(t) as a function of time from irrigation beginning can then be made based on Philip (1957) solution for one-dimensional infiltration from a ponded soil surface to a homogeneous soil. For short time ($t < t_c$) the effect of the gravimetric component is very small

$$I = S t^{0.5}$$

[19]

where I is cumulative infiltration. The time t_c of which the gravimetric component should be included can be determined from Talsma (1969)

$$t_c = 0.1 (2.5/3 K_s)^2 \quad [20]$$

For the long time infiltration

$$I = S t^{0.5} + K_s t \quad [21]$$

Note that methods to estimate K_s and S were introduced in Ch. 2.

The ponding area as a function of time created by a point source is computed as a stepped function

$$A(t) = \sum_{m=1}^I A_m^* \quad [22]$$

where

$$A_i^* = \frac{V_i^j}{I_i^j} \quad [23]$$

and

$$V_I(t) = V_I^j = Q \cdot t - \sum_{m=1}^{I-1} A_m^* \cdot I_m^j \quad [24]$$

where A^* is a segment ponded area, the subscript i is an index denotes the increment ponded area, the superscript j denotes the time, I_i^j is cumulative infiltration in the ponded area segment i at the time j , V_i^j is a cumulative volume of water added to the ponded area segment i at the time j and m is a summation index.

When the water source is moving at a constant velocity along the field we assume that when the distance that a moving emitter passes in a time equal to the time length needed to the ponded zone to approach it's final size is less than that of the ponded zone steady-state radius, the size of

the "moving" ponded area will not differ from that of the "stationary" final ponded area size.

$$\begin{aligned} \text{for } t_v \geq t_p \quad A &= A_f \\ \text{for } t_v < t_p \quad A &= [A | t=t_p=t_v] \end{aligned} \quad [25]$$

where A_f is the final stationary ponded area, t_p is the time takes to the ponded zone borders to reach a distance "x" ($x \leq A_f/l$) from a stationary water source, $t_v = x/v$ is the time takes to the water source to pass the distance x and v is the irrigator velocity. Equation 25 is solved numerically by iterations as

irrigation event by

$$t = x/v \quad ; \quad \text{and} \quad q = Q_1/x$$

27

Relative dry matter yield was computed by using the same yield (Y)-transpiration (T) relations assumed by Childs and Hanks (1975) as

$$Y/Y_{\max} = T/T_p$$

28

where T_p is potential transpiration.

3.3 PROCEDURES

The field experiment were carried out at the same Arava and Yotvata soils described in Ch. 2.

The same technique described in Ch. 2 was used to regulate the low constant discharge rate. For the high rates $Q > 150$ l/h a cluster of drippers was feed from a container elevated 10 m above the ground. The water level in the container was kept constant. The pipe diameter from the elevated container to the cluster of drippers was large enough to minimize the friction head loss.

The borders of the ponded area were determined visually as the point where the free water zone ended. Measurements of the ponded area at different irrigator velocities were carried out by pulling a cluster of drippers, manually, at the constant desired speed using a scale and a timer. At different locations along the drippers path the ponded zone borders were marked so the area could be determined at the end of the pass.

For comparison with sprinklers which is the common irrigation method for alfalfa and for evaluation of the model results a block (360 m x 36 m) of two years old alfalfa on Arava soil which was previously irrigated by

sprinklers with the known commercial irrigation practice (Et crop factor of 1.2, water application of about 65 mm in each irrigation event) was transferred to mobile drip irrigation. The adjacent plots continued to get the previous irrigation regime (sprinklers). To establish uniform and known initial conditions the field was leached with 400 mm (using sprinklers) before the experiment started. Estimation of root distribution in the soil profile was made using the wall profile method (Shani 1985).

The discharge rate of the irrigator was 360 l/(hZm). Plant height were sampled daily between the second and third harvest to monitor plant growth rate. Samples for plant dry matter were taken from four sites (6 m x 6 m) for each treatment. The rest of the field was harvested commercially. Water and salt content were monitored through the experiment. Measurements were taken 24 hour after the irrigation completed. This experiment lasted 80 days.

For comparison with "stationary" drip irrigation, which is the common irrigation method for onion in the Arava valley, and for evaluation of the model results, a field (180 m x 22 m) was irrigated with a mobile drip irrigator. The experiment consisted of four treatments, three water levels of mobile drip, irrigation factor of 0.7, 1.0 and 1.3 of the A-pan evaporation and one water level of the common drip irrigation, factor = 1.0. Each row 180 m long and 1.5 m wide (+ 0.3 m tractor path between two adjacent rows) served as a replicate, three randomly chosen rows for each treatment. The relative water level within the mobile drip treatments was obtained by setting the discharge rate. Changes in the amount of applied water for all treatments in a specific irrigation event was controlled by adjusting the irrigator velocity. Irrigation was applied every two days through the entire growth period.

For purpose of uniformity the field was leached, using sprinklers, with 200 mm, before planting. The whole field was sprinkled daily for the first three weeks to obtain uniform germination. Plants were sampled weekly for growth rate measurements.

Figure - 6a Bed-shape of common drip irrigated onions

Figure - 6b Bed shape of mobile drip irrigated onions

The elevated seed-bed (Figure 6a) which is common for both drip and sprinkle irrigated onion can cause serious problems when applied to mobile drip irrigation because of possible runoff from the bed to the lower and more compacted tractor path. Thus, a special bed-shape was designed and constructed for this project. Instead of the elevated bed, the row is divided to two furrow like basins with leveled flat base. The onion is then planted into this flat base along the row (Figure 6b). The dripper outlets from the irrigator wing are adjusted to irrigate into the basin, so runoff to the tractor path is minimized. The special bed construction was made with bed-shaper connected to the rototiller so no extra passes were needed.

3.4 RESULTS AND DISCUSSION

The ponded zone area created by two different geometries of the water source, a point source and a two meters long line source, as a function of discharge rate is shown in Figures 7 and 8 for Arava and Yotvata soils respectively. Also shown are measurements of the ponded area created by a two meters line source moving at the relatively slow velocity of 12 m/h. The solid line in Figures 7 and 8 is the ponded area calculated from Equation 18. The ponded area increases linearly with the dripper discharge as predicted by Equation 17 or 18. There were no noticeable differences between the different forms of water application and there is a good agreement between the measured values and those computed from Eq. 18 for both soils. The measurements shown in these figures supports the assumptions that the same ponded area is created regardless of the actual geometry of the water source, and that for high discharge rates and low irrigator velocity the ponded area can be predicted by the stationary solutions (Equation 18).

Comparison of computed and measured ponded area as a function of time and dripper discharge is shown in Figures 9-11, for Arava Yotvata and Logan soils respectively. The measured values are the same as in Figures 1-3. The solid lines were computed from Equations 22-24. Except for the very high discharge rate (700 l/h, Yotvata soil) of which serious measurement problems exist, the prediction of the ponded area as a function of the ponding time is good. Equations 22-24 approximate a stepped ponding process assuming one-dimensional infiltration where the ponded area is large enough so the water absorption through the boundaries can be neglected. However, good agreement was obtained also for low discharge rate and ponded area (Figure 11, $Q=0.45$ l/h, $A_f=0.025$ m²), which suggest for the dominance role of the

central ponded area compared with the boundaries in the infiltration process.

The effect of irrigator velocity on the ponded area in different discharge rate is shown for Arava soil in Figure 12. The measurements cover in a range of economical use (see Chapter 4), so the combinations of high velocities with low discharge rate, were not measured (the amount of water application per irrigation event is too small). No noticeable effect of the irrigator velocity was obtained for Arava soil and this range of drippers discharge and irrigator velocity. When the same kind of measurements were made for Yotvata soil some velocity effect was obtained as shown in Figure 13. The solid lines in this figure were computed from Equations 25-26. Because of the higher saturated hydraulic conductivity and sorptivity of this soil (Table 3), the ponded stationary area is much smaller (0.015 m^2 vs 0.4 m^2 from 100 l/h for Yotvata and Arava respectively), t_v [stationary- t_p which results in a smaller ponded area. The computed ponded areas agree with the measurements in the lower discharge rates, it overestimate the ponded area at dripper discharge of 300 l/h and under estimate the ponded area at discharge rate of 420 l/h. The larger error involved in measuring the areas at the high discharge rates, can explain the inconsistency, though the trend and the relative decrease in ponded area are predicted well.

Daily potential ET, mobile drip irrigation water application depth, and sprinklers water application depth of the alfalfa experiment are summarized in Figure 14. The daily A-pan evaporation average is about 6.6 mm, 19.5 mm water were applied every three days in the mobile drip treatment and 66 mm water were applied every ten days in the sprinkle irrigation treatments. So, the the crop factor was 1. The values shown in Figure 14 were served as boundary input parameters for simulating the water

and salt flow in the soil profile, the water uptake by plant and the transpiration rate relative to the potential ET. Relative dry matter yield was computed using equation 28.

Water content and chloride concentration in the soil solution, as a function of depth for the mobile drip irrigation treatment, after 30 and 60 days from the beginning of the experiment are shown in Figures 15-16. The solid lines in both figures are model computation. The water content is steady with time as seen from Figure 15, by both measurements and model calculations. Unlike the water content, chloride concentration in the soil solution is built up (Figure 16). In the depth range of 0.4 to 0.9 the chloride concentration increased from 50 meq/l to about 90 meq/l. The agreement between computed and measured results is very good.

The same trends for water and chloride content in the soil as in Figures 15-16 is illustrated in Figures 17-18. Computed average water content in the effective root zone (0.05-1.3 m depth) as a function of time and irrigation method are shown in Figure 17. The water content in the high frequency mobile drip irrigation treatment reduced very slowly as the time increase. The average water content in the root zone of the less frequent sprinkle irrigation fluctuated much more but showed the same slight decrease with time. The average chloride content in the root zone of the mobile drip irrigated plants increased steadily with time (Figure 18). The chloride concentration in the soil solution of the sprinklers treatment increased generally at the same rate although the fluctuation in the chloride content increased also with time.

The effect of the chloride content increase and the chloride content fluctuation with time on the plant ability to absorbed water is shown through the computed plant roots potential in Figure 19. This parameter was

chosen because it is determined as the required root potential to maintain the transpiration equal to potential transpiration (Nimah and Hanks 1973), and thus it represents the effective soil water potential in the root zone. The time average root potential in the sprinkle treatments is lower than this of the mobile drip irrigated plants as can be seen from the larger area above the mobile drip irrigation line than the area below the line.

Alfalfa fresh and dry matter yields, averages of three harvests are summarized in Table 4. The sprinklers' yield is 4 percent lower than that of the mobile drip irrigation. This difference is not statistically significant but is in a good agreement with the model yield results.

Table ~ 4. Alfalfa fresh and dry matter yields.

	mobile drip Kg/ha	sprinkle Kg/ha	sprink/mob.drp. measured	sprink/mob.drp. model
Fresh	9200	8830	0.96	
Dry Matter	1687	1640	0.97	0.964

Yield differences between the sprinkle irrigated alfalfa and the mobile drip irrigated alfalfa are shown also in Figure 20 as cumulative plant height as a function of time from the last harvest. Height difference of about 0.03 m was measured about a week after the harvest, and it increased slowly to about 0.06 m toward the next harvest time. The growth curve of the two treatments has however a similar shape.

Onion yields are summarized in Table 5. Comparison of the yields, bulb weight, measured for the mobile drip irrigation is at least equal to that of the "stationary" drip irrigation, 83.26 vs 80.55 for the same water level (irrigation factor 1.0). There was no significant yield difference among water levels 1.0 and 1.3 and a significant yield reduction of 16 percent for water level 0.7. The model results of relative yield Y/Y_{max} are in a very good agreement with the measured values.

Table ~ 5. Onion bulb weight. Different letters represent statistical differences of at 0.05 level.

Water level	mobile drip ton/ha	drip ton/ha	Y/Y_{max} measured	relative yield model
0.7	b 723.5		0.84	0.82
1.0	a 832.6	a 800.6	0.97	1.0
1.3	a 859.6		1.0	1.0

Besides simulating the mobile drip irrigation, there is no report known to the authors trying to apply the Childs and Hanks model to onion. The commercial onion bulb yield at the natural harvest time is proportionally related to total dry matter yield, because the canopy content is translocated to the bulb.

comparison between the mobile and stationary drip irrigations of cumulative dry matter and total biomass weight with time is shown in Figures 21-22. The main conclusion from these figures is that both dry and fresh matter growth curves are similar for the two irrigation methods, which agree with the final bulb yield shown in Table 5.

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Figure 7. Pondered area as a function of discharge rate, water source dimension and velocity. Arava

Figure 8. Pondered area as a function of discharge rate, water source dimension and velocity. Yotvata

Figure 9. Pondered area as a function of time. Scattered points are measured data, solid line are model results. Arava

Figure 10. Pondered area as a function of time. Scattered points are measured data, solid line are model results. Yotvata

Figure 11. Pondered area as a function of time. Scattered points are measured data, solid line are model results. Logan

Figure 12. Poded area as a function of emitter velocity and discharge rate, Arava

Figure 13. Pondered area as a function of emitter velocity and discharge rate. Scattered points are measured data, solid line are model results. Yotvata

Figure 14. Pan - A evaporation, and irrigation depth as a function of time. Alfalfa, Arava.

Figure 15. Water content distribution in the soil profile at 30 and 60 days after mobile irrigation treatment started. Scattered points are measured data, solid line are model results. Alfalfa, Arava

Figure 16. Chloride concentration in soil solution distribution in the soil profile at 30 and 60 days after mobile irrigation treatment started. Scattered points are measured data, solid line are model results. Alfalfa, Arava

Figure 17. Comparison of sprinklers and mobile drip irrigation methods effect on changes of the average water content with time. Alfalfa, Arava

Figure 18. Comparison of sprinklers and mobile drip irrigation methods effect on changes of the average chloride concentration in the soil solution with time. Alfalfa, Arava

Figure 19. Comparison of sprinklers and mobile drip irrigation methods effect on changes of the root potential with time. Alfalfa, Arava

Figure 20. Alfalfa growth curve.

Figure 21. Onion fresh matter accumulation with time

Figure 22. Onion dry matter accumulation with time

ABSTRACT

When developing and introducing mobile irrigation equipment, one aims at achieving application efficiencies equal to those obtained by stationary drip installations, as regards homogeneous distribution of water over the entire field, resulting in increased yields and in water economy. In parallel, one aims at reducing the fixed and variable cost of water application per unit of field area.

The irrigation methods which were evaluated in this study are as following :

1. Linear move system, powered by a diesel engine, the water is distributed through depressurized open-pipe hangers, sprayers or sprinklers, while travelling laterally along the field.
2. "Ajanot" irrigation boom (Ramat David) driven by pulsating water motors which also drive the on board carried hose-reels, rolling the hose out while traveling. The water is distributed laterally by depressurized open pipes hanging from the boom.
3. "Neer" irrigation boom (Neer-David and German), towed by the supply hose which is wound on a stationary reel, powered by a water turbine. The water is applied laterally through depressurized open pipes hanging from the boom sprayers or drip emitters.

4. Center pivot irrigation machine driven by a diesel engine. The water is distributed by sprayers or sprinklers. The effective field utilization is reduced by up to 20%.
5. Stationary drip installation, remains spread out over the field during the whole growing season.
6. "Seasonal" drip lines. Is essentially similar to No. 5, except for the low-cost short-life drip lines (which last for 2 seasons only).
7. Sprinklers mounted on metal pipe lines, which are towed station-wise along the field.

The relative cost of water application and seasonal labour requirement for irrigation, per hectare, of these systems are presented in Table 1. The field size brought for each system results from the per-season capacity of the individual unit.

TABLE 1 Relative water application cost (%) and man hours per hectare for different irrigation systems for two types of crops.

Crop type Irrigation System	Vegetable crop - Yotvata			Cotton in central Israel		
	Field size hectare	Man hours	Relative cost %	Field size hect.	Man hours	Relative cost %
Linear move	10.56	9.5	172	57.2	1.6	101
Ajanot boom (Ramat David)	7.50	26.7	175	34.3	2.8	91
Neer boom (German and Neer David)	5.76	21.7	111	28.0	2.2	78
Center pivot	-	-	-	36.0	0.1	131
Drip installation	15.80	40.4	100	36.0	30.0	216
Seasonal drip installation	15.80	40.4	80	36.0	30.0	163
Sprinkler tow lines	-	-	-	36.0	10.0	100

INTRODUCTION

Various irrigation systems are being used in Israel. Each system has advantages and shortcomings. Studies conducted over several seasons by researchers in Israel showed that higher yields had been obtained under various soil conditions, when the water was applied by drip irrigation compared to other irrigation methods, it also resulted in better water economy (1). Hence, when developing or introducing new irrigation systems, one aims at achieving as efficient water application as with drip methods, and to keep investment and labor costs down to a minimum.

There are differences of opinion and estimate concerning manual labor requirement to set up and operate the various irrigation systems. The relevant data for the economic calculations of investment and operational costs may be divided into the three following groups :

- 1) Investment cost of the equipment.
- 2) Capital cost
- 3) Man and tractor cost.

When comparing data from various sources (1,2,3) it became evident that the data concerning investment cost has in most cases been identical for the different sources and so were the estimates for the cost of capital.

On the other hand, there are considerable differences in the estimates of labor requirement, coming from the various sources. As this is an economic study report, it cannot go into examining and judging the correctness of the data received from the different sources. Total cost of the different methods had therefore been calculated from the data presented in the booklet — "Characterization of equipment and cost calculation of irrigation methods",

issued by the extension service. As for verifying the exactness of the data, this requires a special professional conference, in order to choose the cost calculation which corresponds to the actual conditions.

The data on which the economic calculations are based is as follows :

Labor cost	:	\$ 35.- per work day of 8 hours
Tractor cost	:	\$ 10.- per hour (fixed and variable cost)
Annual Repair cost	:	3% of the initial investment of all the equipment.*
Fuel cost	:	0.524 \$ per liter of diesel oil
Depreciation or life span of the irrigation equipment :		
Irrigation machines	:	7 years
Flexible supply hose for irrigation machines **	:	3 years
Connectors to main lines and filters etc:		15 years
Aluminium pipes and sprinklers for tow lines		10 years
Regular drip lines with drip emitters:		5 years
Seasonal low cost short life drip lines		2 years

The calculations are presented in US Dollars. The calculations are based on data from the following publications :

- a. "Linear-Move irrigation systems - a comparative calculation" by M. Farbman of Kur Shimitski, 1982.
- b. "Characterization of equipment and cost calculation of irrigation methods". The Extension Service, Ministry of Agriculture, July 1982.
- c. "Economic analysis of mechanized irrigation methods", by A. Cohen, The Extension Service and Y. Halevi of the Field Services.

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* No repair costs were included for equipment with short life span of only 2 years, such as seasonal drip lines.

** The supply hose of the "Neer" boom is made of high quality polyethylene with expected life span of 7 years.

The calculations take into account only one irrigation season per annum.

The economic evaluation of the above methods was conducted in part for irrigation of vegetable crops at Yotvata, grown in long narrow fields bordered by wind breakers, and in part conducted for irrigating cotton field in central Israel, on larger fields.

A. Description of the equipment and irrigation methods

1. Linear move system

The linear move irrigation machines are constructed of sections (spans) 48-60 m long, each and of an overall length of between 100 to 550 m. Each span is supported at one end by a horizontal frame having two powered wheels while the other end is supported by the frame of the next span. The wheels are driven by electric or hydraulic motors powered by a diesel engine and an electric generator or hydraulic pump, carried on one of the two support frames of the main span. The water application methods commonly used with this system are spacey nozzels or pressure-free open-end pipe hangers.

Water is supplied to the linear-move machine by a flexible-hose between 100 to 180 mm in diam. and between 180 to 240 m in length, which drags behind the machine. The supply hose is being connected to the main line 200 m. ahead of the starting point, enabling the machine to travel a distance of 400 m until the hose extends to its full length to the other side of the supply point, when it has to be reconnected 400 m further on. This job is done manually with the aid of a tractor to tow the hose.

When ending an irrigation cycle along the field, one of two things can be done :

- a) Move over to an adjacent field, and continue to operate in the same manner.
- b) Drive the machine back to the starting point, without irrigating.

This can be done at travel speeds of between 90 to 180 m/h.

Travel speeds while irrigating is a function of the water output of the machine and the amount of water required to irrigate the field. This speed lays between 15 to 50 m/h. The fuel requirement of the engine is 2.5 l per hour of operation, more or less independent of travel speed.

2. "Ajanot" Boom (Ramat David)

This is an irrigation machine having a central drive unit with a boom extending to both sides to a total width of 62 to 78 m. It is driven by water pressure by means of two alternately activated pistons.

The water application method is similar to that on the linear move system, e.g. by sprayers or by open ended pipe hangers. The machine carries a reel with 200 m length of flexible supply hose. The water is supplied through this hose in a similar way as to the previous machine, except that the hose is not dragged on the ground, but wound up on the on board carried reel for the first 200 m of travel and then the hose is rolled off again for another 200 m. of travel beyond the supply point. After irrigating one section of 400 m the end of the hose is towed and reconnected to the next supply point 400 m ahead. When tractor towing the machine to another field or back to the starting point on the same field, the hose is rolled up on the reel, and the boom is collapsed to width of 6 m. The travel speeds during irrigation are similar to those of the linear move system.

3. "Neer" boom, (Neer David and German and a similar machine)

This irrigation machine consists of a boom that extends to both sides of a 3 wheel carriage, to a total width of between 50 to 60 m. The boom travels along the field by towing it by means of the supply hose which is wound on a reel stationed at the head of the field. The reel which is driven by a water-pressure powered turbine can carry up to 400 m length of 90 to 125 mm diam. semi rigid polyethylene (P.E.) hose. The water is applied through spray nozzels or open pipe hangers.

A variation on this and the previous machine operates at Na'an where the boom is towed by a 400 m long steel cable. The machine travels by winding the cable on an on-board carried by water turbine powered reel, so that it is pulled towards the anchoring point 400 m away. A 200 m flexible hose is used to supply water from a point half way along the travel distance.

On both these machines, the boom is easily collapsible, permitting quickly a transfer from plot to plot. Travel speed while irrigating is similar to that of the linear move system.

4. Center pivot system

This is a multi-span machine assembled of 40 to 60 m long sections to a total length of about 600 m. It is constructed and operated similarly to the linear move system except that it pivots around a central supply point. This provides for great convenience of operation, as no long supply hose is required and the machine runs on the same set-up during the

whole season.* However, two problems arise from the circular mode of operation.

- a) Uncomplete coverage of square fields. The uncovered corners may amount to about 20% of field area. This loss could be reduced by adding "corner-systems" at the end of the machine - however, such units are expensive and therefore are rarely used.
- b) The circular motion of the system presents a problem of distributing the water uniformly per unit of area, as every emitter along the boom travels, during the same time period, in a larger circle. This is generally overcome either by using proportionally increasing nozzels which are set at equal intervals along the boom, or by using equal size nozzels, set at decreasing intervals.

The travel speed of the machine is fixed for each irrigation according to the requirements of the field.

5.6. Multiseason and seasonal drip installations.

The drip irrigation delivers precise amounts of water to the root system of the plants. This is achieved by p.e. pipes with drop emitters, layed out at desired spacing along the beds. The spacing of the drop nozzels along these lines depend on the crop type and are generally between 30 to 150 cm. For cotton, the drippers are spaced 100 cm. along the drip lines, of which one is layed-out between every two plant rows, requiring about 5200 m of drip lines per hectar.

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* The machine could be transferred to an adjacent field by means of special equipment, however this option is seldom used.

These lines are nowadays layed out mechanically, enabling a single grower to drip irrigate hundreds of hectares annually.

The seasonal drip lines are made of thin walled p.e. pipes with a built-in drip emitters. They are used in a similar way to the multi-season lines, however, their use is restricted to 2 seasons only compared to 5 seasons of the latter.

The main drawback in using drip irrigation installations lays in the water quality, which varies over the country and varies constantly along the season. This requires a high investment in filtration installations and water treatment equipment, and constant checking in the field for blocked emitters etc. The water quality in some areas, is such that the investment in filtration equipment amounts to 30% of the total drip installation, which increases water application cost by drip methods, considerably.

7. Sprinkler irrigation with towed pipe lines

This irrigation method is the longest established and best known in Israel. The method is based on 3" diam. aluminium pipes, 12 m. long. A towed line is generally 200 m. long, covering 0.3 to 0.35 hectar per position when operated at 16 to 18 m intervals across the field, with a single sprinkler per pipe of 12 m.

The system uses low volume hammer sprinklers with an output of 2000 l/h per line, at a 4-bar pressure. The sprinklers may be set in the field at various height levels according to the requirements of the specific crop.

The main limitation of this method lays in the low uniformity of water distribution, which requires the application of larger quantities of water in order to ensure proper coverage all over the field. The system is highly susceptible to winds and to variations in water pressure, which in some regions cause runoff, resulting in soil erosion and heavy financial losses to the growers. This method also requires daily input of man and tractor hours during the whole season, for towing the lines from one set up to the next, along the field and for returning to the starting point.

These limitations and others are the reason for the gaining popularity of the other irrigation methods like drip installations and mobile systems.

B. Cost effectiveness for irrigating vegetables of Yotvata.

The irrigation method adaptable to the narrow fields of Yotvata which were included in the economic evaluation are as follows :

- 1) Linear move system: Two spans of 48 m each ply a short unit of 36 m, having a total length of 132 m.
- 2) "Ajanot" boom, Ramat David, independent unit 62.5 m wide.
- 3) German boom, independent unit 48 m wide.
- 4) Multiseason drip installation, life span of p.e. pipes and drip emitters: 5 years.
- 5) Seasonal drip system, life span of drip lines; 2 years.

The water supply to the field is identical for all the methods. Travel speed of the irrigation machines is based on covering a distance of 400 m during 14 hours, daily, or 28.5 m per hour of operation. The water is applied every second day at a rate of 16 mm, requiring an output of 450 l per hour per meter of field length (l/h/m). This amount of water is

essential under the high evaporation conditions of this region.

The crops concerned are onions, raddishes, tomatoes, green peppers and alfalfa, requiring 50 irrigations per season.

The calculations of the application cost of water by the various methods are presented herewith as following :

1. Linear move system

Initial cost of a 132m wide machine	\$ 40,400.-
Cost of 200 m 4" diam. flexible supply hose	\$ 6,600.-
The machine travels 800 m every 2 days, the irrigated area amounts to 132x800	= 10.45 ha.
50 irrigations are required per season, labor & tractor input per irrigation are 1 hour of 2 people + tractor	
Capital return cost of the machine 40400×0.205	\$ 8,262.-
Capitalreturn cost of hose 6600×0.402	\$ 2,653.-
Annual repair cost 3% of investment	\$ 1,410.-
Labour cost $2 \times 50 \times 35:8 =$	\$ 437.-
Tractor cost $1 \times 50 \times 10 =$	\$ 500.-
Fuel cost $(28+8) \times 50 \times 2.5 \times 0.524$	\$ 2,358.-
Total annual application cost	\$ 15,620.-
Annual application cost per hectar 15620: 10.56	\$ 1,479.-

2.. "Ajanot" boom, Ramat David.

Initial cost of 62.5 m wide machine \$ 25,400.-

Cost of 200 m 4" diam. flexible supply hose \$ 6,600.-

The machine travels 1200 m every 2 days, the
irrigated area is $1200 \times 62.5 =$ 7.5 ha

Labor and tractor requirement 6 reconnectings of
hose* for 1200 m, 0.5 man hours + tractor each.

Towing the machine back to starting point, 0.5 hours
of 2 people with tractor.

Capital return cost of the machine 25400×0.205 \$ 5,207.-

Capital return cost of hose 6600×0.402 \$ 2,653.-

Annual repair cost 3% of investment \$ 960.-

Labour cost $(6 \times 0.5 + 2 \times 0.5) \times 50 \times 35: 8$ \$ 875.-

Tractor cost $(6 \times 0.5 + 1 \times 0.5) \times 50 \times 10$ \$ 1,750.-

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Total annual application cost \$ 11,445.-

Annual application cost per hectar $11,445 : 7.5$ \$ 1,526.-

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* This method as explained before, requires only 3 set ups per
1200 m. However, changing the direction of the reel from roll-up
to lay-out requires attention of operator + vehicle.

3. German boom

Cost of 48 m. wide boom plus reel with 200 long hose \$ 1600

The machine travels 1200 m every 2 days.

The irrigated area is 1200 x 48 5.76 ha

Labour and tractor requirements are : 6 reset ups for
1200 m 0.333 (20 min) man hours and tractor, each
towing the machine back to the starting point.
0.5 man hours + tractor

Capital return cost of machine (1600×0.205) \$ 3,280.-

Annual repair cost, 3% of investment \$ 480.-

Labour cost ($6 \times 0.333 + 1 \times 0.5$) x 35 x 50 : 8 \$ 547.-

Tractor cost ($6 \times 0.333 + 1 \times 0.5$) x 10 x 50 \$ 1,250.-

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Total annual application cost \$ 5,557.-

Annual application cost per hectar $5557:5.76$ \$ 965.-

4. Multi-annual drip installations

Cost of p.e. pipes and drippers	\$ 19,000.-
Cost of connectors and filters	\$ 13,000/-
Size of irrigated area	15.3 ha
Labour and tractor requirement to lay out and roll up equipment,	
20 hours of 2 people + tractor per hectare	
Labour and tractor requirement for irrigation application	
0.25 man hours + tractor 50 times per season	
Capital return cost of pipes and drippers 19000×0.264	\$ 5,016
Capital return cost for connectors & filters 13000×0.131	\$ 17,013
Annual repair cost 3% of investment 32000×0.03	\$ 960
Labor cost for seasonal layout and roll up $15.8 \times 40 \times 35:8$	\$ 2,765.
Tractor cost for seasonal lay out and roll up $15.8 \times 20 \times 10$	\$ 3,160
Labour cost for irrigation $0.25 \times 50 \times 35:8$	\$ 55
Tractor cost for irrigation $0.25 \times 50 \times 10$	\$ 125
Total annual application cost	\$ 12,784
Annual application cost per hectar 1278: 15.8	\$ 872

5. Seasonal drip system

Cost of plastic pipes with built in drippers	\$ 5,000
Connectors and filtration equipment	\$13,000
Size of irrigated area 15.8 hectar	
Labour and tractor requirement for layout and roll up and for irrigation application as for system 4.	
Capital return costs of drip pipes 5000×0.576	\$ 2,880.-
Capital return costs of connector and filters 1300×0.131	\$ 1,703.-
Annual repair cost (connectors and filters) $13000 \times 3\%$	\$ 390.-
Labour cost for seasonal layout and roll up	\$ 2,765.-
Tractor cost for seasonal layout and roll up	\$ 3,160.-
Labour cost for irrigation application	\$ 55.-
Tractor cost for irrigation application	\$ 125.-
Total annual application cost	\$ 11,078.-
Annual application cost per hectar $11078:15.8$	\$ 701.-

The cost of irrigation application, for growing vegetable crops in Yotvata, by 5 different application methods are summarized in Table 2.

TABLE 2. Cost of 5 different application methods for growing vegetables
in Yotvata, in US\$

Method Cost item	Linear Move System	Ajanot boom Ramat David	German boom	Multi Annual Drip Layout	Seasonal Drip Layout
Total investment	47,000	32,000	16,000	32,000	18,000
Capital return cost	10,915	7,860	3,280	6,719	4,583
Annual repair cost	1,410	960	480	960	390
Labour cost layout + roll up	-	-	-	2,765	2,765
Tractor cost layout + roll up	-	-	-	3,160	3,160
Labour cost for applic.	437	875	547	55	55
Tractor cost for applic.	500	1,750	1,250	125	125
Fuel cost	2,358	-	-	-	-
Total annual application cost	15,620	11,445	5,557	13,784	11,078
Size of irrigated area - ha.	10.56	7.5	5.76	15.8	15.8
Application cost per hectar	1,479	1,526	965	872	701
Relative cost of method %	170	175	111	100	80

C. Cost effectiveness for irrigating cotton in central Israel

The evaluation calculations of the different methods for irrigation of cotton will be done for field sizes suitable for each method. The daily water requirement taken into account is 8 mm. A water supply installation is available for all the systems.

Every grower has to adapt the calculations and assumptions to his own particular conditions and data.

The methods which were evaluated for irrigation of cotton are as follows :

1. Linear move system, irrigating every 5 days.
2. "Ajanot" boom, Ramat David, irrigating every 5 days.
3. "Neer" boom, Neer David and German and similar, every 5 days.
4. Center pivot system - every 5 days.
5. Drip irrigation by multi-annual installation, every 3 days.
6. Drip irrigation by seasonal installation, every 3 days.
7. Sprinklers irrigation by towed metal pipes, every 12 days.

The calculations are for water outputs along the field of 2000, 1000 and 500 liter per hour per meter (l/h/m).

No breakdown time or slow down because of pressure drop, have been taken into account in these calculations. Hence, the actual results in effective irrigation hours may be shorter, so that the irrigated area may be smaller.

There are limitations with regard to the length, width and leveling of the fields available for irrigation, by machines such as the linear move system. The choice and set up of an irrigation machine has therefore to be done according to the particular conditions of the field to be irrigated.

All the calculations are based on the data presented in the introduction.

1: Linear move system

Total water output, $300 \text{ m}^3/\text{h}$, supplied through a 6" dia. flexible hose, 200 m. long. Daily water requirement of crop. 8 mm, applied every 5 days in 40 mm portions. 10 irrigations per season.

a. 2000 l/h/m water output along the field

Total width covered by machine	143 m
Travel speed while irrigating	52.5 m/h
Time required to irrigate 1 set up (of 400 m)	7 h 38 min
No. of set ups per field	10
Effective application hours per irrigation cycle	76h 20 min
Non operational travel time (return)	40 h

Transfer and reconnect hose 0.5 hours of man and tractor each. Return to starting point, 2 hours of man with tractor.

Investment cost in machine	\$ 534,000
Investment cost in hose	\$ 6,600
Investment cost in connectors etc.	\$ 600
Size of irrigated area $143 \times 52.5 \times 7.633 \times 10$	57.3 ha

Capital return cost for machine 53400×0.205	\$ 10,947
Capital return cost for hose 6600×0.402	\$ 2,653
Capital return cost for connectors 6000×0.131	\$ 786
Annual repair cost 3% of total investment	\$ 1,980
Labour cost $(0.5 \times 10 + 4) \times 10 \times 35 : 8$	\$ 394
Tractor cost $(0.5 \times 10 + 2) \times 10 \times 10$	\$ 700
Fuel cost $116.3 \times 10 \times 2.5 \times 0.524$	\$ 1,524
Total annual application cost	\$ 18,984
Annual application cost per hectar $18984 : 157.3$	\$ 331 .

- b. 1000 l/h/m water output along the field, all other conditions are equal.

Total width covered by machine	286 m
Travel speed while irrigating	26.25 m/h
Time required to irrigate 1 set up	15.25 h
No. of set ups per field	6
Effective application hours, per irrigation cycle	91 h
Non operational travel time (return)	24 h
Transfer and reconnect hose, 0.5 hours of man and tractor each.	
Return to starting point, 2 hours of 2 man with tractor.	
Investment cost in machine	\$ 63,400
Investment cost in supply hose	\$ 6,600
Investment cost in connectors etc	\$ 6,000
Size of irrigated area $286 \times 26.25 \times 15.25 \times 6$	68.7 ha
Capital return cost for machine 63400×0.205	\$ 12,997
Capital return cost for supply hose 6600×0.402	\$ 2,653
Capital return cost for connectors 6000×0.131	\$ 786
Annual repair cost 3% of total investment	\$ 2,280
Labour cost $(0.5 \times 6 + 4) \times 10 \times 35 : 8$	\$ 306
Tractor cost $(0.5 \times 6 + 2) \times 10 \times 10$	\$ 500
Fuel cost $115 \times 10 \times 2.5 \times 0.524$	\$ 1,506
Total annual application cost	\$ 21,028
Annual application cost per hectar $21028 : 68.7$	\$ 306

c. 500 l/h/m water output along the field.

Total water output $200 \text{ m}^3/\text{h}$ - all other conditions equal.

Total width covered by the machine	381 m
Travel speed while irrigating	13.1 m/h
Time required to irrigate one set up	30.5/h
No. of set ups per field	3.5
Effective application hour per irrigation cycle	106.75 h
Non operational travel time (return)	14 h

Transfer and reconnect hose 0.5 hours of 1 man and tractor each

Return to starting point 2 hours of 2 men with tractor

Investment cost in machine	\$ 73,400
Investment cost in supply hose	\$ 6,600
Investment cost in connectors etc.	\$ 6,000
Size of irrigated field $381 \times 13.1 \times 30.5 \times 3.5$	53.3 ha

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Capital return cost for machine	\$ 15,047
Capital return cost for hose	\$ 2,653
Capital return cost for connectors	\$ 786
Annual repair cost 3% of total investment	\$ 2,580
Labour cost $(0.5 \times 4 + 4) \times 10 \times 35:8$	\$ 263
Tractor cost $(0.5 \times 4 + 2) \times 10 \times 10$	\$ 400
Fuel cost $120.75 \times 2.5 \times 0.524$	\$ 1,582

Total annual application cost	\$ 23,341
Annual application cost per hectar $23341:53.3$	\$ 437

- Remarks: 1) The cost advantage is not in favour of the widest machine. Cost per hectar for the 381 wide machine is considerably higher than for the 2 shorter ones.
- 2) A linear move irrigation machine travels on a fixed track while irrigating and when returning to the starting point. Moving the machine to a field which is not aligned with this track, requires to tow each span separately. Although this shortens the non-operational time (return) of the machine, cost for tractor and labour is increased considerably.

2. "Ajanot" boom, Ramat David

Daily water requirement of crop: 8 mm, supplied every 5 days
in portions of 40 mm. 10 irrigations per season.

a. 2000 l/h/m water output along the field

Planned water output	125 m ³ /h
Total width covered by machine	78m
Travel speed while irrigating	40 m/h
Time required to irrigate one set up	10 h
No. of set ups per field	11
Effective application hours per irrigation cycle	110h
Transfer position 0.5 hours of man and tractor each	
Return to starting point, 2 hours of 2 man with tractor	
Investment cost in machine	\$ 30,500
Investment cost in supply hose	\$ 4,500
Size of irrigated field $78 \times 40 \times 11 \times 10$	= 34.3 ha
Capital return cost for machine 30500×0.205	= \$ 6253
Capital return cost for hose 4500×0.405	= \$ 1809
Annual repair cost, 3% of total investment	= \$ 1050
Labour cost $(0.5 \times 11 + 4) \times 10 \times 35 : 8$	= \$ 416
Tractor cost $(0.5 \times 11 + 2) \times 10 \times 10$	= \$ 750
Total annual application cost	\$ 10,278
Annual application cost per hectar $10278 : 34,3$	= \$ 299.6

b. 1000 l/h/m water output along the field

planned water output:	62.5 m ³ /h
Total width covered by machine	78m
Travel speed while irrigating	20 m/h
Time required to irrigate 1 set up	20 h
No. of set ups per field	6
Effective application hours per irrigation cycle	120 h
Transfer position 0.5 hours of man and tractor each	
Return to starting point 2 hours of 2 man and tractor	
Investment cost in machine and hose	\$ 35,000
Size of irrigated area 78x20x6x20	18.7 ha

Capital return cost for machine and hose	\$ 8062
Annual repair cost, 3% of total investment	\$ 1050
Labor cost (0.5x6+4)x10x35:8	\$ 306
Tractor cost (0.5x6+2)x10x10	\$ 500
Total annual application cost	\$ 9918
Annual application cost per hectar 9918:18.7	= \$ 530

c. 500 l/h/m water output along the field

Planned water output	31 m ³ /h
Total width covered by machine	78 m
Travel speed while irrigating	9.9m/h
Time required to irrigate 1 set up	40h
No. of set ups per field	3
Effective application hours per irrigation cycle	120 h
Transfer position 0.5 hours of man and tractor each	
Return to starting point 2 hours of 2 man and tractor	
Investment cost in machine and hose	\$ 35,000
Size of irrigated area $78 \times 9.9 \times 3 \times 40$	9.27 ha

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Capital return cost for machine and hose	\$ 8062
Annual repair cost 3% of total investment	\$ 1050
Labor cost $(0.5 \times 3 + 4) \times 10 \times 35 : 8$	\$ 241
Tractor cost $(0.5 \times 3 + 2) \times 10 \times 10$	\$ 350

Total annual application cost	\$ 9703
Annual application cost per hectar $9703 : 9.27$	\$ 1047

Remarks: The "Ajanot" irrigation machine is collapsible with relative ease, which enables to tow the machine by tractor from one field to another. There are no restrictions in transferring the machine to a remote field even if this requires some driving along traffic roads.

3. "Neer" boom, Neer David and German

Daily water requirement of crop: 8 mm, supplied every 5 days
in 40 mm portions. 10 irrigations per season.

Supply hose 110 mm diam. 400 m. long.

a. 2000 l/h/m water output along the field

Planned water output	96 m ³ /h
Total width covered by machine	50 m
Travel speed while irrigating	48 m/h
Time required to irrigate 1 set up	8.33 h
No. of set ups per field	14
Effective application hours per irrigation cycle	116.6 h
Transfer position, 0.3 hrs of man and tractor	
Return to starting point, 2 hours of 1 man and tractor	
Investment cost in machine and hose	\$ 27,000
Size of irrigated area 50x48x8.33x14	28 ha

Capital return cost for machine and hose 27000×0.205	\$ 5535
Annual repair cost 3% of total investment	\$ 810
Labor cost $(0.3 \times 14 + 2) \times 10 \times 35:8$	\$ 271
Tractor cost $(0.3 \times 14 + 2) \times 10 \times 10$	\$ 620

Total annual application cost	\$ 7236
Annual application cost per hectar $7236:28$	\$ 258

b. 1000 l/h/m water output along the field

Planned water output	48 m ³ /h
Total width covered by machine	50 m
Travel speed while irrigating	24 m/h
Time required to irrigate 1 set up	16.7 h
No. of set ups per field	7
Effective application hours per Irrigation cycle	117 h
Transfer position 0.3 hours of man and tractor	
Return to starting point 2 hours of 1 man and tractor	
Investment cost in machine and hose	\$ 27,000
Size of irrigated area 50x24x16.7x7	14 ha

Capital return cost for machine and hose	\$ 5535
Annual repair cost 3% of investment	\$ 810
Labor cost $(0.3 \times 7 + 2) \times 10 \times 35$	\$ 88
Tractor cost $(0.3 \times 7 + 2) \times 10 \times 10$	\$ 410
Total annual application cost	\$ 7653
Annual application cost per hectar 7653:14	\$ 547

c. 500 l/h/m water output along the field

Planned water output	24 m ³ /h
Total width covered by machine	50 m
Travel speed while irrigating	12 m/h
Time required to irrigate 1 set up	33.3 h
No. of set ups per field	4
Effective application hours per irrigation cycle	132.9 h
Transfer position, 0.3 hours of man and tractor	
Return to starting point 2 hours of 1 man and tractor	
Investment cost in machine and hose	\$ 27000
Size of irrigated area 50x12x33.3x4	8 ha

Capital return cost for machine and hose	\$ 5535
Annual repair cost 3% of investment	\$ 810
Labor cost $(0.3 \times 4 + 2) \times 10 \times 35:8$	\$ 140
Tractor cost $(0.3 \times 4 + 2) \times 10 \times 10$	\$ 320

Total annual application cost	\$ 6803
Annual application cost per hectare 6803:8	\$ 850

Remarks:

This irrigation machine is easily collapsible, permitting fast hitching to towing tractor and may be moved from one field to another without restrictions.

4. Center pivot system

Daily water requirement of crop: 8 mm, supplied every 5 days in 40 mm portions, 10 irrigations per season.

Planned water output	131 m ³ /h
Total application width of the boom	340 m
Size of circular area covered	36 h
Travel speed on extreme circle, while irrigating	19.4 m/h
Effective application hours per irrigation cycle	110 h
Start irrigation cycle 0.25 man hours	
Investment cost in machine	\$ 60,000

Capital return cost $60,000 \times 0.205$	= \$ 12,300
Annual repair cost 3% of investment	= \$ 1,800
Labour cost $0.25 \times 10 \times 35:8$	= \$ 11
Fuel cost $110 \times 10 \times 2.5 \times 0.524$	= \$ 1,441

Total annual application cost	= \$ 15,552
Annual application cost per hectar $15552:36$	= \$ 432

5. Drip irrigation by multiannual installation

Size of irrigated area (with 1 installation unit)	36 ha
Investment cost in p.e. pipes and drippers	\$ 43,200
Investment cost in connectors, filters etc.	\$ 28,800
Labour requirement for lay out and roll up	30 h/ha
Tractor requirement for lay out and roll up	10 h/ha

Capital return cost for p.e. pipes and drippers 43200×0.264	= \$ 11,405

Capital return cost for connector and filters etc 28800×0.131	= \$ 3,773

Annual repair cost 3% of total investment	= \$ 2,160

Labor cost $30 \times 36 \times 35 : 8$	= \$ 4,725

Tractor cost $10 \times 36 \times 10$	= \$ 3,600

Total annual application cost	= \$ 25,663

Annual application cost per hectar $25663 : 36$	= \$ 713

6. Drip irrigation by seasonal installation

Size of irrigated area (with 1 installation unit)	36 ha
Investment cost in drip pipes	\$ 11,200
Investment cost in connectors, filters etc.	\$ 28,800
Labour requirement for lay out and roll up	30 h/ha
Tractor requirement for lay out and roll up	10 h/ha

Capital return cost for drip pipes $11,200 \times 0.576$	= \$ 6,451
Capital return cost for connectors, filters etc. 28800×0.131	= \$ 3,771
Annual repair cost 3% for connectors and filter only	= \$ 864
Labor cost $30 \times 36 \times 35 : 8$	= \$ 4,725
Tractor cost $10 \times 36 \times 10$	= \$ 3,600

Total annual application cost	= \$ 19,413
Annual application cost per hectare $19413:36$	= \$ 539

7. Sprinkle irrigation by towed metal pipe lines

Daily water requirement of crop: 8 mm, supplied in portions of 96 mm every 12 days. 5 irrigations per season.

Investment cost in pipe lines with sprinklers	\$ 32,000
Investment cost in auxiliary equipment	\$ 3,300
Size of irrigated area	36 ha
Labour requirement for seasonal lay out and for towing of lines from set up to set up and restart	10 h/ha
Tractor requirement per season	10 h/ha

Capital return cost for sprinkler lines 32000×0.163	= \$ 5,216
Capital cost for auxiliary equipment 3300×0.131	= \$ 432
Annual repair cost 3% of investment 35300×0.03	= \$ 1,059
Labour cost $10 \times 36 \times 35:8$	= \$ 1,575
Tractor cost $10 \times 36 \times 10$	= \$ 3,600

Total annual application cost	= \$11,882
Annual application cost per hectar $11,882:36$	= \$ 330

The cost of applying water by the various systems to irrigate cotton in the center of Israel is summarized in Table 3.

SUMMARY

The cost per hectar for water application, to irrigate vegetable crops at Yotvata and for irrigating cotton in central Israel are shown in Table 2 and 3.

When classifying the method for irrigation of vegetable crops at Yotvata according to cost per hectar, the order will be as following;

1. Seasonal drip installation	\$ 701
2. Multiannual drip installation	\$ 872
3. German irrigation boom	\$ 965
4. Linear move system	\$1504
5. "Ajanot" boom Ramat David	\$1526

The cost classification order of the systems to irrigate cotton in central Israel will be as following :

1. Neer boom Neer David and German	\$ 258
2. Ajanot boom Ramat David	\$ 300
3. Towed sprinkler lines	\$ 330
4. Linear move system	\$ 331
5. Center pivot system	\$ 432
6. Seasonal drip installation	\$ 539
7. Multiannual drip installation	\$ 713

An additional choice criteria besides cost effectiveness, could be the labor requirement of the system, especially if this is scarce.

This is summarized in Table 4.

TABLE 4.

LABOR REQUIREMENT PER GIVEN FIELD SIZE AND PER HECTAR - MAN HOURS

Irrigation method	Linear move system	Ajanot boom Ramat David	Neer Boom Neer David	German Boom	Center Pivot System	Drip Lay-out	Seasonal Drip Layout	Sprinkler Tow Lines
Type of crop								
Vegetable Crops								
Yotvata								
Total man hours	75	200	-	125	-	645	645	-
Size of field	10.5	7.5	-	5.8	-	15.8	15.8	-
h/ha	7.1	26.7	-	21.6	-	40.8	40.8	-
Cotton in Central Israel								
Total man hours	90	75	62	-	25	1080	1080	360
Size of field	60	27	28	-	36	36	36	36
h/ha	1.5	2.8	2.2	-	0.7	30	30	10

when developing and introducing mobile irrigation equipment, one aims at achieving applications efficiencies as high as those obtained by drip installations. In parallel, one aims at reducing, as far as possible, the fixed and variable cost of water application per unit of field area.

Cost of germination irrigation (with towed sprinkler lines) had been excluded from the calculations of water application cost for all the systems of irrigation of cotton.

Capital return cost had been calculated for growing a single crop per annum. If equipment is used for irrigating two crops per year, capital return cost will decrease proportionally to the size of the additional field.

Variation in expected yields resulting from specific irrigation methods, is not accounted for in the calculations.

DESCRIPTION OF COOPERATION

A review of the research that has been done in Israel and in Texas, and an adaptation and refinement of the research plan for the third year was made through a visit of E. A. Hiler and B. Lyle to Israel at the end of the project's second year.

Final analyses of the models and field results and the final report were made during U. Shani's sabbatical leave in the USA.

MAIN ACHIEVEMENTS OF THE RESEARCH

This project helped in the recognition, though not alone, and in the wide acceptance of the linear move irrigation systems in the Israeli agricultural practice. About 40 percent of the cotton irrigated area is planned to be converted to this method. The concept of "Low Energy" irrigation machine is well accepted by the American irrigationist as well.

The main contribution of this research is in alerting of the possibility of runoff and nonuniform water application, especially for soils with low infiltration capacity, and in developing quantitative methods to estimate this possibility.

A field method to estimate the soil hydraulic conductivity function was developed. An estimation of the soil hydraulic properties is essential for the models used in this study but also the use of other models to predict the factors that influence irrigation design, crop yield or leaching requirements.

The methods of Childs and Hanks (1975) for estimating relative yield were extended to another crop (onion), and were examined and compared with field measurements under the extreme desert conditions of the Arava valley in Israel.

BENEFIT TO AGRICULTURE

This project helped in the recognition, though not alone, and in the wide acceptance of the linear move irrigation systems in the Israeli agricultural practice. About 40 percent of the cotton irrigated area is planned to be converted to this method. The method of "Low Energy" irrigation machine is widely accepted in the American irrigation practice as well.

The main contribution of this research is in alerting of the possibility of runoff and nonuniform water application, especially for soils with low infiltration capacity, and in developing quantitative methods to estimate this possibility. Many technical improvements of the irrigators and of soil cultivating practices were initiated and were tested in this project related field experiments.